Internal Corrosion in Conductor Cables of Power Transmission Lines: Characterization of the Atmosphere and Techniques for Faults Detection.

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ABSTRACT

This paper presents a characterization of the atmosphere in three electrical substations of a brazilian utility, representing three different environments, and the study of some techniques used to detect faults in conductor cables employed on power transmission lines. The characterization of the atmosphere was made according to ISO 9223 and ISO 9224 standards, determining the weight-loss of metallic coupons and collecting pollutants by specific device. The study compares several available techniques and chose one to be applied in conductor cable inspection of power transmission lines.

Key words: power lines, conductor cable, inspection techniques, atmospheric corrosion.

1. INTRODUCTION

The search for better and more efficient energy services is demanding from the electric utilities more investments in new equiments to monitor their electrical system, and so to prevent events or faults which could misoperate the system, by anticipating possible solutions. On power transmission lines, for example, the conductor cables are exposed to climatic variations (such as wind, rain, etc) and usage conditions for several years. A problem that occurs to these cables is their gradual wear which can cause their rupture and consequently serious problems, if it is not detected in time. As older a power transmission line is, more its cables are susceptible to present problems.

To reduce these problems, the utilities inspect routinely their cables trying to find out flaws. However some methods used to do this task do not have enough accuracy and may carry wrong diagnosis out, making the inspection and maintenance procedures very expensive. As a consequence, many cables may be prematurely replaced, by precaution, while quite a lot remaining in service may be seriously damaged and in a dangerous condition [1].

So, it is important to characterize the atmosphere where cables are installed and to study techniques to detect flaws on cables, to know their actual conditions, properly identifying bad sectors that must be removed from the good ones that may continue in service, avoiding waste of money.

2. ATMOSPHERIC CORROSION

Corrosive contaminants present in atmosphere, both natural and artificial, tend to affect the useful lifetime of metallic structures and others equipments.

The atmospheric corrosion shows up indoor as such outdoor. The importance of the atmosphere as a corrosive agent is confirmed by the number of scientific publications, in several countries, treating corrosion tests on different metallic materials by long exposed period of time.

The corrosive action of the atmosphere depends, basically, on the factors:

- relative humidity
- pollutant substances (particles and gases)
- temperature
- stay time of a electrolyte film on a metallic surface

Besides these, climatic factors such as wind direction and intensity, rainfall and solar radiation must be taken into account.

2.1 Atmosphere Characteristics

The environments are normally classified by its aggressiveness as a function of the type and amount of pollutants found in the atmosphere. In this way, they are classified as:

- Rural atmosphere – when the environment is pollution free and the material deterioration is caused only by relative humidity, temperature, rain and solar radiation.
- Urban atmosphere – in this case the aggressiveness of the environment is characterized by pollutants from small industrial plants and combustion chambers, besides climatic factors.
- Industrial atmosphere – the environment is too influenced by pollutants exhaled from large industrial plants.
- Marine atmosphere – in this environment the most important pollutants are the salts brought by winds flowing from sea to land.

In some situations, it may eventually happen the combination of two or more atmosphere types, as for instance the marine together with the urban and industrial.

Considering the metallic corrosion, the pollutants having more influence on the process are: SO_2, H_2S, NH_4, NO_x, NaCl and solid particles.

There are several attempts to quantify the amount of the two principal atmospheric pollutants, chloride ions and sulphur compounds, found out in each atmosphere type. The Table I shows an example of this [2].

The problems caused by atmospheric corrosion on power transmission lines may be separated in two groups: galvanized structures corrosion and conductor cable corrosion.

In this work, the focus is on conductor cables corrosion.

Table I – Atmosphere classification

Type of environment	Pollutants in the atmosphere	
	SO_2 ($mg.dm^{-2}.d^{-1}$)	Cl^- ($mg.m^{-2}.d^{-1}$)
Rural	**< 0.25**	**< 0.3**
Urban	**0.25 < < 1.25**	**< 0.3**
Industrial	**> 1.25**	**< 0.3**
Coastal	**< 0.25**	**0.3 < < 30**
Marine	**< 0.25**	**> 30**

2.2 Methodology

The methodology adopted in this work followed the ISO9223 [3] and ISO9224 [4] standards and consisted in installing atmosphere corrosion assay apparatus at three different electrical plants to aim at classifying the corrosiveness level and gathering information to analyse and classify the micro climate of the studied regions.

The assay apparatus has:

- test samples made of carbon steel, copper, aluminium and zinc
- devices to collect chlorides and sulfur compounds from the air
- temperature (T) and relative humidity (RH) sensors

The exposure time of the test samples varied from 6 months up to 24 months at each region, and the analysis method was based on determining their weight-loss.

The pollutants were monthly verified during 12 months, and their amount evaluation in atmosphere fitted the suitable norms.

The results of corrosiveness level and atmosphere classification also agreed with the applicable norm.

2.3 Results

2.3.1 Analysis and Evaluation of Corrosion Rates:

The Table II shows the average corrosion rates of the metallic materials evaluated at the three assay regions.

Table II – Average corrosion rates of the materials

Region	1	2	3
Material	**(mdd)**	**(mdd)**	**(mdd)**
Carbon steel	**1.01**	**14.26**	**11.30**
Zinc	**0.11**	**0.66**	**0.67**
Copper	**0.12**	**0.53**	**0.56**
Aluminium	**0.01**	**0.03**	**0.02**

(mdd-milligram by square decimeter by day)

It can be determined the category of atmosphere corrosiveness as a function of the corrosion speed of each metallic material exposed at these regions, based on the suitable norm. The Table III shows the corrosiveness category to the materials considered.

Table III – Corrosiveness category as function of corrosion rate

Region	1	2	3
Material	**(mdd)**	**(mdd)**	**(mdd)**
Carbon steel	**C2 - low**	**C4 - high**	**C4 – high**
Zinc	**C2 – low**	**C4 – high**	**C4 – high**
Copper	**C2 – low**	**C4 – high**	**C4 – high**
Aluminium	**C1 - neglected**	**C3 - medium**	**C2 - low**

2.3.2 Analysis and Evaluation of Pollutants: The Figures 1 and 2 show the amount of chlorides and sulphur compounds, respectively, collected at the three regions studied.

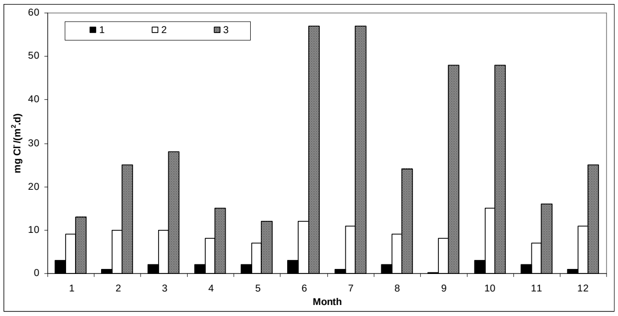


Figure 1 – Amount of chlorides collected

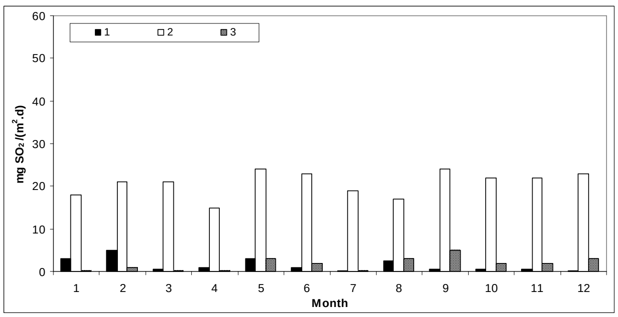


Figure 2 – Concentration of SO_2

2.3.3 Analysis and Evaluation of the Wet Surface Time: A determinant external factor of the atmospheric corrosion intensity is the time that a metallic surface remains wet, called time ot wetness (TDH). According to norms, the TDH is evaluated based on continuous registered values of relative humidity and temperature. It is defined as the number of hours, calculated during a year interval, where the relative humidity is more than or equal to 80% and the temperature is more than or equal to 0^{o}C.

The Figure 3 shows the TDH values calculated at the three assay regions.

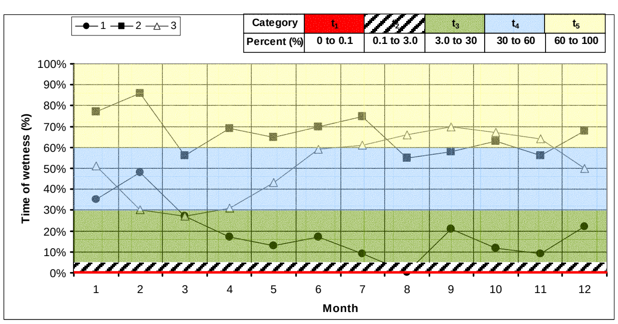


Figure 3 – Time of wetness

2.3.4 Analysis of the 3 Assay Regions Based on these results and according to the suitable norms, the regions were classified as:

Region 1 - This region was classified with the denomination **B0A0**, a typically rural atmosphere, free of contamination by chrolides and sulphur compounds. It is inside the $\mathbf{t_3}$ category, which represents dry, cold or temperate weathers, having condensing and precipitating time intervals, and low probability to form electrolyte on metallic surfaces.

So the region 1 is little aggressive to those metals used in the test, carbon steel, aluminium, copper and zinc. Any metallic structure installation in this region, like power transmission towers for instance, will not need anticorrosive protection, besides the galvanized carbon steel.

Region 2 - The classified denomination to this region was **B1A1**, a typically mixed atmosphere, weakly contamined by chlorides and sulfur compounds. Its category is the $\mathbf{t_5}$: very wet, hot or temperate weathers, having condensing and precipitating time intervals, and very high probability to form electrolyte on metallic surfaces.

The region 2 is very aggressive to carbon steel, aggressive to copper and zinc and little aggressive to aluminium. Any metallic structure installation in this region will need anticorrosive protection systems. Carbon steel structures or equipments must be coated with organic shelter in addition to galvanization, what is called duplex anticorrosive protection system.

Region 3 - The denomination to region 3 was **B1A0**, a typical marine atmosphere, weakly contamined by chlorides and free of contamination by sulphur compounds. It is inside the **t4** category: wet, hot or temperate weathers, having condensing and precipitating time intervals, and high probability to form electrolyte on metallic surfaces.

This region is aggressive to copper, carbon steel and zinc, and little aggressive to aluminium. Any metallic structure instalation in this region will need anticorrosive protection systems. Carbon steel structures or equipments will need a duplex protection system like that described to region 2.

3. CABLE INSPECTION TECHNIQUES

The other goal in this work was to study techniques that allowed detection of flaws in wire ropes and, together with the characterization and classification of the atmospheres, to determine the time interval between cable inspections or maintenances aiming at to reduce costs and avoid risks.

3.1 Failure Mechanisms

The common failure mechanisms for wire rope are fatigue, ductile overload, wear and corrosion [5]. In power transmission lines, the corrosion is one of the principal cause of conductor cable deterioration [6].

Corrosive points cause strain concentration and avoid the free movement of wires and strands increasing the tension on the wires. These effects may speed up the development of fatigue ruptures. The wires may also corrode along their surface, and this may reduce their cross sectional area and consequently their mechanical properties [5].

The corrosive severity varies along the cable length and is more noticed at high pollution areas and/or at areas where sudden temperature and/or humidity changes happen [7]. The analysis carried out on item 2 pointed to the corrosive severity of the studied regions in this work.

Trying to minimize the failure risks and their consequences, security norms and codes recommend the realization of periodic inspections to know the actual cable conditions [1] [5]. These regulations present inspection methods, the most common failure causes, replacement criteria and maintenance procedures for cables.

Therefore, inspection techniques must attain the norms, looking for improving upon safety and economic aspects, and the testing procedures must indicate when the replacement criteria described on norms does or does not apply to the considered cable. The non-destructive testing (NDT) are more appropriated to do this task.

3.2 Non-Destructive Testing

The NDT techniques belong to a branch of material science related to aspects of uniformity, quality and utility of materials and structures. They essentially refer to all methods that allow to test and inspect materials without damage to them [8].

Many NDT procedures have been proposed to detect material flaws using several methods: visual, acoustic, mechanical, penetrating liquid, magnetic, electromagnetic induction etc [1] [9] [10]. To conductor cables of power transmission lines, the magnetic and electromagnetic methods give better results on flaw detection, showing great accuracy and easy use, than the others one.

The visual method using a photographic or video camera is very slow and errors may occur due to image definition, luminosity etc. The workings of the other methods make it difficult for them to be utilized at overhead transmission lines, besides they have small accuracy [7] [9].

Considering these factors the magnetism and electromagnetic induction methods were studied on this work.

3.3 Results

The two techniques were analyzed thorough laboratory test, taking into account factors as facility to assemble or buy probes, their precision, types of signal delivered, among others.

3.3.1 Electromagnetic Induction: Eddy current inspection is one of the NDT methods that works on the principles of electromagnetic induction [8] [11] [13].

When an alternating current flows in a coil in close proximity to a metallic surface, the magnetic field of the coil will induce circulating (eddy) currents in that surface. The magnitude and phase of this current will affect the coil impedance [11] [12] [13].

Any defect in the material will disrupt the eddy current flow, thus altering the impedance of the coil (probe). Measuring the variation of the coil impedance may then help to detect changes on the mechanical characteristics of the material, and contribute to warn risk situations.

The eddy current detection involves several factors:

- type of analysed material
- number of layers of this material
- characteristics of the probe – size, type (absolute, differential), …
- characteristics of the signal – amplitude, frequency, duration, …
- measuring circuit

Due to practical aspects concerned with this technique, it was decided to postpone its analysis and tests in this work.

3.3.2 Magnetism: The other NDT of wire ropes studied was based on the magnetism method. Its probe is made of permanent magnet and sensor coils that give a voltage proportional to the induced magnetic flux in the rope under test (Eqs. (1), (2) and (3)).

$$\phi = \langle \mathbf{B}, d\mathbf{A} \rangle = \int \mathbf{B} \cdot d\mathbf{A} \qquad (1)$$

where,

ϕ – magnetic flux
$\mathbf{B}$ – magnetic field vector
$d\mathbf{A}$ – area element vector
$\langle \, , \rangle$ - scalar product

When the rope is magnetically saturated the longitudinal flux will be proportional to its cross-sectional area [1] (Eq. 2).

$$\phi = B \cdot A \qquad (2)$$

where,

B – magnitude of $\mathbf{B}$
A – area crossed by $\mathbf{B}$

By Faraday law, variations in the magnetic field around a coil induce a voltage, v, in the coil given by,

$$v = -N \frac{d\phi}{dt} \qquad (3)$$

where N is the number of turns of the coil.

Therefore, any change of the coils voltage is a measure of change of this area, which can be used to detect flaws in the cable.

Substituting Eq. (2) in Eq. (3) results,

$$v = -N \cdot B \cdot \frac{dA}{dt} \qquad (4)$$

By Eq. (4), as N and B are constants, any detected change in v corresponds to change in A.

The Figure 4 ilustrates this technique. A magnet saturates longitudinally a segment, l, of the cable and a coil around this segment is used as a sensor.

Any variation of the cross-sectional area A of the cable (occurred, for instance, by faults like corrosion, abrasion or broken wire) causes change in the magnet flux, ϕ, in the cable. Moving the cable at a speed $\mathbf{u}$, the flux inside the cable, at the segment *l*, will change inducing a voltage, *v*, in the sensor given by Eq. (4).

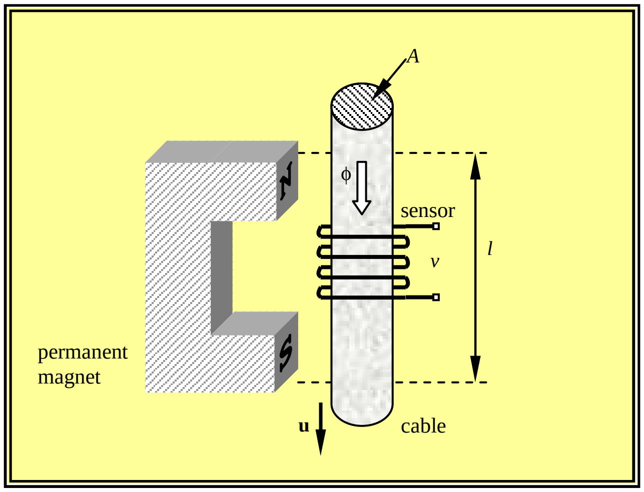


Figure 4 – Magnetic flux induced in a cableby permanent magnet

In the cable segments without flaw, the voltage value will be practically constant (v_c). If the cable has a segment with a flaw that changes its cross-section, when this flaw enter the sensor, it modifies v as ilustrated at x_1 in Figure 5, and when it leaves the sensor, it changes v again, as indicated at x_2 in this figure.

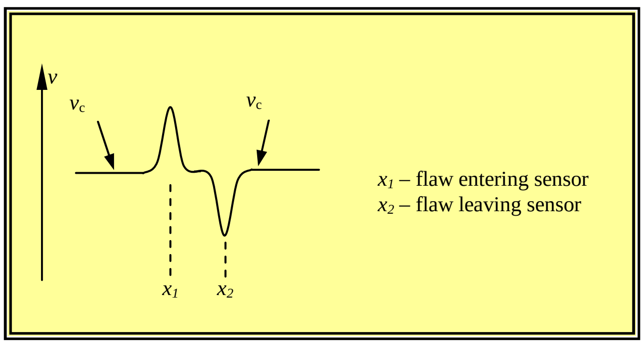


Figure 5 – Voltage variation in the sensor causeb by flaw

In the laboratory tests realized, the probe was placed on a cable sample having known defects, and the coils voltages were acquired by an acquisition system and displayed on graphic form. The defects are grouped into 4 different types totalling 31 flaws:

1. broken wires
2. cross-sectional area reduction by mechanical abrasion
3. cross-sectional area reduction by chemical abrasion
4. hybrid (broken wire+cross-sectional area reduction)

The cable is marked at 1m segments, and in these segments the flaws are made. A segment with flaw is followed by one without flaw.

A flaw may be single or multiple. In this paper it is single when only one occurs to a segment, and it is multiple otherwise. The flaws have the following characteristcs:

longitudinal extension from 5mm to 50mm (types 2 and 3),
quantity by cross-section from 1 to 4 and
distance to each other (at the same segment) from 5cm to 20cm.

The Figure 6 shows the signals acquired from the probe for some of these flaws. The signal analysis of the Figure 6 shows that the acquisition of raw signals makes it possible to indicate sectors of the cable having changes on its cross-sectional area.

These signals suggest that classifying methods, such as neural networks, fuzzy system, specialist systems, etc, mayn be used to identify the type and/or severity of flaws, and to warn possible critical situations of the cable.

4. CONCLUSION

This work presented an atmosphere characterization and the study of some wire rope inspection methods.

The atmosphere classification of three electrical substations of a brazilian utility, representing three different environments, was carried out according to ISO9223 [3] and ISO9224 [4] standards.

Based on the results achieved at 3 assay stations, it was possible to determine the aggressiveness of the studied regions. It was shown that the region 1 is typically rural, little aggressive to the used materials, and, therefore no special anticorrosive protection will be need to its metallic structures. The region 2 is typically industrial and the region 3 is marine. They were classified as very aggressive and aggressive, respectively, to some used metals indicating the necessity of special anticorrosive protection to their metallic structures.

Two non-destructive testing methods are discussed for wire rope inspection: magnetism and electromagnetic induction. However one of them is adopted and used in this study.

After a brief consideration upon the electromagnetic induction method, it was decided to postpone its study.

The magnetism technique was then tested and analyzed using an acquisition system and a probe made of permanent magnet and sensor coils. The probe was placed on a cable sample having known defects, the acquisition system acquired the voltage of the coils and displayed them on graphic form.

The analysis of the raw signals showed that this technique was able to detect the flaws, indicating till quite small defects. It also pointed to the possibility to implement a fault classifier having capability to indicate its type and severity.

New studies must continue this work. An automatic classifier is one very promising, other that would be very interesting is to correlate the detected flaws with the atmosphere type, aiming for to improve maintenance/replacement schedule of cables used in power transmission lines.

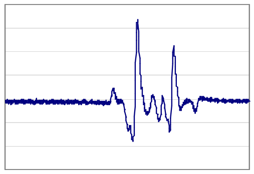
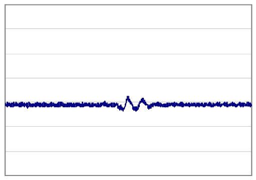
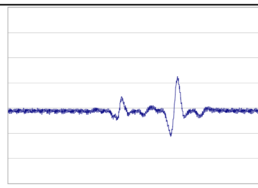
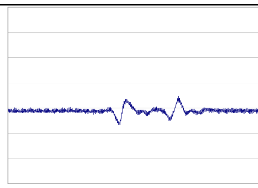
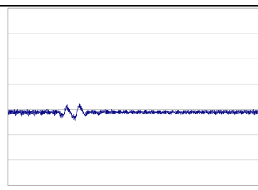
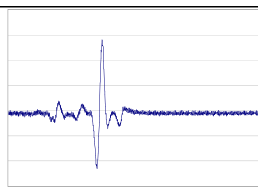
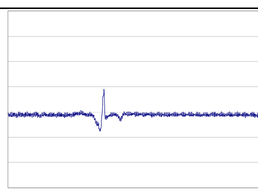
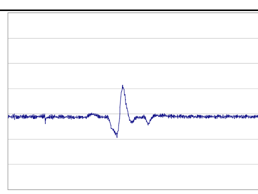
Fault	Raw signal
4 broken wires (2/section, distance: 15cm)	
2 reductions of cross-sectional area (extension: 5mm and 10mm) (1/section, distance: 5cm) (mechanical)	
2 reductions of cross-sectional area (extension: 5mm and 25mm) (3/section, distance: 20cm) (mechanical)	
2 reductions of cross-sectional area (extension: 50mm and 30mm) (1/section, distance: 5cm) (mechanical)	
2 reductions of cross-sectional area (extension: 5mm and 10mm) (1/section, distance: 5cm) (chemical)	
2 reductions of cross-sectional area (extension: 5mm and 25mm) (3/section, distance: 20cm) (chemical)	
1 broken wire and 1 reduction of cross-sectional area (extension: 5mm) (hybrid)	
2 broken wires and 2 reductions of cross_sectional area (extension: 15mm) (hybrid)	

Figure 6 – Raw signal from the magnetic probe

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