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Research on the pollution performance and degradation of superhydrophobic nano-coatings for toughened glass insulators

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Abstract: Most of the research efforts to enhance the pollution performance of glass insulators have been focused on room temperature vulcanizing (RTV) silicone rubber coatings to cover the original hydrophilic surface of glass with a hydrophobic polymeric one. However, in recent years, advanced superhydrophobic nano-coatings, with intrinsic self-cleaning properties, have been developed as a possible alternative to silicone. This paper presents a research carried out in an outdoor test station, where one insulator string composed of nano-coated glass insulators was monitored for over two years and its performance compared with other identical insulator strings, but composed by RTV silicone-coated and non-coated glass insulators. The test station was located in a heavily polluted area of France and the insulator strings were energized at transmission voltage level to represent real operational conditions. The pollution performance and degradation were investigated through leakage current analyses and quarterly visual inspections of the superhydrophobic surface. The results showed that the superhydrophobic nano-coating was only effective when it was new and during a short period of time. Later on, it was subjected to a gradual degradation resulting in a loss of hydrophobicity until reaching a steady hydrophilic condition.

1. Introduction

High-voltage insulators are a key component of overhead transmission and distribution lines providing mechanical support to the conductor and withstanding the electrical and environmental stresses they may be subjected to. However, this last point is not always an easy task to achieve. Insulators installed in harsh environments and exposed to severe pollution may cause flashovers and unplanned line outages, and it constitutes one important challenge utilities have to face to ensure the continuous supply of electrical energy. The pollution performance of insulators is, therefore, crucial in maintaining the reliability of power systems [1].

Insulators made of toughened glass are widely used on account of their tough and lasting surface properties and their mechanical reliability [2]. Most of the research efforts to enhance their pollution performance have been focused on room temperature vulcanizing (RTV) silicone rubber coatings to cover the original hydrophilic surface of glass with a hydrophobic polymeric one [3]. The response of an insulator to wetting and, by extension, to pollution is greatly affected by the surface material, with an important distinction between hydrophilic and hydrophobic materials. A hydrophobic surface is water-repellent, while a surface that is easily wetted by water is hydrophilic. Hydrophobic properties are, consequently, of interest to improve the pollution performance of insulators by inhibiting the formation of continuous and conductive water films which may bridge their surface causing a flashover [4].

RTV silicone coatings consist~~s~~ of a base silicone polymer of polydimethylsiloxane (PDMS), optional extending fillers such as alumina tri-hydrate (ATH) or ground quartz to resist erosion under dry-band arcing, a catalyst, reinforcing filler, pigment, an adhesion promoter, and a cross-linking agent [5]. The coating is dispersed in a solvent such as naphtha, or a non-flammable one, to act as a carrier medium to transfer the material to the insulator. The installation of RTV silicone-coated glass insulators grew rapidly among utilities as they keep the inherent properties of toughened glass such as mechanical reliability and easiness of inspection while upgrading their pollution performance in order to eliminate [6] or, at least, sharply reduce the need for washing.

In recent years advanced superhydrophobic (initial contact angle > 150º [7]) nano-coatings, with intrinsic self-cleaning properties, have been developed as a possible alternative solution to silicone. Self-cleaning is the ability of a surface to wash out the contaminants when water drops come in contact with the surface, and the traditional areas where this technology has been applied to glass include architectural glazing, facades and windows, marine vessels and solar panels [8]. Nano-coatings are based on a polymeric resin which chemically reacts with the silica-based glass forming a covalent bond and producing an ultrathin layer at nano-scale levels. This means that the nano-coating shares electrons with the molecules in the glass itself, thus becoming part of the glass and transforming the natural hydrophilic surface of regular glass into a new superhydrophobic and self-cleaning surface. The application of these nano-coatings to glass insulators might be of interest to provide superior performance under pollution [9].

Some investigations in the United Kingdom compared the performance of porcelain insulators with and without nano-coatings in the laboratory. It was reported that nano-coated distribution 33kV post-insulators showed an increment in the flashover voltage up to 18% under artificial rain tests as per IEC 60060-1 [10]. Cap and pin insulators were compared in artificial pollution tests carried out according to the clean fog method of IEC 60507. The nano-coated sample showed a high suppression in the leakage current activity compared with the non-coated one [11]. However, it is important to mention here that standardized pollution tests are intended for porcelain and glass insulators, and they are not directly applicable to nano-coated ones.

The lack of testing standards is a challenge when researching new materials such as superhydrophobic nano-coatings for insulators and it makes it difficult to study their performance. This constraint was also highlighted by EPRI, in the United States, during the presentation of their research approach for advanced coatings [12]. Furthermore, as stated in a recent technical review of superhydrophobic coatings for high-voltage outdoor insulators, the evaluation of the performance over the long term is even more challenging [13]. The electrical and environmental stresses the insulators are subjected to under operational conditions may affect the life expectancy and performance of the nano-coatings and, at present, this is still a field to be investigated.

In view of the limitations of laboratory tests, this paper presents a research carried out in an outdoor test station, where one insulator string composed of nano-coated glass insulators was monitored for over two years, and its performance compared with other identical insulator strings, but composed by RTV silicone-coated and non-coated glass insulators. The test station was located in a severely polluted area of France and the insulator strings were energized at transmission voltage level to represent real operational conditions. Degradation on nano-coated insulators is investigated through the evaluation of the effectiveness in the leakage current suppression and quarterly visual inspections of the superhydrophobic surface.

The paper is organized as follows: in Section 2 the field monitoring procedure is described including the test objects, set-up, site description and leakage current data collection. Section 3 summarizes the test conditions, i.e. meteorological and site pollution severity stresses. Section 4 presents the pollution performance analyses, surface monitoring results and electrical discharges observations. Finally, the conclusions are drawn in Section 4.

2. Field monitoring procedure

2.1. Test objects and set-up

The superhydrophobic nano-coating was applied to the insulators in a factory. After the installation in the field, the hydrophobicity was compared with standard non-coated glass insulators. The measurement of the hydrophobicity was performed following the spray method included in IEC 62073 [14]. As shown in Fig. 1, the water sprayed on the surface of the non-coated insulators formed continuous water films, corresponding to hydrophobicity class HC 6. That is a hydrophilic surface. However, on the other hand, only discrete and small droplets were formed on nano-coated insulators corresponding to hydrophobicity class HC 1, the most hydrophobic level. The evidences between both materials are clear when zooming the surface area.

For this investigation, the insulator selected was the anti-fog type U160BSP standardized as per IEC 60305. The drawing of the insulator is shown in Fig. 2 and all the relevant dimensional features are detailed in Table 1. The deep under-ribs of this insulator type provide longer creepage distance per unit and it is particularly suitable for polluted and/or coastal areas. The insulator string installed in the field was composed by ten U160BSP units of superhydrophobic nano-coated glass insulators. It was mounted in parallel to other three identical strings, but composed by non-coated glass, half coated (bottom part) and full silicone-coated glass insulators as shown in Fig. 3.

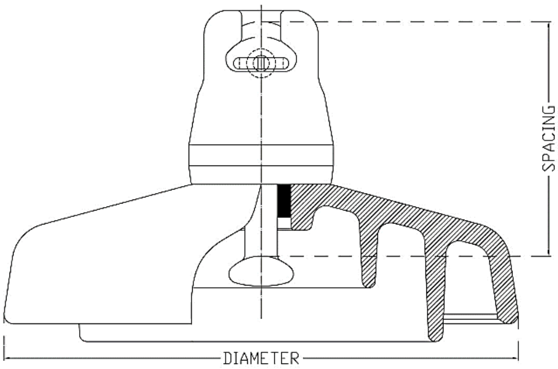

Fig. 2. *U160BSP anti-fog profile insulator* [15].

Table 1 Dimensional features

U160BSP anti-fog profile insulator	
Spacing	146 mm
Diameter	320 mm
Creepage distance	545 mm
▪ Top	30 %
▪ Bottom	70 %
Surface	3.428 cm^2
▪ Top	33 %
▪ Bottom	67 %
Protected creepage distance	355 mm
▪ Top	7 %
▪ Bottom	93 %

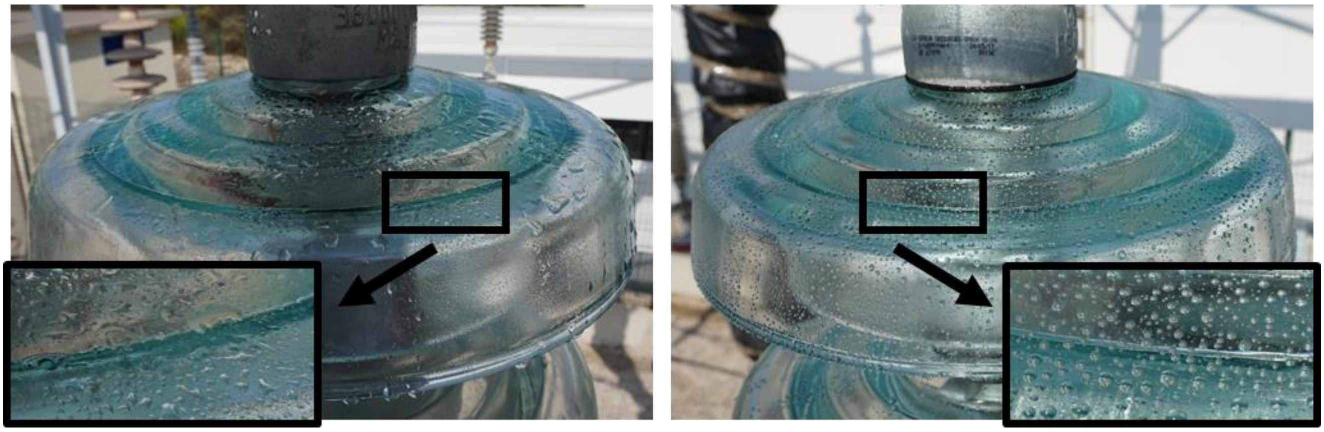

Fig. 1. *Hydrophobicity comparison between non-coated (left) and superhydrophobic nano-coated glass insulators (right).*

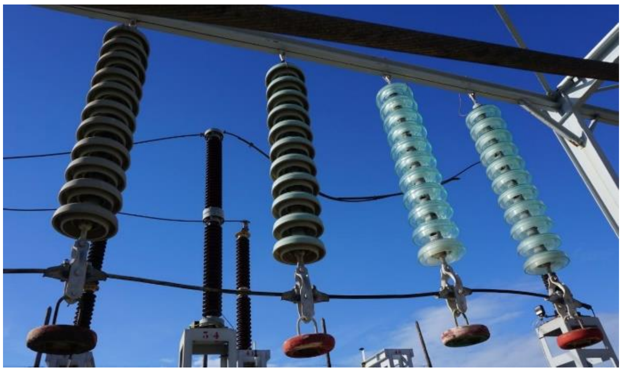

Fig. 3. *Test set-up. From left to right: full-coated, half-coated, non-coated and nano-coated glass insulators.*

Those three strings were installed one year in advance to carry out a separate study [16]. All four strings were energized with the same conductor at 245 / √3 kV giving a Unified Specific Creepage Distance (USCD) of 38.5 kV.

Two additional reference strings composed by ten non-coated glass and RTV full silicone-coated insulators were also installed one year in advance in a non-energized nearby area. The purpose of these strings was to carry out site pollution severity (SPS) measurements in terms of equivalent salt deposit density (ESDD) and non-soluble deposit density (NSDD). These data also allowed for the estimation of the pollution on the energized strings, so that it is possible to compare the performance of the new and fully clean nano-coated string with the performance of the other three strings. This issue is discussed further in later sections.

The field monitoring program was conducted over a period of twenty-six consecutive months in order to cover each season of the year twice. In this way, the test objects were exposed in an effective way to the environmental stresses of the emplacement and to all the relevant stages of pollution deposition, including the build-up of contaminants on the insulator surface during the dry summers as well as the self-washing by rain during the humid winters of the site.

2.2. Site description

The test station was established by Électricité de France (EDF) near Marseille in France. It was equipped with its own power transformer to test electrical equipment and new materials at transmission level without propagating disturbances or outages into the network. The test site was exposed to a combination of salt fog from the Mediterranean Sea and industrial pollution from a nearby power station and petrochemical industries as shown in Fig. 4. The station was usually under strong winds coming from the North West bringing a combination of heavy maritime and industrial pollution. These outdoor circumstances create a challenging environment for testing insulators under severe service conditions.

The test station was situated in a warm Mediterranean climate corresponding to Csa subtype according to the Köppen climate classification system. Consequently, warm to hot dry summers with mild and humid winters are expected. A dedicated weather station was installed for recording the meteorological parameters such as temperature, relative humidity, rainfall, winds and solar radiation every five-minutes.

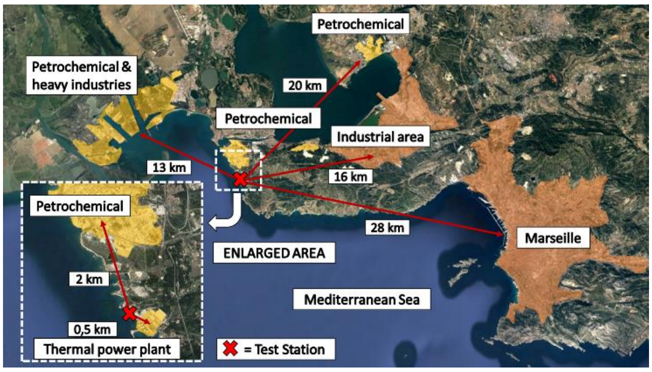

Fig. 4. *Tests station location map and industrial pollution sources in the nearby area.*

2.3. Leakage current monitoring

Every insulator string installed in the energized area was connected to leakage current sensors through a stand-off insulator installed at the ground side of the string, so that it guides the current through the measuring instrument associated to a data acquisition system. This general test arrangement is usually used at several insulator test stations worldwide [17]. The peak amplitude of the leakage current is widely recognized as a meaningful indicator of the insulator performance [18]–[21] as it provides an indication of how close the insulator string is to flashover.

Leakage current is narrowly linked to the hydrophobicity of the insulator surface. Hydrophobic surfaces prevent the formation of continuous and conductive water films decreasing the leakage current activity and improving the insulator performance under pollution. On this basis, leakage current was found to be particularly suitable to carry out the present research on the pollution performance and degradation of superhydrophobic nano-coatings by means direct comparison of its leakage current levels with the non-coated and RTV silicone-coated glass insulators ones. The maximum positive and negative peaks exceeding 10 mA over a five-minute interval were recorded for each insulator string of the energized area during the monitoring period, from October 2017 to November 2019. During that period of time, the voltage application was mostly continuous with the only exception being the scheduled trimestral shutdown due to inspection.

3. Weather and Site Pollution Severity

3.1. Meteorological conditions

The collected weather data affecting the work conditions of the insulators were analysed and summarized in Table 2. The light rainfall intensity and the low precipitations during the monitoring period may have complicated the natural self-washing of the insulator's strings. The combination of low washing with the high relative humidity, exceeding 75% most of the time, and the sustained winds bringing pollution from the sea and the petrochemical hubs, has resulted in prone conditions for the development of leakage currents across the insulator strings. It is also worth highlighting the high UV conditions of the site, with more than 3.000 hours of yearly solar radiation.

3.2. Directional dust deposit gauge

A directional dust deposit gauge (DDDG) is a device consisting of four collector tubes each with a slot in the side and a jar mounted at the bottom and arranged as to face and gather pollution from the North, South, East and West directions. It is located on a support column at 3 m height above ground level and its dimensions are standardized in accordance with IEC-TS 60815[22]. DDDG monitors windborne dust and they have been successfully used to assess the pollution levels and to determine the Site Pollution Severity (SPS) for insulators in different countries such as Iran [23], South Africa [24], Oman [25] or Sweden [26]. The DDDG measurement procedure consists of removing the container jars at monthly intervals and mixing the deposed polluted dust with 500 ml of demineralized water. Then, the conductivities of the solutions are measured and the normalized DDDG values for each direction, expressed in µS/cm and referred to a volume of 500 ml over a 30-day month interval, are calculated as follows:

$$DDDG_{N,S,E,W} = \sigma_{20} \times \frac{V_d}{500} \times \frac{30}{D} \tag{1}$$

where σ_{20} is the conductivity corrected to 20ºC, V_d is the volume of the solution, and D is the number of days the DDDG has been installed. The average of the four DDDG values gives the monthly Pollution Index (PI) which can be used for the determination of the SPS class. During the monitored period, the average PI was 185,15 µS/cm the first year and 200,31 µS/cm the second. The maximum yearly values were reached in Dec-2017 with 441,45 µS/cm and in Feb-2018 with 518,75 µS/cm respectively. These values correspond to a SPS class defined as typed "Heavy" in IEC-TS 60815. The monthly PI data are shown in Fig. 5.

3.3. Reference insulator strings

Two additional non-energized reference insulator strings composed by ten non-coated and ten RTV full silicone-coated insulators were installed in a nearby area to carry out ESDD and NSDD pollution measurements. Note this method involves the removal of the deposed pollution from the surface of the insulator to measure it in terms of soluble and non-soluble deposit densities and thus it shall not be directly performed over the energized strings in order not to modify the natural pollution collected by them. As mentioned before, the new and fully clean nano-coated insulator string was installed one year after the arrangement of the other strings. As there was no reference string composed by nano-coated insulators available, the purpose of this approach was focused on checking the accumulated pollution of the non-coated and RTV full silicone-coated insulators at the beginning of the test as well as following up on the pollution accumulation on the insulators. To achieve this, a pragmatic approach was adopted based on three different measurement intervals on fixed insulators: every three months, every year and every two years.

As shown in Fig. 5, despite having accumulated pollution at the beginning of the monitored period, there was a very marked decrease in the pollution levels during the first year. By comparing the yearly with the biyearly ESDD, it is possible to observe a convergence which basically expresses the natural washing of the non-coated and silicone coated insulators. This situation suggests that the nano-coated insulators were exposed to similar conditions and the comparative analysis among them is reasonable. The NSDD was also measured, but the data were of little relevance due to the low amount of non-soluble pollution: the maximum NSDD were reached in Nov-2019 giving 0,008 mg/cm^2 and 0,062 mg/cm^2 for the non-coated and the RTV full silicone-coated insulators respectively.

Table 2 Summary weather statistics

Variables	Mean ± SD	Min	Max	Percentiles 5th	25th	50th	75th	95th
Temperature (ºC)	13.46 ± 5.59	-3.90	28.33	4.55	9.39	13.21	17.67	22.79
Relative humidity (%)	74.27 ± 13.28	14.44	97.00	49.00	65.41	76.21	84.96	92.00
Rainfall rate (mm/h)	3.47 ± 6.68	0.05	118.55	0.48	1.00	1.82	3.69	10.48
Solar radiation (W/m^2)	171.92 ± 255.00	0.00	1163.40	0.00	0.00	2.92	302.27	755.02
Wind speed (m/s)	4.30 ± 3.10	0.00	17.53	0.00	1.88	3.85	6.31	10.11

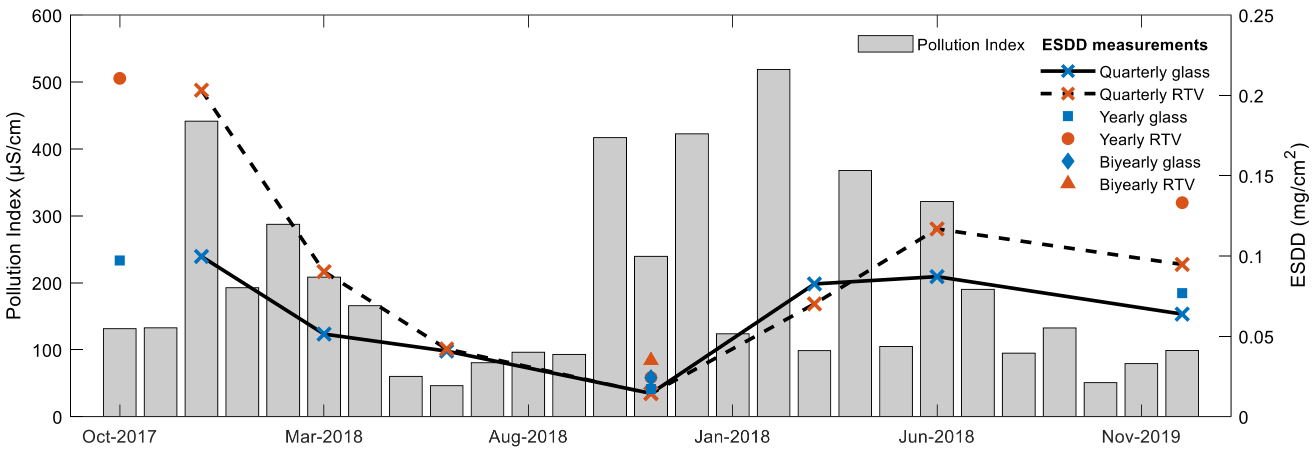

Fig. 5. *Pollution Index and ESDD levels for the reference strings during the monitored period.*

A chemical analysis was performed in order to know the ionic composition of the pollutants. The results showed a high concentration of sulfate SO^{2}_{-4} (36%), Cl^{-} (32%) and Na^{+} (16%), which confirm the hypotheses expected because the tests station is located in a coastal location near several industrial factories. Other minor pollutants found were Ca^{2+} (11%), NO^{3-} (≈ 2%), K^{+} (≈ 2%) and Mg^{2+} (≈ 1%).

4. Pollution performance analysis

The following detail the procedures and analyses carried out to investigate the pollution performance and degradation of the superhydrophobic nano-coated insulator string. A schematic diagram summarizing the monitored data and the analyses is shown in Fig. 6.

4.1. Leakage current activity

The leakage current across an insulator string is related to the probability of having a flashover and is one of the most suitable parameters to assess the pollution performance of the insulators in the field. In this respect, the nano-coated insulator string was evaluated through a leakage current comparative analysis with the non-coated and RTV silicone-coated insulator strings throughout the monitored period. The maximum leakage current pulses exceeding 10 mA over a five-minute interval were recorded for each insulator string installed in the energized area during twenty-six consecutive months, and the data were processed and classified into six different current ranges.

On a quantitative basis, and as summarized in Table 3, the superhydrophobic nano-coated insulator string showed a notable reduction of the leakage current activity when compared to the non-coated one insulator string. In every current range the pulses were lower and, considerably, much lower in the case of the three upper ranges. However, when we observe the full picture comprising all the test objects, the RTV full silicone-coated insulator string clearly showed the best pollution performance as it had the lowest leakage currents at all ranges. It was also remarkable to observe the suppression of leakage current activity found into the two upper current ranges. On the other hand, the RTV half silicone-coated insulator string showed slightly more leakage current pulses than the full silicone-coated one, but the global performance can be considered very similar. This highlights that the bottom surface of cap and pin insulators plays the major role in the pollution performance in insulators with deep under-ribs like the U160BSP. In the following analyses, the RTV half silicone-coated string can be considered similar to the RTV full silicone-coated one and, therefore, it is not included for reasons of simplicity.

4.2. Performance ratios and time evolution

The previous results suggested that the superhydrophobicity showed by the nano-coated string at the beginning of the test might have been subjected to a gradual degradation along the monitoring period. To investigate it, the leakage current data were divided into nine quarterly time consecutive periods, keeping the same six current ranges detailed before. On the assumption that the non-coated insulator string is hydrophilic and that it represents the fully loss of hydrophobicity -or worst case scenario- for nano-coated and RTV full silicone-coated insulator string, the following was defined as the leakage current relative performance ratio:

$$PR_{i,j} = \frac{LC_{i,j}}{LC_{glass,i,j}} \qquad (2)$$

where $PR_{i,j}$ is the relative performance ratio, $LC_{i,j}$ are the number of leakage current pulses registered in the range i during the period j for a certain insulator string, and $LC_{glass\ i,j}$ is the same but referred to the non-coated glass insulator string, which is the base. Although the PR in (2) is an estimative indicator based on the sum of the leakage current pulses classified into groups, it provides valuable information. When this indicator is between 0 and 1, the pollution performance of the studied string is improved with regard to the non-coated glass, where 0 represents a perfect leakage current suppression, and 1 represents the non-suppression case, i.e. with similar current activity to the non-coated glass insulator string. The time evolution of the relative performance ratios for the nano-coated (PR_n) and the RTV full silicone-coated insulator string (PR_{RTV}) are presented in Fig. 7, as well as the boxplot showing the median and the quartiles per each quarter and current range. In the case of the nano-coated insulators, it is very remarkable to observe the progressive convergence from 0, at the beginning, to around 1 at the end of the monitored period. The initial superhydrophobicity was very effective the first two quarters and, as shown in the example in Fig. 8, the leakage current activity was practically suppressed. However, later, the effect got gradually lost and the leakage current raised up to a PR around one. That increase would represent the loss of hydrophobicity until reaching a steady hydrophilic condition. In the example in Fig. 9 the leakage current activity related to pollution events in the eighth quarter is presented. In contrast to the previous figure, here it can be observed that the leakage current had identical levels and followed identical patterns to the non-coated glass insulator string.

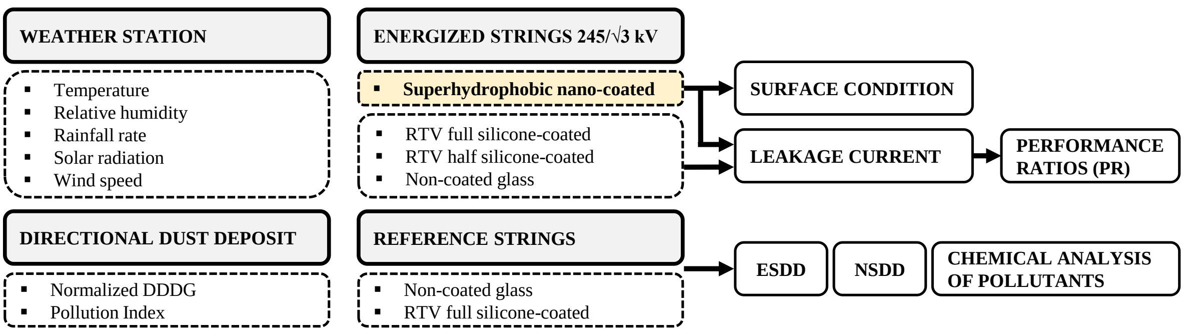

Fig. 6. *Schematic diagram of the monitored data and the pollution performance analysis.*

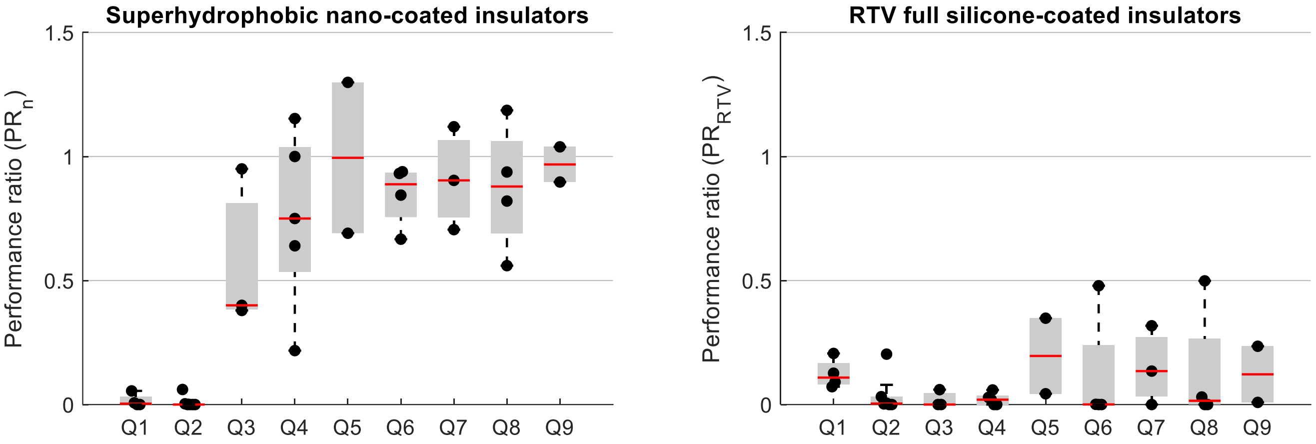

Fig. 7. *Quarterly performance ratios for superhydrophobic nano-coated (left) and RTV silicone-coated insulators (right).*

Table 3 Summary of the leakage current activity during the monitored period

Insulator string	Number of pulses per leakage current range					
	10-50 mA	50-100 mA	100-200 mA	200-300 mA	300-400 mA	400-500 mA
Non-coated glass	54081	4801	1495	271	170	11
Superhydrophobic nano-coated	38387	3496	751	66	14	2
RTV half silicone-coated	31045	688	149	10	0	0
RTV full silicone-coated	27939	183	69	7	0	0

It is important to highlight that no recovery of hydrophobicity was observed and the loss of hydrophobicity was irreversible. On the other hand, the RTV full silicone-coated insulator string had a PR below 0.5 and the leakage current suppression was very effective during the entire monitored period. The oscillations in the PR can be attributed to the dynamics of the hydrophobicity recovery and no clear degradation trends were found. The much more prolonged hydrophobicity during the monitored period, and the recovery phenomenon, make this technology more suitable and effective to improve the pollution performance of glass insulators in polluted conditions.

4.3. Surface condition monitoring

Quarterly visual inspections were carried out to detect signs of surface degradation and pollution accumulation in the nano-coated insulators. The pollution distribution, in general, was not uniform and the bottom surfaces exposed to the North West wind direction presented more pollution deposits. Those areas of the insulator were analysed in detail as they revealed better the behaviour of the nano-coating.

As shown in Fig. 10, a gradual transition from discrete circular pollution deposits in Q2 and Q3 to deposits with more irregular shape in Q3 and Q4 occurred. In Fig. 11, from Q6 to Q9 the situation intensifies and runnels and continuous polluted spots were formed, especially in Q9. These surface changes suggest that the hydrophobicity was gradually lost in certain areas throughout the monitored period, which is consistent with the previous findings.

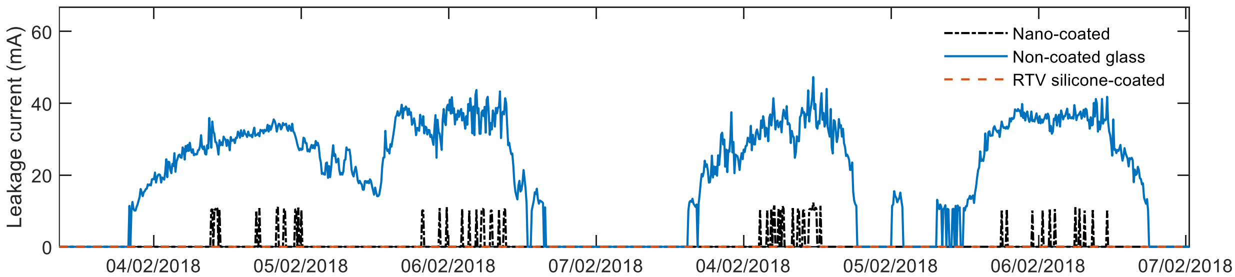

Fig. 8. *Leakage current activity related to pollution events in the second quarter Q2 of the monitored period.*

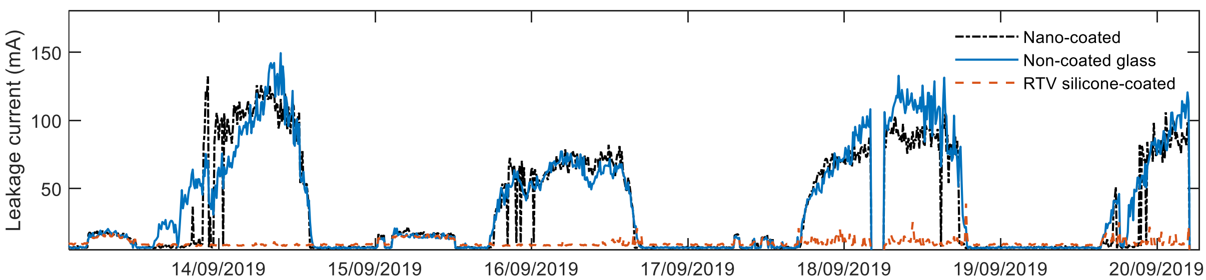

Fig. 9. *Leakage current activity related to pollution events in the eighth quarter Q8 of the monitored period.*

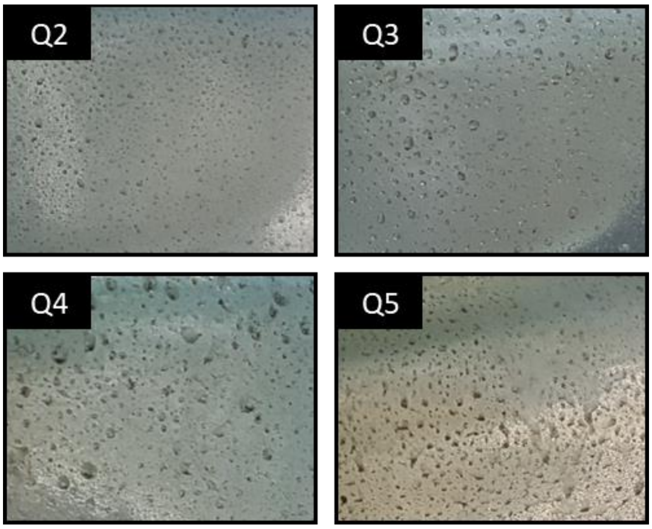

Fig. 10. *Surface condition of the nano-coated insulators at the end of the quarters Q2, Q3, Q4 and Q5.*

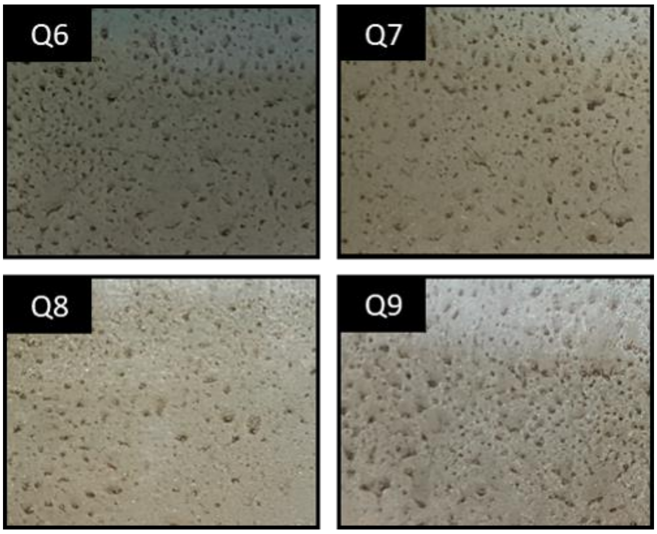

Fig. 11. *Surface condition of the nano-coated insulators at the end of the quarters Q6, Q7, Q8 and Q9.*

4.4. Dry band arcing observations

The occurrence of electrical discharges might have been one of the root causes of the surface degradation of the nano-coated insulators, but it was not possible to record them in video during the entire monitored period. Nevertheless, at the end of the ninth quarter, a camera was installed to film the dry band arcing activity due to dew-condensation wetting one day early in the morning. As shown in Fig. 12, the nano-coated and the non-coated insulator strings had dry band arcing activity simultaneously while no electrical discharges were observed in the same time period for the RTV full and half-coated insulator strings. This result shows that the loss of hydrophobicity in the nano-coated insulator string resulted in a hydrophilic state similar to the non-coated insulator string.

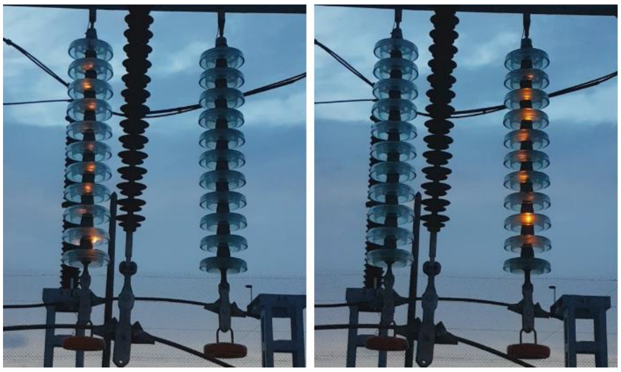

Fig. 12. *Simultaneous dry band arcing activity in the non-coated (left) and nano-coated insulators string (right).*

5. Conclusions

Toughened glass insulators coated with a superhydrophobic nano coating were monitored for over two years in a test station located in a heavily polluted area of France, and its pollution performance was compared with RTV silicone-coated and non-coated glass insulators. The main findings of the study carried out are summarized below:

I. The superhydrophobicity showed by the nano-coated insulator string is only effective when it is new and during a short period of time. Later on, it is subjected to a gradual degradation resulting in a loss of hydrophobicity until reaching a steady hydrophilic condition similar to the non-coated glass insulator string.
II. The leakage current analyses and the surface inspections did not reveal recovery of the hydrophobicity and, thus, the degradation seemed to be irreversible.
III. The RTV full and half silicone-coated insulator string showed lower leakage current levels and a better and more stable pollution performance throughout the whole monitored period
IV. At present, to enhance the pollution performance of glass insulators in harsh environments, RTV silicone coatings seem to be the best choice due to their field performance and durability. Further research is needed in the field of superhydrophobic nano-coatings to improve their endurance under conditions of outdoor pollution.

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