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Online PD detection on high voltage underground power cables by acoustic emission

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Abstract

Acoustic waves produced by partial discharges inside in dielectric materials can be detected using acoustic emission (AE) sensors. This detection can be analyzed in the time domain. AE sensors are immune to electromagnetic interference and provide a nonintrusive and nondestructive detection and a galvanic decoupling with respect to the electric network. This work presents the experimental results of AE sensors characterization and the online detection capability in the environment near cable accessories. The AE technique of partial discharge detection can be applied as a test method for preventive or predictive maintenance (condition-based maintenance) to equipment or facilities of medium and high voltage. Represents an alternative method to electrical detection systems, conventional or not, who continue to rely on the detection of current pulses. This paper presents characterization tests of the sensors AE through comparative tests of partial discharge on accessories for underground power cables.

Keywords: Power cables; Underground installation; Partial discharges; Failure detection; Online detection; Acoustic detection.

1. Introduction.

Continuity and reliability of underground power cable networks is affected by the high failure rate of

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accessories used in the installation like joints and terminals [1], [2], [3]. This is primarily due to the stringent quality testing, during complete manufacture process of underground power cables, such as dielectric strength and partial discharge (PD). These tests ensure the absence of initial defects.

The cable accessories cannot be evaluated 100% during installation [4], [5], after manufacturing and testing of accessories, it may be able to receive damage during the cable installation. Due to this process is prone to errors and damage, which can difficult to detect during the acceptance test of the cable installation, due to the limitation of field test. That are less rigorous than laboratory tests like high voltage level, sensibility and less test time, and in many cases the partial discharge test is not performed [4].

2. Partial Discharges (PD) detection.

The standard and others conventional PD detection systems are based on pulse detection of current or voltage [6], [7], these method has a number of advantages and disadvantages:

Disadvantages:

- The field tests are too sensitive to the radio frequency interferences, due to absence of electromagnetic shield.
- Radiofrequency interference is reduced or eliminated by discrimination systems that can be filtered or cover the PD.
- Inductive methods are limited by shield cable construction.
- The capacitive methods are limited in sensivity due its low coupling capacity with respect to capacity of the objet under test.
- PD detection equipment is expensive and difficult to install in the field.

Advantages:

- Allows PD level detection.
- Complimented with standard PD localization systems.
- The use of double sensor allows the auto calibration and analyzes the PD direction in cable accessories.
- Exist high voltage (HV) commercial applications

2.1. Detection with acoustic sensors

Different methodologies based on pressure variations in the insulation cable surface, offers an alternative solution to the PD detection problem of accessories. This method does not have all the same disadvantages and advantages than electric sensors [7]. The disadvantages and advantages for this method are:

Disadvantages:

- Currently most of the major sensors and detection systems are developed.
- Specific applications for HV cables accessories are not sold.
- Sensitivity reduction due to attenuation by the distance from the defect and the elevated cable

temperature.

- External detectors for medium voltage cables have limited sensitivity due to the several interfaces present on the cable accessories, like air-insulation.
- PD level is not possible to determine.
- Calibration procedure is complex.

Advantages:

- Insensitivity to electromagnetic noise.
- It is a non-destructive method.
- Sensors with high sensitivity, the signal can be analyzed by conventional equipment.
- Wide range of frequency spectrum.
- The shielded cable construction does not affect the sensor installation.
- High mechanical strength.
- High electrical resistivity, offers electric decoupling respect to HV potential.
- The commercial price is lower than other sensors.

3. Concepts of PD detection by acoustic emission

PD in the inner dielectric systems can be described by a small explosion. Molecular collision, that excites the emission of acoustic pressure waves, these waves propagate through the insulation material [8], [9], [10]. The mechanical waves are detected using electro-acoustic sensors, sensitive to pressure changes that occur on the surface of dielectric material and that surround the cavity or defect, especially on the semiconductor layer between dielectric material and conductor.

The transferred energy produced by PD in the cavity, can be calculated using the difference between the stored energy before and after the presence of PD. The magnitude of the energy released (W) in Joule, expressed in terms of rms excitation voltage of the discharge (V_i) in volts, the electric charge in Coulombs (q_c), which is transferred when there is a discharge in a type defect cavity, can be expressed by

$$W \cong (1/\sqrt{2})q_c V_{i(rms)} = 0.707 q_c V_{i(rms)} \qquad (1)$$

The energy can be present different orders of magnitude different between ranges of 10-9 to 10-5 J [11], [12]. Furthermore, the amount of energy varies with insulation thickness and can cause different effects locally. These effects include sound waves due to radiation energy.

In order to verify the energy quantity present during the discharge in a spherical cavity, a simulation by Finite Element Analysis (FEA) was performed. Specifically, the simulation was carried out in a cavity of 1 mm in diameter near the inner screen surface of insulation with a thickness of 18 mm. The properties correspond to an underground power cable with XLPE insulation for 76/132 kV, 1 x 400 mm^2 aluminum conductor. Figure 1 shows the FEA results, it can be seen the increment of the voltage gradient in the semiconductor cavity close to the inner screen. The energy produced by PD in the cavity when a 77 kV is applied, is in a range between 25.6 x 10^{-5} and 5.59 x 10^{-5} J, respectively to the zone of maximum gradient and minimum gradient in the cable.

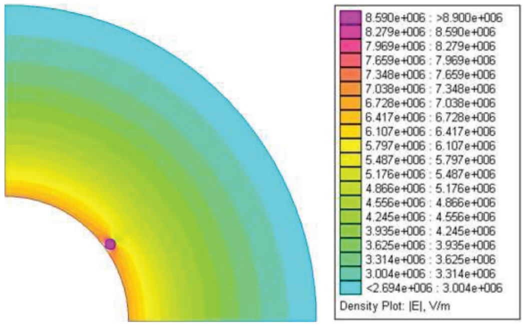

Fig. 1.FEA simulation of electric field distribution [V/m] in a power cable with a void across the conductor insulation

The discharge sound wave propagates through the medium with a speed (c) m/s with longitudinal waves, causing local changes in pressure (p) in Pascal, density (ρ) in kg/m^3 and displacement of the molecules. The equation of wave propagation for spherically symmetric pressure fields is [13], [14]:

$$\nabla^2 p = \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} \tag{2}$$

The PD pulses are very short durations, ranging from 1 ns to hundreds of ns. This causes the frequency spectrum of the acoustic waves generated to be very broad and in the ultrasonic range such that the frequency is of the order of kHz and MHz [8], [11], [15], [16].

If the PD in a cavity is a simple point source, generally very small, less than 1 μm, the PD activity initially, emits spherical acoustic waves with radial symmetry, as shown in fig. 2.

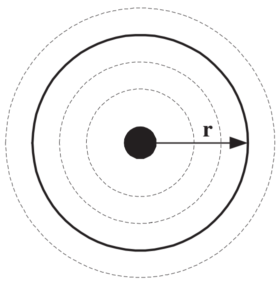

Fig. 2. Acoustic wave propagation from source point.

When, the PD occurs in the interior of the cable insulation, the electric field has the maximum variation along the radial direction. This direction has the shortest in the propagation of spherical sound waves to the border with different media. According to the representation in fig. 3, r represents the radius from the source point in m.

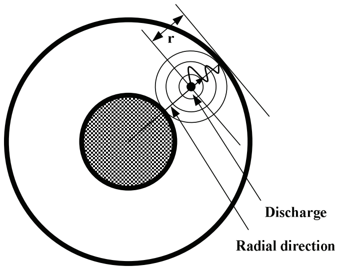

Fig. 3. Radial propagation of the acoustic wave.

The pressure fronts of the acoustic waves, first reach both semiconductive layers and the conductor, with the difference in time depending of the position of the discharge in the insulation. Between these points, refracted or reflection wave is produced, depending on the specific acoustic impedance ($\vec{z}$), which is defined as the ratio of sound pressure of the medium ($\vec{p}$) in Pascal and the associated particle velocity ($\vec{v}$) in m / s.

$$\vec{z} = \frac{\vec{p}}{\vec{v}} \tag{3}$$

this wave can be expressed

$$\vec{z} = \rho_o c \cos\beta\, e^{j\beta} \tag{4}$$

where (ρ_o) is the characteristic density of material in kg/m^3 and β the angle between the sounds pressure direction and particle velocity in the material. $\beta = 0$ when the angle of the sound wave is plane.

The wave fronts that travel in non-radial directions, such as cable axial direction (see fig. 4), go a long way, but eventually also reach and impact obliquely on the semiconductor layers and conductor.

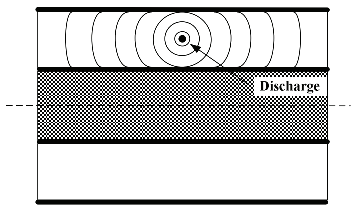

Fig. 4. Axial propagation of acoustic waves.

The sound longitudinal velocity in polyethylene increases linearly with the density and can vary from about 2,003 m/s to 1,977 m/s, depending on the material curing degree [17].

In most polymers commonly used like insulation for medium and high voltage cables, the attenuation coefficient decreases approximately linearly with the Young's modulus. (*E*) [8]. Equation 5 represents the Young's modulus as a function of the curing degree of the material, its magnitude decreases with temperature increment [18].

$$E = \rho.c^2 \tag{5}$$

The strong influence of attenuation is the limiting factor for long distances with this detection technique, however for short length cable installation and accessories this technique is sensitive.

4. Evaluation of acoustic detection system

In order to evaluate the acoustic detection system, a HV test transformer and a cable installation in laboratory were used. Putting electro acoustic sensors placed in the splice and terminals proximity, as shown in figure 5.

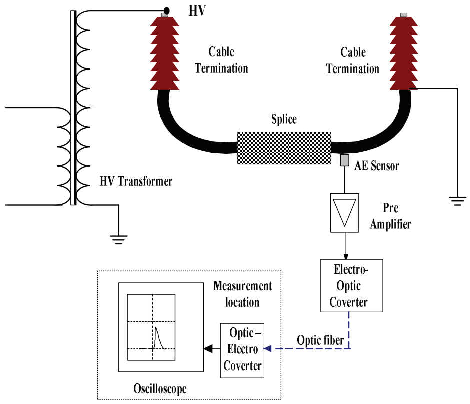

Fig. 5. Acoustic system test scheme, EA sensor placed close to the splice.

The sensors placed on each side of the splice, are activated by acoustic waves. The sensors generate response signals that are sent to a pre-amplifier, which can combine different signals, as shown in fig. 6. The electro acoustic sensor (EA) offers the sensitivity for on line detection of the cable system or periodically (preventive detection) of the PD activity. Special variations with the time of the PD activity can generate alarms for different levels of activity due to degradation of the accessories.

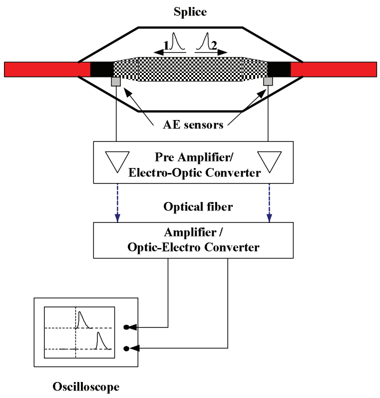

Fig. 6.Schem of acoustic system test, with two sensors placed in the inner splice

Figure 7 show the sensor EA place near to HV splice. The components system is: EA sensor, pre amplifier with a wide band between 1 to 5000 kHz, electro-optic converter, fiber optic cable for connection to optic-electric converter. The equipment for the signal analysis and measurement was a digital oscilloscope with a spectrum analyzer of the 200 MHz and 1G Sa/s.

Fig. 7. Sensor placed near of the high voltage splice.

5. Experimental results

PD detection experiments were performed using two methods: electrical, using a commercial PD detector and Electroacoustic using EA sensors. Electrical detection allows us to obtain the discharge magnitude in pC and verify that the electro-acoustic system detects the PD presence.

In order to characterize each of the PD signals, typical cable defects in the preparation were artificially added. The defects included are: a). Cuts in the outer semiconductor, b). Holes in the insulation due to the preparation of the splice or terminals, and c). Semiconductor material remaining in the insulation surface. These defects were made in two types of cables, one for high voltage, with XLPE insulation for 76/132 kV and 1x800 mm^2 Al conductor and other one for medium voltage of XLPE insulation for 12/20 kV and 1x240 mm^2 Al conductor.

The results obtained, are consistent with wave propagation trough a distance due to the wave attenuation when the wave travel through the cable insulations. Table 1 shows results for three types of defects and the location of the EA sensor, with respect to each failures investigated of one commercial PD detector compared to the EA sensor.

Table 1 Measurements depending of defect location

Defect type	Voltage (kV)	PD measurement (pC)	Acoustic Measurement (mV)	Sensor location
a	70	40	136	In semiconductor, 25cm from the defect.
a	70	80	164	In semiconductor, 50 cm from the defect.
b	12	40	3,68	In semiconductor, 50cm from the defect.
b	14	50	5,6	In semiconductor, 50 cm from the defect.
b	17	70	10	In jacket, 50 cm from the defect.
c	8,4	60	5,6	In semiconductor, 10 cm from the defect.
c	8,2	64	No detection	In semiconductor, 90 cm from the defect.
c	16,2	80	2	In semiconductor, 90 cm from the defect.

The characteristic of signal depend of each type defect as shown in figure 8, together with the acoustic response obtained and the corresponding Fast Fourier Transform.

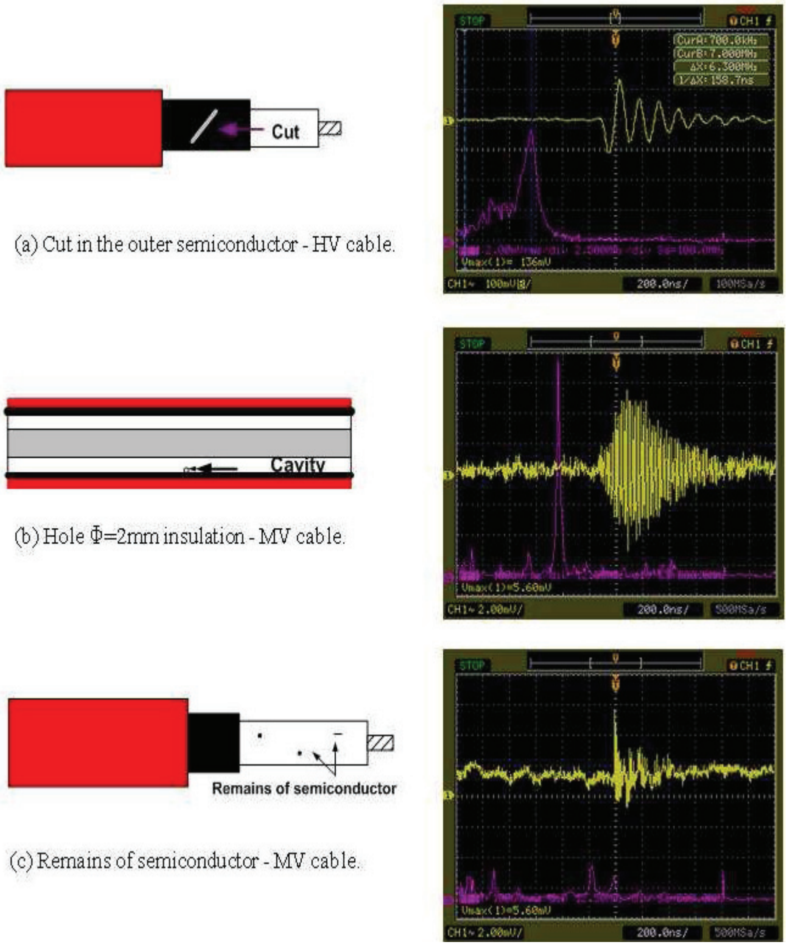

Fig. 8. Type of PD presented respect defect type.

The EA sensors could be affected by distance sensor position due to wave attenuation across the insulation and the type of defect. When more closely the EA sensor of the accessories the signal is more stable (see figure 10a and 10b) and the failure correlation can be performed using the FFT analysis respect to the commercial PD detector.

6. Conclusions

The evolutions of the EA sensor presented here is an alternative to electric system for the detection of PD inception in cable accessories for on-line applications.

The system EA has shown greater sensitivity of detection with internal partial discharge in the insulation with cavity type under the external semiconductor layer, respect to discharges caused by others defects in the terminals preparation.

The sensitivity level reached, from 40 pC discharges, is a promising alternative for MV applications, but for HV applications needs more investigation.

Based on the response of the EA sensors, these can be used to detect different types of defect.

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