Detection of Corona Effect on Composite Insulators

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***Abstract*— In the last decades, there has been a great increase in the use of polymeric materials in insulation, due to their advantages over ceramic and glass insulators. In Portugal, composite insulators are used in medium, high and very high voltages, mainly in coastal regions. Corona effect consists in the disruption of a gaseous dielectric, in the proximity of energized conductors, associated with losses and premature ageing of the materials, with particularly severe consequences in the case of polymeric materials. Regarding the detection of this phenomenon, this work explores different technologies that consist in ultraviolet radiation, electric field, ultrasound or radiofrequency measuring devices. Regarding the mitigation of corona effect, the methodology of corona rings is discussed. When analyzing the service experience with composite insulators, it was noted that a significant number of insulation failures are due to their premature ageing, which is caused by corona effect. With the aim of studying the influence of different agents in the occurrence of corona effect, an experimental component was conducted and explored in this dissertation. The tests consisted in the application of different mechanical defects and pollution on the surface of polymeric insulators, which were then tested at different voltages. Corona effect may reveal a need for surface cleaning or replacement of the insulator in case there are significant defects related to the premature ageing of the insulator.**

***Index Terms*— Composite insulator, corona effect, detection of corona effect, polymeric material ageing, composite insulator service experience**

I. Introduction

BY the 1980s, polymeric materials began to be used both as coating of glass and ceramic insulators and as insulators itself [1] because of their high mechanical and dielectric supportability. Since then, its use has been growing (Fig. 1) and, considering that this growth continues to accentuate, it is necessary to study the factors that constraint its usage.

The main advantage on the use of composite insulators is their higher performance over traditional ceramic and glass insulators, under pollution conditions. In Portugal, they are currently used in medium, high and very high voltage lines, mainly located in coastal regions, where there is strong saline pollution.

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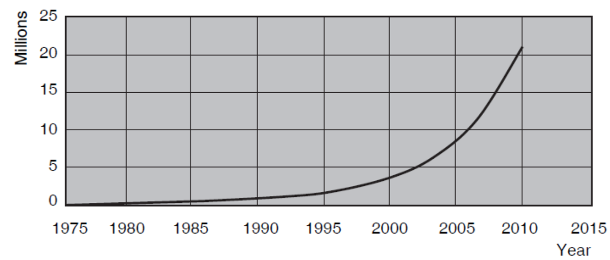

Fig. 1 – Number of polymeric insulators, for voltages higher than 69 kV, extracted from [2]

The corona effect consists on the partial disruption of a gaseous dielectric when subjected to high electric fields, usually occurring in high and very high voltage lines, near the junction between the insulator and the conductor. This phenomenon results in interference with low frequency communications, audible noise, energy losses and an accelerated ageing of the insulators, with particularly serious consequences on polymeric materials.

This accelerated material ageing is indicated as one of the major disadvantages in the use of polymeric insulators since it results in the reduction of the material supportability, increasing the chance of insulation failure and, possibly, lead to an interruption in the energy transportation.

So, with the purpose of taking measures that mitigate corona effect, it is important to proceed to its detection. In this work, the detection measures explored take advantage of different technologies: ultraviolet imaging, radiofrequency receiving antennas, ultrasound sensors and electro optic sensors.

Regarding corona effect mitigation, the use of corona rings will be explored.

For a better comprehension of the occurrence of corona effect on composite insulators, the service experience of some energy transportation agents from different countries was gathered, as shown in chapter III**.**

With the aim of studying the factors that can cause or accentuate the corona effect, the experimental procedure conduced are explained in chapter IV.

II. Composite Insulators

A. Physical Properties

Polymeric materials have several characteristics that make them a viable option in insulating, such as high dielectric strength, hydrophobicity, malleability, low weight, practicable cost of production and high mechanical support [3], vital for overhead line insulation.

The high dielectric strength is a fundamental characteristic by which these are considered good insulating materials.

One of the most relevant advantages of this type of material is its hydrophobicity because, unlike ceramic materials, polymeric materials repel particles of water from rain that would lay on its surface. This aspect is important for insulators in polluted environments because if impurities accumulate on the surface of the insulator, the presence of water could contaminate it.

Since the polymeric materials are malleable, safety is another advantage over the ceramic materials, which are brittle. This property makes them not only vulnerable to vandalism, but also subject to explode or break in extreme cases of atmospheric disasters or natural catastrophes, which can lead to projection of pieces at high speeds and unpredictable directions.

The low weight of polymeric materials is convenient for their transport and application in overhead lines.

The practicable production cost of polymeric materials grants that these are an economically viable alternative over the traditional ceramic insulators.

Mechanical withstand is another key feature for insulators due to the elongation and torsional mechanical forces associated with the operation on overhead lines.

The insulators operating on overhead lines are subjected to elongation and torsional mechanical forces.

Currently, the insulator polymeric housing can be made of silicone, epoxy or EDPM (Ethylene Propylene Diene Monomer). Depending on the characteristics of the application site, the silicone can be produced with the objective of meeting specific specifications.

The most common subtypes of silicon are LSR (Liquid Silicone Rubber), RTV (Room Temperature Vulcanizing silicone rubber) and HTV (High Temperature Vulcanizing silicone rubber) [1].

B. Degradation Mechanisms – Laboratorial Tests

The ageing of the insulators is the loss of physical properties over time, reducing their dielectric and mechanical withstand due to one or more agents: ultraviolet radiation, high temperatures, water infiltration, corona effect or even high-speed particles due to strong winds or storms.

The understanding of the impact that the degradation mechanisms have on insulating materials is possible by conducting laboratorial tests with stresses similar to the ones found in the regions to be simulated.

The tests may consist of applying only one ageing mechanism (simple tests) or several ageing mechanisms simultaneously (multiple stress tests).

1) CEA tracking wheel test

This test is included in the category “salt-fog” as it aims to test the strength of an insulator to erosion, by subjecting it to a salt water spray.

The insulator is mounted in a wheel test (Fig. 2) and subjected to a voltage depending on its leakage distance (28.6 mm/kV).

This test is usually conducted following one of two different procedures, low salt concentration with the duration of 1600 hours, or high concentration during 1000 hours [4].

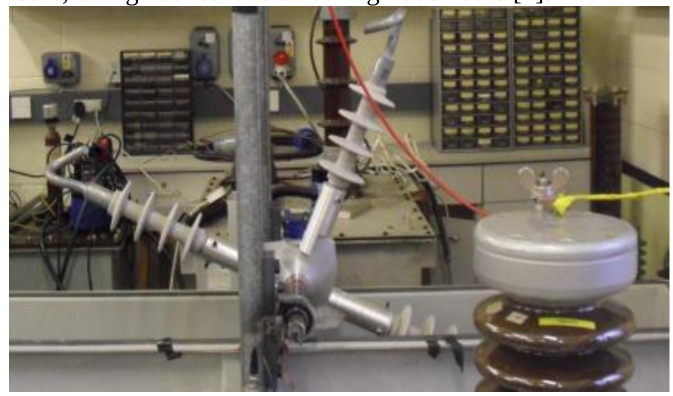

Fig. 2 – Insulators on a wheel test, extracted from [5]

2) CEA salt-fog procedure

Another simple stress test which aims to verify the performance of insulators when polluted with cement particles and salt spray, with the purpose of simulating industrial regions.

This test has no specified duration and is over when insulation failures occurred in all the insulators [4].

3) CIGRE 5000 hours test

This is a multiple stress test designed to simulate the conditions found in regions of France with high pollution levels. It is divided into several periods. In each of those, and with an applied voltage, the insulators are subjected to a different stress: demineralized rain, heating, humidification, solar irradiance and salt spray.

The duration of the test is 5000 hours, equivalent to 10 years of natural ageing [4].

4) ENEL 5000 hours test

This ENEL test is a modification of the previous CIGRE test, with more accentuated conditions (higher values of salt concentration and solar irradiance) to simulate the erosion mechanisms found in areas with high pollution in Italy.

C. Importance of Corona Effect

Among the mentioned degradation mechanisms, the corona effect is referred as one of the main constraints on the performance of composite insulators, due to its impact on the premature ageing of the polymeric material.

It is important to characterize the corona effect by exploring its consequences, modes of failure to which it is associated, and the methodologies that can be used to detect and mitigate it.

III. Corona Effect

A. Consequences

The motivation of this work is that the corona effect degrades the polymeric material of the material, also resulting in acoustic noise, interference in communications and energy losses.

The process of material degradation is essentially due to chemical reactions and has consequences on dielectric and mechanical properties [6]. The dielectric strength of the materials is reduced, making partial discharges on their surface more common and lowering the withstand voltage of the insulator. As for the mechanical changes, the appearance of fractures in the polymeric material leads to the exposure of the fiberglass core, becoming vulnerable to meteorological agents and partial discharges that causa its degradation and carbonization [7].

As for the acoustic noise, it is caused by collisions between electrified particles (free electrons and ions) created by corona effect and air molecules, producing audible vibration [8].

Interference may occur in low frequency communications, such as radio and television signals, due to the electrical signals emitted by the partial discharges [9].

This phenomenon is also associated with energy losses in the form of heat and noise.

B. Detection Methods

With the purpose of reducing the number of failures in the energy transportation, it is essential to ensure the detection of partial discharges caused by the preliminary corona effect. If that is not achieved, ageing will become more pronounced until insulation failures occur and, consequently, energy transportation gets interrupted.

Corona effect detection can be achieved through ultraviolet cameras, radio frequency antennas, electric field measurement sensors or even ultrasound receiving probes.

1) Ultraviolet camera

The dominant corona effect detection method [10] takes advantage of the fact that it emits radiation in the air in a wavelength range between 210 and 500 nm [11], thus providing the opportunity for the development of a band pass filter, to be incorporated into a camera, properly sized so that it is a sensible to UV (Ultraviolet) radiation.

The Israeli company OFIL has developed the DayCor range of cameras, incorporated with a bandpass filter, allowing only passage at wavelengths between 240 and 280 nm. This range, commonly referred to as the “solar blind region”, was chosen because the solar radiation emitted in this band has practically no intensity when reaching the surface of our planet due to the ozone layer filtering, allowing daytime detection [11].

Concerning to the images obtained by the camera, the DayCor use bispectrality, that is, through filtering and reflection phenomena, separates the incident radiation into two distinct components, one ultraviolet and the other visible, as shown on Fig. 3.

The UV radiation is then filtered to exclude the wavelengths outside the solar blind area and is then received by a suitable sensor. On the other hand, the visible radiation is received by another sensor dimensioned for processing the wavelengths of this radiation range.

Finally, a bispectral image with the two synchronized components is obtained by using the visible signal as background on which the UV emission points are printed [12].

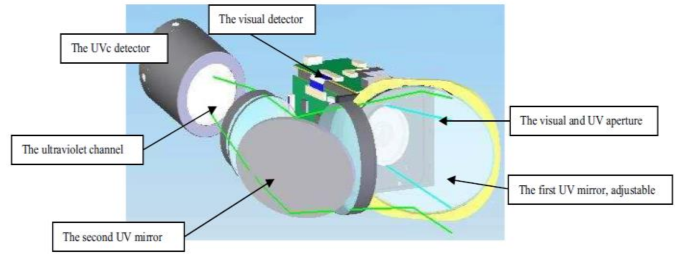

Fig. 3 – Scheme of a bispectral UV camera, adapted from [12]

2) Radiofrequency Antenna

Alternatively, corona detection can be performed using radiofrequency measurement devices.

This technology takes advantage of a circuit specified in IEC 60270, connected to an antenna for reception of radiofrequencies, thus measuring the electromagnetic emissions, in high frequency ranges, caused by corona effect.

The PDS100 model, used mainly in the detection of partial discharges in substations, is commercialized by the American company Doble. This apparatus is dimensioned for reception in the range of 50 to 1000 MHz and may be extended to 25 to 1900 MHz, if an appropriate telescopic antenna is used.

If the data measured by the sensor is to be used in inspection reports, it can be properly interpreted using appropriate software.

3) Electric Field Measuring Sensor

Taking in account that the partial discharges modify the electric field on the insulators surface, another method of detection is achieved through an EO (Electric-Optical) electric field detection sensor, a prototype of the company Kapteos [13].

The principle of operation of the sensor is based on the Pockel effect, it contains a crystal that produces birefringence (crystalline property related to refraction) [14], then sends signal via optical fiber to an optoelectronic processing unit. This measures the electric field by its proportionality with the square of the measured refractive index (Kerr effect) [15].

4) Ultrasound Probe

Finally, another method of corona effect detection takes advantage on the fact that partial discharges associated with this phenomenon cause the air molecules to vibrate at various frequencies (namely at high frequencies). In this way, corona detection can be performed using a calibrated probe for ultrasound detection, which then converts them to an audible frequency range, such as the Ultraprobe range (by the company UE Systems), which are sensitive to frequencies between 20 and 100 kHz [16].

In addition to corona effect, electrical tracking and arcs emit characteristic ultrasounds, which after conversion by the probe can be identified by the user through his hearing. On the other hand, after the recording of these sounds, spectral analysis software can also be used and is particularly useful when direct interpretation is dubious. Some of the most recent apparatus allow to perform this spectral analysis in the field

[16].

One of the limitations of this technology is that the measurements require to be carried out at short distances, with the maximum range of Ultraprobe 10,000 and 15,000 being about 10 meters, as it was possible to understand through contact with the company UE Systems. This value can be doubled using a UWC (Ultrasonic Waveform Concentrator) which is particularly useful for inspection of line insulators, as shown in Fig. 4.

Fig. 4 – Ultraprobe 10,000 equipped with UWC, extracted from [16]

C. Comparison between detection methods

The Table A was elaborated with the objective of comparing the detection methods previously mentioned. It contains information provided, through contact via e-mail, by the companies UE Systems, Kapteos and Doble.

Such table contains aspects such as the accuracy and detection range of the methodology and its vulnerability to audible noise. It is also specified which technologies require a line of sight for the element to be inspected as well as the possibility of recording the obtained data, allowing the use in inspection reports. Finally, the possibility of integration with other complementary inspection technologies for land, automobile or air inspections is mentioned.

Regarding the dependence on atmospheric conditions, although it is relevant factor, it was decided not to include it in Table A, since the four methodologies present a similar behavior. In the presence of precipitation, the detection of corona effect is discouraged because the deposition of raindrops on insulators on overhead lines can cause the occurrence of corona effect [17]. This situation means that it is not possible to conclude whether the corona effect detected is due only to the rainfall or whether it would also occur in dry weather due to the ageing or defect of the materials.

Another characteristic shared by the four methodologies is that none of these require physical contact with the electrical system to be inspected. This is a beneficial detail because preferring non-invasive technologies can ensure that inspections are conducted with better security.

The detection range is considered the maximum distance, which ensures correct corona effect detection, between the apparatus and the electrical system to be inspected.

A methodology is highly accurate if the user can clearly identify where corona effect occurs. On the other hand, it is considered that a methodology has reduced accuracy if only allows to indicate a region, more uncertainly, where corona effect occurs. This is a determinant factor since if a detection method is accurate, the area to be rectified by the maintenance teams can be specified.

Another aspect in which the methodologies can be compared is the need for an obstacle-free line of sight. This is required both by the UV cameras and by the Kapteos sensor. On the other hand, ultrasonic probes and radiofrequency antennas have the advantage of admitting obstacles (trees, for example) between them and the element to be inspected.

The influence of audible noise on the detection of corona effect is important because it can be a constraint both for high noise urban areas and for the possibility of carrying out the detection on board of a motored vehicle.

A methodology can be useful for integration in reports if it allows to obtain backup in a format to be incorporated in reports (photographs or graphs).

The possibility of integrating a detection method with different technologies into a single device is important because, as it allows a more complete defect detection, it can result in a reduction of travel expenses and number of devices carried.

An investigation of the prices of different solutions was also carried out, as shown in Table A.

TABLE A – COMPARISON OF DETECTION METHODOLOGIES

	UV	***Kapteos sensor***	**Ultrasound**	**RF**
Detection range	High (50-150m)	High (100m)	Low (5-20m)	Low
Accuracy	High	High	Low	Low
Line of sight needed	Yes	Yes	No	No
Dependent on audible noise	No	No	Yes	Yes
Useful for reports	Yes	Yes	No	No
Backup	Photograph / Video	Signal acquisition	Sound recording	Graph
Type of inspection	Land/Air (helicopter)	Land/Air (helicopter)	Land	Land
Integration with different technologies	With IV camera (*gimball*)	No	No	With Acoustic sensor
Price	**OFIL** ROMpact Daycor: 18.500 €	**Kapteos** EOprobe + EOsensor: 25.000 €	**UE Systems** UP10000: 9.995 € UP15000: 13.995 €	**Doble** PDS100: 13.530 €

D. Mitigation Solutions

One of the phenomena that leads to high electric fields, causing corona effect, is the non-uniform distribution of voltage along the chains of insulators. This leads to the electric field being higher near some insulators, exceeding the critical electric field value.

To prevent this situation, corona rings (also called regularization rings [18]) may be used to avoid regions of higher electric field near the insulators. These accessories may have different geometries and dimensions, depending on the voltage in the conductors and the characteristics of site where they are intended to be incorporated. Its dimensioning is based on optimization algorithms, allowing to simulate the redistribution of electric field considering the number of corona rings and the characteristics of remaining elements [19]. With respect to the number of corona rings to be applied in each insulator chain, it depends on the voltage to which it is subject.

In some cases, the corona rings are designed in a specific shape that allows them to work as an arcing horn. For this purpose, an arcing horn is applied to the terminal next to the post so that, in case of electric arc, the discharge occurs through the air gap between the ring and the arcing horn [20]. This ensures that the electric arc does not occur on the surface of the insulator, significantly reducing the damage caused and preventing its breakage.

E. Service Experience with Composite Insulators

As in the Chapter II, the occurrence of corona effect results in accelerated ageing of the polymeric material. If preventive measures are not taken, the reduction of the electrical and mechanical supportability can lead to insulation failures of different types, such as brittle fracture, flashover or flashunder.

The occurrence of partial discharges, on the surface of composite insulators, causes chemical reactions in the fiberglass core, degrading it. The supportability of the material is reduced over time, possibly resulting in a brittle fracture, which consists of a partially inelastic break of the core, causing the mechanical rupture of the insulator [21].

If preventive measures are not taken, partial discharges, associated to corona effect, increase in intensity over time and, in extreme causes, can result in an electric arc (flashover).

In some cases, the ageing results in the puncture of the polymeric material, allowing the deposition of water droplets from precipitation near the core, enhancing the occurrence of partial interior arcs. Considering that the intensity of these increase with time, this phenomenon may even result in an internal electric arc, also called flashunder [22].

Next, the service experience with composite insulators based on studies in the USA, China and Portugal, will be presented.

1. Composite Insulators in USA

Motivated by the occurrence of failures in composite insulators in the USA, at 115, 132 and 138 kV voltage levels (Fig. 5), EPRI (Electric Power Research Institute) started in 2006 to conduct a study with the purpose of understanding them so that they could be later prevented [23].

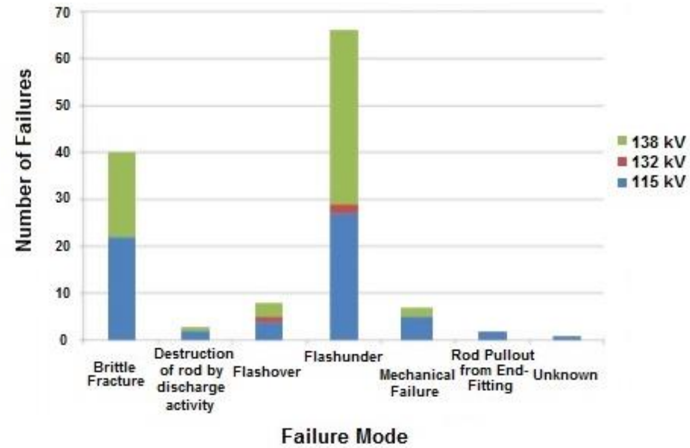

Fig. 5 - Failure modes in composite insulators in USA, extracted from [24]

The researchers focused at the insulators of the 115 and 138 kV lines, detecting corona effect in a significant number of those. In the cases where corona effect was detected, corona rings were applied, followed by a new inspection. It was found that its application totally mitigated corona effect in all insulators [23].

Then some insulators were removed from service and subjected to visual inspection. The insulators that showed the greatest signs of ageing were the same where previously corona effect was detected [24]. For this reason, it can be concluded that this is the main cause of premature ageing, responsible for the failures in the composite insulators.

2. Composite Insulators in China

Later than in the USA, the composite insulators started being used in China in the late 1990s, and between 1996 and 2006, their number increased exponentially from about 50,000 do 2,2 million. In 2009, they were already the most used type of insulator, representing 36% of all insulators installed [25].

One of the studies developed in this subject, was conducted by Prof. Guan Zhicheng, from Tsinghua University. The study went through the accounting and investigation of the failures occurred between 2000 and 2006 (Fig. 6).

When analyzing the graph, it is noted that 69% of the failure modes are related to defects in the manufacture because, as previously mentioned, a brittle fracture is a failure mode that results from ageing of insulators.

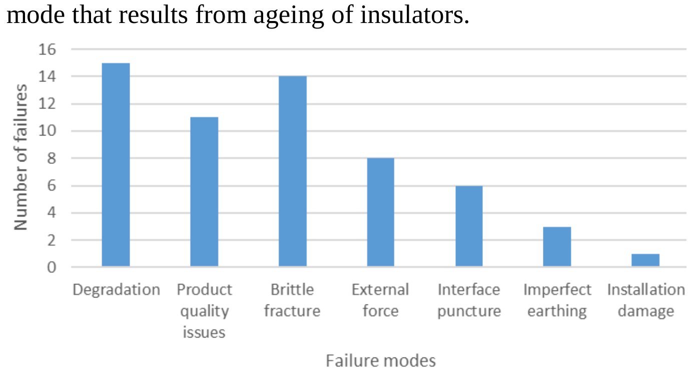

Fig. 6 - Failure modes in composite insulators in China, extracted from [25]

When doing a quantitative analysis of failure modes, it can be verified that their proportion is very small, because there were failures in 58 composite insulators out of a total of 2,2 million installed. On the other hand, considering that most of these have been applied to the Chinese lines for about a decade, more accurate conclusions will require a longer service experience.

3. Composite Insulators in Portugal

Regarding the use of line composite insulators in Portugal, these began to be used by REN in 2007 (Fig. 7), and are currently also used by EDP Distribuição, in medium, high and very high voltages.

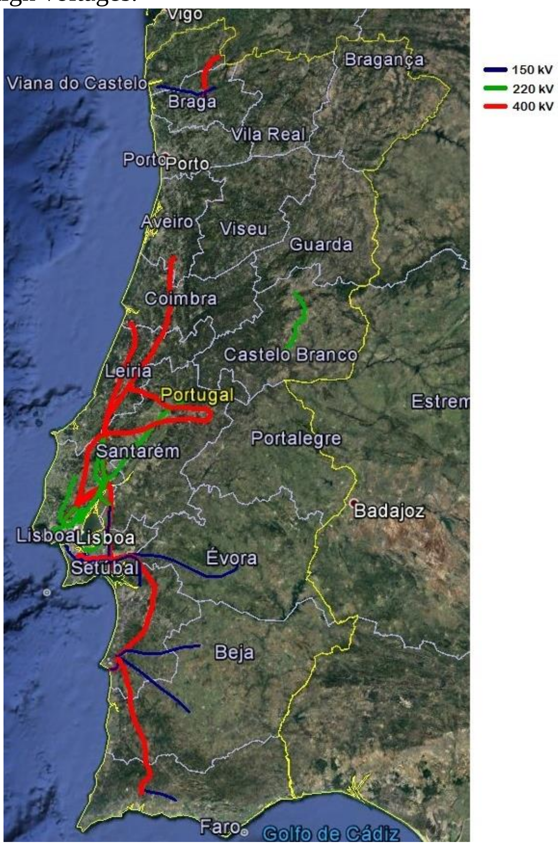

Fig. 7 – Overhead lines with composite insulators, from REN

Due to their good performance under pollution conditions, composite insulators in Portugal are mainly used in coastal regions, with the aim of taking advantage of their properties in conditions of salt pollution and high humidity.

IV. Experimental Procedure

The experimental component was divided into 3 different experiments. To perform the detection of partial discharges, the ultraviolet camera SWE-400, from SweSystem, was mounted in a rack along with its power supply and a signal processing unit (Fig. 8), which grants the interface between the gimball and the monitor and computer. By using the software provided by this same company, WebcamViewer and VideoView, photos and videos can be saved, in real time, directly on the hard disk of a computer.

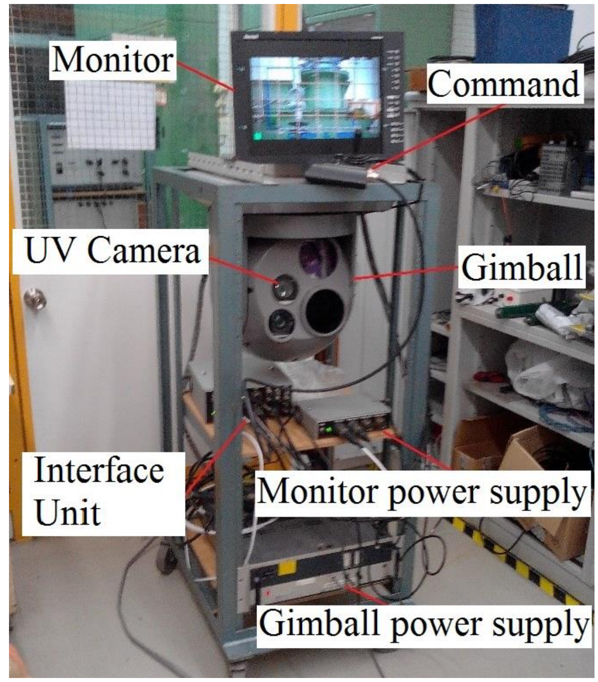

Fig. 8 – Apparatus used for corona detection

A. Detection of corona effect on a composite insulator

The tests were conducted with the objective of detecting corona effect on a composite insulator (Fig. 9) which was stored in Labelec facility for about 6 years and has never been used or subjected to voltage.

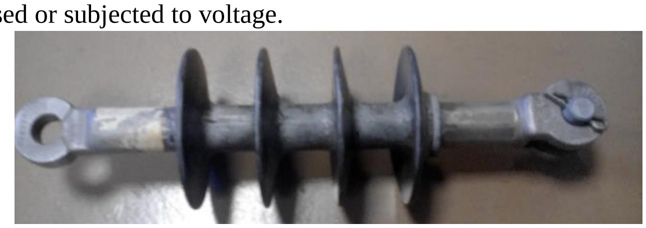

Fig. 9 – Composite insulator tested in experiment 1

This experiment was divided into 10 different tests:

- Test 1 - Dry insulator, no defects
- Test 2 - Dry insulator, copper string applied
- Test 3 - Wet insulator with water
- Test 4 - Dry insulator with puncture (1st shed)
- Test 5 - Dry insulator with puncture (1st shed) and cut (4th shed)
- Test 6 - Wet insulator with puncture (1st shed) and cut (4th shed)
- Test 7 - Wet insulator with puncture (1st shed) and cut (4th shed)
- Test 8 - Dry insulator with puncture (1st shed) and cropping (4th shed)
- Test 9 - Wet insulator with puncture (1st, 2nd and 3rd sheds) and cropping (4th shed)
- Test 10 - Wet insulator with puncture (1st, 2nd and 3rd sheds) and cropping (4th shed)

In each of the tests, the insulator was subjected to several AC voltages and using the gimball, for each case, an illustrative image of the detection of corona effect was obtained. The test results are presented in Table B.

TABLE B – RESULTS OF EXPERIMENT 1

Test	Applied Voltage (kV)	Partial Discharge
Test 1 - Dry insulator, no defects	5, 10, 12, 14, 18, 20, 23	No
Test 2 - Dry insulator, copper string applied	5 10 15 20 23	No Yes Yes Yes Yes
Test 3 - Wet insulator with water	5 10 15 20 23	No Yes Yes Yes Yes
Test 4 - Dry insulator with puncture (1st shed)	5, 10, 15, 20, 23	No
Test 5 - Dry insulator with puncture (1st shed) and cut (4th shed)	5, 10, 15, 20, 23	No
Test 7 - Wet insulator with puncture (1st shed) and cut (4th shed)	10 15 20	Yes Yes Yes
Test 8 - Dry insulator with puncture (1st shed) and cut-out (4th shed)	5, 10, 15, 20, 23, 25, 30, 35	No
Test 9 - Wet insulator with puncture (1st, 2nd and 3rd sheds) and cut-out (4th shed)	5 10 15 20 23	Yes Yes Yes Yes Yes
Test 10 - Wet insulator with puncture (1st, 2nd and 3rd sheds) and cut-out (4th shed)	5, 10, 15, 20, 23, 25, 30, 35	No

It was planned the Test 6 to be conducted with the wet insulator. However, after the application of water on its surface, a delay in the application of voltage led to the insulator having repelled most of the water from its surface, leading to results like those obtained Test 5. For this reason, Test 6 is not included in Table B.

Based on the tests, it can be concluded that the insulator, in dry conditions, maintained high dielectric supportability when subjected to the mechanical defects. That is shown by the absence of both corona effect and electric arc in tests 4, 5, 8 and 10, for all voltages applied.

The objective of test 2 was to test the influence of the decrease of the leakage distance in the occurrence of corona effect. However, the partial discharges detected were located on the edge of the copper conductor, due to its pointy geometry.

It has been also noted that the insulator repelled the water from its surface, so it can be concluded that its storage had no significant consequences on its hydrophobic properties.

The water at the surface of the insulator played a major role in the tests, as it significantly enhances the occurrence of corona effect, as verified in tests 3, 7 and 9.

In test 9, it was noted that the partial discharges were mainly located between the 3rd and 4th sheds. This is due to the fact that the cut-out on the 4th shed was carried out in a direction close to the puncture of the 3rd shed, reducing the leakage distance on this region.

It was noted the occurrence of effluvia, indicators of the occurrence of partial discharge, in unexpected regions away from the insulator (Fig. 10). These were noted to have occurred with greater intensity and frequency in the tests on which corona effect was detected. It can be then deduced that these are only perturbations in the air molecules, caused by its partial disruption, but that have spread, instead of being circumscribed to the surface of the insulator.

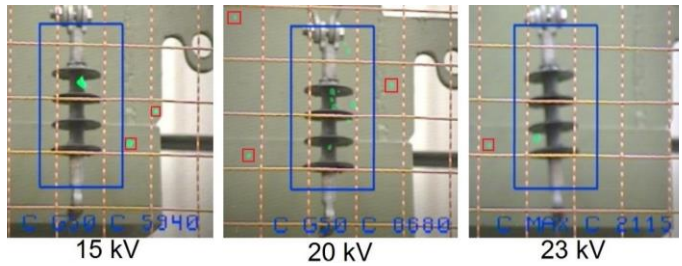

Fig. 10 – Effluvia away from the insulator surface

B. Detection of corona effect on a new composite insulator

The tests described below were performed on a new 46 kV polymeric insulator provided by EDP Distribuição (Fig. 11). The tests were conducted with and without corona rings applied.

The application of corona rings in the experiment allow to verify their influence in presence of different defects. This way, it will be possible to verify its practicality in regions where the occurrence of defects in the surface of the insulators is frequent.

Fig. 11 – Composite insulator tested in experiment 2

Pollution (ashes) was applied on the surface of the insulator to study its influence on the occurrence of corona effect, with and without the simultaneous deposition of water. On the other hand, cropping was applied on the insulator sheds to simulate bird attacks in polymeric insulators, which lead to a decrease in the leakage distance.

To mitigate the corona effect, a corona ring, designed for 230 kV electrical systems, provided by Labelec, was used.

This experiment, which results are shown in Table C, was divided into 8 tests:

- Test 1 - Dry insulator, no defects
- Test 2 - Dry insulator, ashes applied on its surface
- Test 3 - Wet insulator, ashes applied on its surface
- Test 4 - Wet insulator, ashes applied on its surface and corona ring near the 1st shed.

- Test 5 - Dry insulator with cropping (1st, 2nd, 3rd, 4th and 5th sheds)
- Test 6 - Dry insulator with cropping (1st, 2nd, 3rd, 4th and 5th sheds) and ashes applied on its surface
- Test 7 - Wet insulator with cropping (1st, 2nd, 3rd, 4th and 5th sheds) and ashes applied on its surface
- Test 8 - Wet insulator with cropping (1st, 2nd, 3rd, 4th and 5th sheds), ashes applied on its surface and corona ring near the 1st shed.

TABLE C – RESULTS OF EXPERIMENT 2

Test	Applied Voltage (kV)	Partial Discharge
Test 1 - Dry insulator, no defects	10, 15, 20, 25, 26	No
Test 2 - Dry insulator, ashes applied on its surface	10	No
	15	No
	20	No
	25	Yes
	30	Yes
Test 3 - Wet insulator, ashes applied on its surface	10	No
	15	No
	20	No
	25	Yes
	30	Yes
Test 4 - Wet insulator, ashes applied on its surface and corona ring near the 1st shed.	10, 15, 20, 25, 30	No
Test 5 - Dry insulator with cut-out (1st, 2nd, 3rd, 4th and 5th sheds)	10	No
	15	No
	20	No
	25	Yes
	30	Yes
Test 6 - Dry insulator with cut-out (1st, 2nd, 3rd, 4th and 5th sheds) and ashes applied on its surface	10	No
	15	No
	20	No
	25	Yes
	30	Yes
Test 7 - Wet insulator with cut-out (1st, 2nd, 3rd, 4th and 5th sheds) and ashes applied on its surface	10	No
	15	No
	20	No
	25	Yes
	30	Yes
Test 8 - Wet insulator with cut-out (1st, 2nd, 3rd, 4th and 5th sheds), ashes applied on its surface and corona ring near the 1st shed.	10	No
	15	No
	20	No
	25	No
	30	Yes

The results obtained in the tests 2, 3, 5, 6 and 7 show that both the cut-outs in the sheds and ash deposited on the surface of the insulator result in a reduction of the critical electric field value, leading to the occurrence of corona effect for voltage levels 25 and 30 kV.

About the hydrophobic properties, it was noted that the insulator had a very strong tendency to repel the water from its surface, avoiding its contamination. This behavior led to the same results obtained for the equivalent tests whether the insulator was initially dry or wet, as in tests 2 and 3, 6 and 7.

Based on the tests 3 and 4, the good performance of the corona ring was noted, even considering its oversizing when compared to the applied voltages. In fact, its application completely avoided the occurrence of corona effect.

For the tests 7 and 8, similar conclusions can be drawn from those of 3 and 4. But with the particularity that, in the corona ring test, corona effect occurred at the opposite end of the insulator. This situation can be mitigated by applying a second corona ring near the affected extremity.

C. *Detection of corona effect on a ceramic insulator with polymeric housing*

The experiment 3 was conducted to detect corona effect on a 30 kV polymeric coated ceramic insulator (Fig. 12), which was divided into 6 tests:

- Test 1 - Dry insulator, no defects
- Test 2 - Dry insulator, ashes applied on its surface
- Test 3 - Wet insulator, ashes applied on its surface
- Test 4 - Wet insulator, soil applied on its surface
- Test 5 - Dry insulator with salt applied on its surface
- Test 6 - Wet insulator with salt applied on its surface

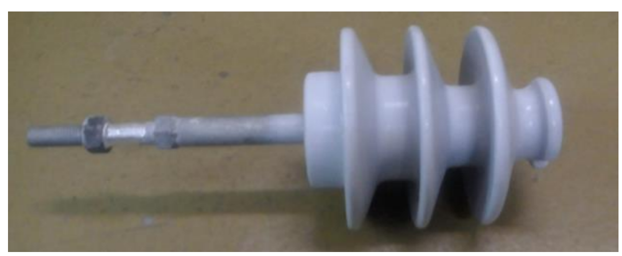

Fig. 12 – Polymeric coated ceramic insulator used in experiment 3

The results of this experiment are shown in Table D.

The mechanical defects that were intended to be applied to the insulator would be the removal of part of the polymeric coating and the breaking of part of the 1st shed, that that its impact could be testes in the occurrence of corona effect. However, that was not possible since such damage would be irreversible and thus not fulfilling the need to preserve the mechanical integrity of the insulator.

Based on the results of tests 2 and 3, it is found that the impact of ash applied on the surface strongly depends on the condition of the insulator, being dry or wet.

For the voltage levels applied, the ashes used in test 2, deposited on the dry insulator, did not cause corona effect, so it can be concluded that the critical voltage value is, in this case, higher than 30 kV.

TABLE D - RESULTS OF EXPERIMENT 3

Test	Applied Voltage (kV)	Partial Discharge
Test 1 - Dry insulator, no defects	10, 15, 20, 25, 30	No
Test 2 - Dry insulator, ashes applied on its surface	10, 15, 20, 25, 30	No
Test 3 - Wet insulator, ashes applied on its surface	10	No
	15	Yes
	20	Yes
	25	Yes
	30	Yes
Test 4 - Wet insulator, soil applied on its surface	10	No
	15	No
	20	Yes
	25	Yes
	30	Yes
Test 5 - Dry insulator with salt applied on its surface	10	No
	15	No
	20	No
	25	No
	30	Yes
Test 6 - Wet insulator with salt applied on its surface	10	No
	15	No
	20	No
	25	Yes
	30	Yes

With respect to test 3, that fact that the insulator was wet after the application of ash on its surface resulted in an accentuated decrease of its critical voltage value, resulting in the occurrence of corona effect for voltages over 15 kV.

The application of soil on the surface of the insulator when it was wet, in test 4, led to the occurrence of corona effect for voltages over 20 kV.

The application of salt and water on the surface of the insulator, in test 6, led to the occurrence of corona effect for the voltages 25 and 30 kV, with the occurrence of partial discharges sufficiently intense to produce an audible noise, making possible its visual and auditory detection.

During the conduction of the test 6, it was also noted that the partial discharges occurred mainly near 2 distinct regions at the base and edge of the 1st shed, as can be seen in Fig. 13. Since this was not detected in the remaining tests of this experiment, it was inferred that it was due to a lack of homogeneity in the salt distribution on the surface of the insulator, causing it to be contaminated irregularly.

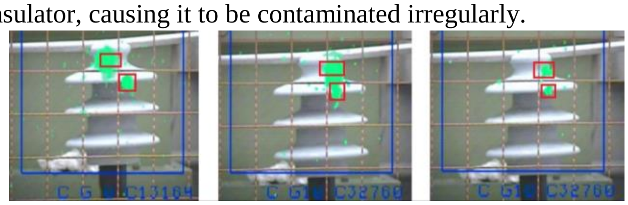

Fig. 13 – Detection of corona effect in test 6

V. CONCLUSIONS

The main objective of this work was the study of the occurrence of corona effect on composite insulators, supported by a theoretical component, which went through the description of its consequences and methodologies of detection and mitigation, and by another practical, which consisted in the conduction of experimental tests.

Based on both the analysis of the characteristics of Table A and the contact with Labelec, some conclusions were drawn regarding different methodologies for corona detection.

Of the four methodologies studied, the most appropriate for the detection of corona effect in overhead line insulators is through UV cameras, due to its high accuracy, reach, versatility and the possibility of integrating its backups into inspection reports.

Regarding the methodology that uses RF measurement, it is more appropriate for use in substations. These devices, in addition to allowing detection of corona effect, companies such as Doble, sell accessories that also provide them acoustic sensitivity, enabling a more complete detection.

Regarding the use of composite insulators, different service experiments were observed in the different countries studied.

USA was one of the pioneer countries in the use of composite insulators, with more than thirty years of service experiment. Through a study conducted by EPRI, focused on composite insulators in lines of 115, 132 and 138 kV, it has been demonstrated that failures due to corona effect can be avoided using corona rings.

In the case of China, there has been a low number of insulation failures in composite insulators. However, most of these have been installed in lines for about a decade, so the service experience is still reduced when compared to USA.

Through the conduction of experimental tests, it was possible to verify the influence of different types of defects and pollution in the occurrence of corona effect.

In the tests on which pollution was deposited on the surface of the insulator, it was noted that the it was the use of salt that potentiated most significantly the occurrence of corona effect. In fact, the partial discharges, particularly intense when the insulator was wet, revealed in the laboratory the need for special care (inspections and more frequent cleaning) with insulators operating in coastal regions.

With respect to the application of defects, it was found that the more pronounced the cropping in the insulator sheds, the lower the leakage distance became, resulting in a lower critical voltage.

With the aim of having a better understanding about the effects of ageing, it would have been important to include, in the experimental tests, a medium voltage composite insulator removed from service. However, that was not possible.

With the present work, it was possible to draw conclusions about the advantages, but also the precautions to be taken in the use of composite insulators. To avoid the premature ageing of polymeric materials, measures should be taken to mitigate corona effect, such as corona rings or periodic cleaning on the surface of the insulators, of adjustable frequency depending of the pollution levels of the site.

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References

[1] A3.21, CIGRÉ Working Group, "Aspects for the Application of Composite Insulators to HV Apparatus," CIGRÉ Technical Brochure 455, 2009.

[2] F. Schmuk, J. Seifert, I. Gutman, A. Pigini, "Assessment of the Conditions of Overhead Lines Composite Insulators," CIGRÉ, Paris - França, 2012.

[3] CIGRÉ task force 33.04.01, "Polluted Insulators: A Review of Current Knowledge," CIGRÉ, Paris - França, Junho 2000.

[4] Al Bernstof, Michael G. Comber, "Design Test Report - Report No. EU1530-H," 19 12 2005. [Online]. Available: http://www.hubbellpowersystems.com/resources/test-reports/EU1530-H.pdf. [Accessed 30 01 2017].

[5] G. ALICE, "Tracking wheel test for dc polymeric insulators," Università Degli Studi di Padova, Padova - Itália, 2011.

[6] Maoqiang Bi, Stanislaw M. Gubanski, Henrik Hilborg, Jens M. Seifert, Bin Ma, "Effects of Long Term Corona and Humidity Exposure of Silicone Rubber Based Housing Materials," Electra, Chongqing, 2013.

[7] G. H. Vaillancourt, S. Carignan, C. Jean, "Experience with the Detection of Faulty Composite Insulators on High-Voltage Power Lines by the Electric Field Measurement Method," "IEEE Transactions on Power Delivery, Vol.13", Quebec - Canadá, Abril 1998.

[8] X. Li, X. Cui, T. Lu, D. Wang, Z. Wang and H. Zhang, "A Platform for Multiple DC Corona Effects Measurements and Analysis," IEEE Intrumentation and Measurement Techonology Conference, Pequim, 2015.

[9] J. Parmar, "Electrical Notes & Articles," 23 Março 2011. [Online]. Available: https://electricalnotes.wordpress.com/2011/03/23/what-is-corona-effect/.

[10] Y. Limin, Zhangyu, "Ultraviolet Image Processing Method in Corona Detection," *2nd International Workshop on Computer Science and Engineering, WCSE 2009*, vol. 1, pp. 327-331, 2009.

[11] M. Linder, S. Elstein, P. Linder, J. M. Topaz e A. J. Phillips, "Daylight Corona Discharge Imager," EPRI - Energy Delivery and Utilization Center, Lenox, USA, 1999.

[12] R. Stolper, J. Hart e N. Matatho, "The design and evaluation of a Multi-Spectral Imaging Camera for the inspection of transmission lines and substation equipment," CSIR, South Africa, 2005.

[13] C. Volat, L. Duvillaret and G. Gaborit, "Detection of AC Corona Discharges Using an Electro-Optic E-field Sensor," IEEE International Symposium on Electrical Insulation, Chicoutimi, 2012.

[14] Dr. R. Paschotta, "RP Photonics Encyclopedia," RP Photonics Consulting, [Online]. Available: www.rp-photonics.com/pockels_effect.html.

[15] M. Souza, "Efeito Kerr," 2 Dezembro 2013. [Online]. Available: https://prezi.com/dmy9a2_sehml/efeito-kerr/.

[16] UE Systems, "The Ultrasound Approach," UE Systems, 2016. [Online]. Available: http://www.uesystems.com/applications/electrical-inspection. [Accessed 22 8 2016].

[17] O. Lineneberg, Interviewee, *Atmospheric Conditions.* [Interview]. 05 02 2006.

[18] R.S. Gorur, E.A. Cherney e J.T. Burnham, Outdoor Insulators, Phoenix - Arizona - Estados Unidos da América: Ravi S. Gorur Inc., 1999.

[19] E. Niedospial, "Design and Application of Corona and Grading Rings for Composite Insulators," IEEE Power Engineering Society Transmission and Distribution Conference, York - EUA, 2012.

[20] Working Group B2.21, "On the use of power arc protection devices for composite insulators on transmission lines," CIGRÉ Technical Brochure 365, Paris - França, 2008.

[21] M. J.Geramian, Z. Hamnabard, M. Mohseni, S. Dolatshahi, "Cired," 2001. [Online]. Available: http://www.cired.net/publications/cired2001/1_17.pdf. [Accessed 26 01 2017].

[22] "12 Examples of Insulator 'Failure'," INMR, 24 12 2015. [Online]. Available: http://www.inmr.com/examples-insulator-failure/2/. [Accessed 25 01 2017].

[23] "Learning from Recent Service Experience with Composite Line Insulators," INMR, 8 9 2016. [Online]. Available: http://www.inmr.com/learning-recent-service-experience-composite-line-insulators. [Accessed 17 11 2016].

[24] "Service Experience with Composite Line Insulators: EPRI Perspective," INMR, 18 3 2014. [Online]. Available: http://www.inmr.com/service-experience-composite-line-insulators-epri-perspective/3/. [Accessed 17 11 2016].

[25] G. Zhicheng, "Failures of Composite Insulators in China," INMR, 24 12 2015. [Online]. Available: http://www.inmr.com/failures-composite-insulators-china/. [Accessed 06 12 2016].