TECCIENCIA

Incidence of Corrosion on Electric Power Losses in ACSR Cables

Incidencia de la corrosión en las pérdidas de energía eléctrica en cables ACSR

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Abstract

This research performed a marine atmosphere simulation, using a saline fog chamber as a means to generate accelerated corrosion of conducting aluminum with steel reinforcement, used to construct electric power transport networks. The rate of corrosion was determined through the gravimetric method that consisted in measuring the loss of mass taking place in the sample. The experiment was conducted by taking three samples of ACSR (Aluminum with Steel Reinforcement) cable of different gauges, which received a flow of alternate current while the metal was being corroded. Through measuring equipment, electric power consumption was recorded to verify changes in the energy transported, given the exposure of the samples to corrosion. Likewise, voltage and current were measured to determine the system's stability. Results showed that the hours of exposure of the samples in the saline fog chamber generated greater effects in galvanized steel, causing damage to its zinc layer, in contrast to aluminum that turned out to be more resistant to this type of contaminant. Also, the electric power losses registered were not significant; possibly due to the sample's exposure and energizing times.

Resumen

En la presente investigación se realizó una simulación de atmosfera marina, utilizando la cámara de niebla salina como medio para generar la corrosión acelerada del conductor de Aluminio con refuerzo de acero, el cual es utilizado en la construcción de redes de transporte de energía eléctrica. La velocidad de corrosión se determinó por el método de gravimetría que consistió en la medición de la pérdida de masa que presentó la probeta. El experimento se hizo tomando tres probetas de cable ACSR de diferente calibre, al cual se le aplicó un flujo de corriente alterna mientras se corroía el metal. Mediante un equipo de medida se registró el consumo de energía eléctrica para verificar la presencia de cambios en la energía transportada, debido a la exposición de las muestras a la corrosión. De igual manera la tensión y la corriente se midieron para determinar la estabilidad del sistema. El resultado mostró que las horas de exposición de las probetas en la cámara de niebla salina generaron mayor afectación en el acero galvanizado causando daño en su capa de zinc, al contrario del aluminio que mostró ser más resistente a este tipo de contaminante. Así mismo las pérdidas de energía eléctrica registradas no fueron significativas debido posiblemente al tiempo de energización y de exposición de las probetas.

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1. Introduction

In electric power distribution network systems in the Colombian Atlantic coast we can find medium voltage (MV) lines of 13,200 and 34,500 Volts (V). These networks are currently constructed with aluminum (Al) [1] [4] wires with a steel core (ACSR)) [2] [5] [7]. Although in the past cables were made out of copper (Cu), these are no longer used due to their high costs and repeated theft.

Corrosion, a natural phenomenon and the main cause of metal deterioration [11] [15], occurs due to chemical or electrochemical reactions between an electrolytic environment and the material exposed to this environment or the electrical contact between two metal, one more noble than the other.

Colombia's Atlantic zone has problems with its electric networks; in part because it is quite close to the sea and because of high temperatures and relative humidity [2] [7], making them vulnerable to chemical attack due to the mixture of salt and water and/or the reaction of carbon dioxide with water [17] [18].

Companies dedicated to electric power transmission and distribution [19] [24], offering their services in Colombia's Atlantic zone, have shown greater interest in the corrosive effects on their ironwork and structures, given that saltpeter deteriorates metals until their rupture, causing surges and interruptions in the power distribution lines [25] [28].

The aim of this research was to learn of the incidence of corrosion upon electric power losses to study its behavior in saline environments. Thus, ACSR is the conductor studied herein (given that it is the one currently used), through a test bench that simulates an electric network exposed to a normal environment and to a saline environment to obtain results that help to delve into studying the phenomenon described and contributing in the search for solutions to problems caused by electric power losses.

2. Methods

The tests were conducted in two stages:
The first consisted in subjecting the three ACSR conductors composed by aluminum wires (1350 H 19), with steel core covered by galvanized zinc, gauges No. 4, 2, and 1/0, lengths of 158, 112, and 83 cm, respectively, connected to a three-phase busbar (240 V / 120 V) of the protection panel of the Corporation for Corrosion Research (CIC, for the term in Spanish), whose electric power supply comes from the Piedecuesta municipal grid. Thereafter, the electric power

consumption was measured at the source input and on the installed load, requiring a test bench – as security against electrical risk – for electrical connections where protection and measurement equipment are installed. Afterward, electric measurement instruments were implemented to check on the behavior of currents, voltage, and energy consumption.

It should be mentioned that the first stage is provided as control and reference test to compare the variables presented after the application of accelerated corrosion of the cables. The second phase replicated the previous procedure, adding the saline fog chamber (SFC) intervention to which a saline solution was poured composed of five parts of sodium chloride (NaCl) and 95 parts of type IV demineralized water and prepared according to ASTM B117 standard (chapter 8 – saline solution), under CIC supervision.

The samples (bare ACSR cable) were connected to each other, according to gauges via aluminum-aluminum connector and their loads with bimetallic connectors to permit closing the circuit and accomplishing the reading of parameters like amperage, voltage, and energy. The gauges of the samples exposed were number 4, 2, and 1/0; these were placed on plastic supports and separated to avoid short circuit and subjected during 337.5 h to the simulation of saline atmosphere and with drying times to accelerate the corrosion effects; during this period, the ACSR cable was energized and energy consumption was recorded in kilo watt-hour (kWh).

3. Results and Analysis

With SFC, uniform corrosion was reproduced, associated to a marine atmosphere in which corrosion factors, like temperatures of 35 °, relative humidity at 100%, saline fog, and alternate humidification and drying cycles.
Also, considering the material with which the conductors are composed, it is pertinent to state that it is common for aluminum to present localized (pit type) and galvanic corrosion due to contact between aluminum and galvanized steel.
The marine-type atmospheric conditions reproduced by the SFC is charged with corrosive contaminating agents, like sodium chloride (NaCl); however, due to the SFC characteristics, it was not possible to replicate dust as another one of the contaminants that are part of a marine atmosphere. The spray pressure of the saline solution in mist form was of 12 psi.

3.1. Analysis of the corrosion tests process

Exposure of the cables in the saline fog chamber began on 26 March 2014 at 7:00 a.m. and culminated on 09 April 2014

at 8:30 a.m. The samples were exposed for a total of 337.5 hours (14 days + 1.5 h).
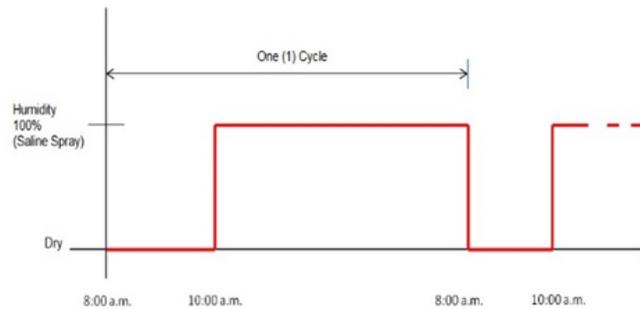
Figure 1 Exposure cycles.

During the 337.5 h of operation, the chamber maintained a constant cycle in which it had two hours of drying from 8:00 to 10:00 a.m. and the saline spray from 10:00 a.m. to 8:00 a.m. of the following day (Fig. 1). These two hours of drying were carried out to diminish the permanence of the humidity film on the metallic surface and, thus, increase the rate of corrosion.

Figures 2 and 3 show, on the metallic surface of the samples, the layers of contaminants; in this case, NaCl residues and the presence of corrosion.

Upon terminating the exposure period, the specimen was dismounted from each of the gauges exposed and then, through scaling the corrosion products were eliminated. By taking the Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens (ASTM G1 standard), the mean rate of corrosion was obtained with the following equation:

$$R = \frac{K*W}{A*T*D} \tag{1}$$

Where:

K: is a constant 8.76e04 (this value of the constant is used to have the results in millimeters per year (mm/p.a.)).
W: mass loss in grams
A: area in cm²
T: time of exposure in hours
D: density in g/cm^3 (see appendix X1 ASTM G1).

The area of the #4 ACSR was 316.3279 cm²; its initial mass was 97.1934 g, and the final mass after scaling was 96.06 g; lastly, density was at 2.705 g/cm³. The mean rate of corrosion was 0.343802207 millimeters per year.

The gauge #2 ACSR showed an area of 282.8465959 cm², initial mass of 159.99 g, and final mass of 158.8 g. The rate

of corrosion was 0.403700293 MPa. A = 265.2262063 cm², initial mass of 179.3887 g, final mass of 179.69 g, and for

the #1/0 gauge the rate of corrosion was 0.976340343 MPa (Fig. 4). Small pits on the aluminum and degradation of the zinc film on the steel were observed via BX46 optical microscope (Figs. 5, 6, 7, and 8).

3.2. Analysis of the energizing test process

Within the use of the correlation, the criteria shown in Table 1 were selected to determine if the test was satisfactory. This was done to verify a linear association between two variables.

The relationship of voltage with respect to current during the tests conducted with load could be observed; by correlating these two factors, an average correlation of 0.99 (0.997585893) and a standard deviation of 0.002 (0.002122663) was obtained, indicating that the test complies with the relationships that can be attributed to the electric variables in question. When comparing between input and output voltage for each phase, the results presented in Fig. 9 were obtained.

According to Table 7, an excellent degree of agreement exists among the voltages registered for each of the three phases, which ranged from a correlation coefficient of 0.998 to 1.

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Figure 2 Specimen after 337.5 h of exposure to the saline fog.

Figure 3 Samples after 337.5 h of exposure to saline fog.

It is important to indicate that for day 02 April, the measurements evidenced a registry of the three phases, which were close to coinciding: Va 0.9998, Vb 0.9997, and Vc 0.9997.

This event may be explained because: for the date the measurement was registered no voltage fluctuation was noted; also, the loads applied to the three phases were basically resistive elements. Consequently, no difference was observed between input and output voltage, which guaranteed the stability of the test in question on voltage registry and control. Similarly, it was established that the only variable in the system is associated to electric power consumption and the variables inherent to the behavior of the electric elements.

Likewise, the input and output currents were measured and compared (Fig. 10) to minimize the variables that can affect the analysis of the test results. Until now, the tests agree with the expectations, but the input voltage is not equal to the output voltage, as with the current. Even so, a variable can explain what occurs in the system, the input voltage, and the output voltage. For this purpose, we take the actual voltage value recorded for the three phases at the input and output; the input voltage corresponds to the voltage provided by the grid, and the output voltage is that delivered to the load (Fig. 11).

To assess the evolution of conductors within the system, voltage, current, and power values are taken during several days of the test around one hour of continuous charge. This difference of the power value presented in a power average for each day, as well as a standard deviation of the results, is shown in Fig. 12, evidencing an average loss in the system.

It may be stated that the resistance in the system is determined by the division between the system's voltage and current (Fig. 13).
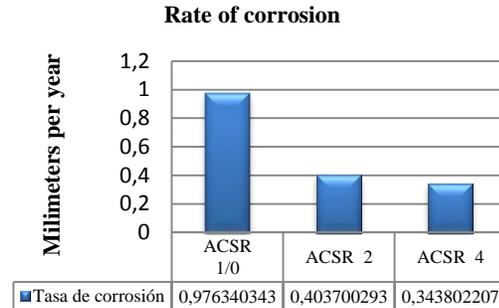
Figure 4 Average rate of corrosion
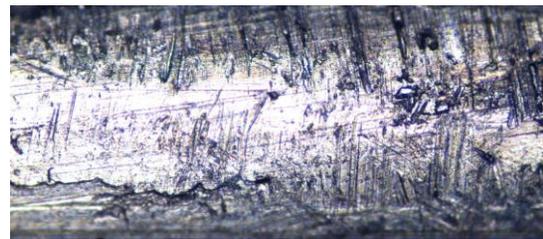
Figure 5. Aluminum before entering the SFC

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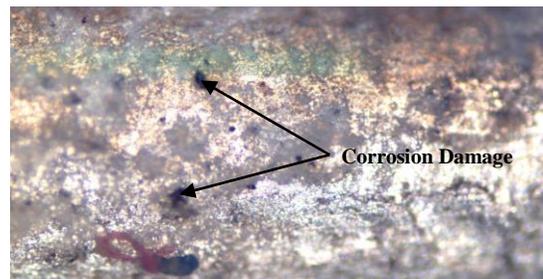
Figure 6. Aluminum after exiting the SFC

Figure 7. Steel core before exposure to the saline fog
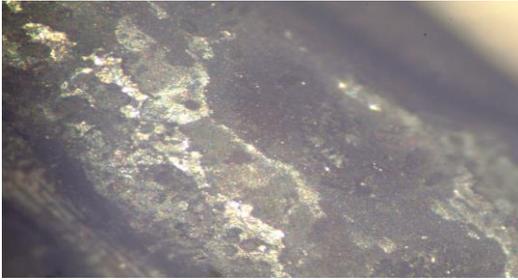
Figure 8. Steel core after exposure to the saline fog

Correlation coefficient	Degree of agreement
0	Null
<0.40	No agreement
0.40-0.60	Moderate agreement
0.60-0.75	Regular agreement
0.75-0.85	Good agreement
0.85-1	Excellent agreement

Table 1 Degree of agreement for the correlation in the test
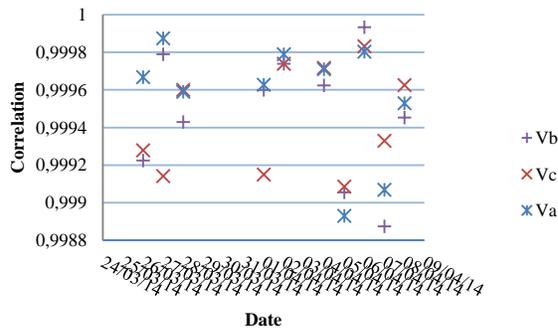
Figure 9 Input vs. output voltage correlation
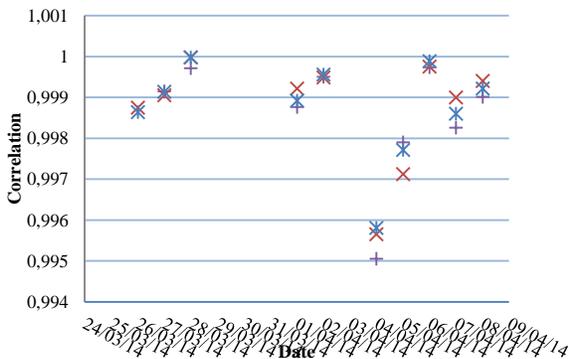
Figure 10 Input vs. output current correlation

Given the continuity of the test, during days 07/04/2014 and 08/04/2014 the slope is calculated during one hour every 5 min to contemplate the evolution of the slope and the cut-off point during these two days. The equation of resistance in the system, where "r" represents the system's resistance "per unit", (R_{sist}) is the constant resistance value that represents the system, and "mr" represents the slope that controls the system's total resistance variation over time:

$$r = R_{sist} + mr * t \tag{2}$$

By analyzing the data "per unit", the evolution of slope (mr), which is calculated with Equation 3 and its tendency over time, evidenced in Figures 14, 15, and 16 with domain from 0 to 1800 every 5 min, would yield an estimate of the affectation of the material as time passes.

$$b = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sum (x - \bar{x})^2} \tag{3}$$

4. Conclusions

The samples, after having been subjected to corrosion during the 337.5 h, did not show major surface damage, according to that registered through the Olympus BX46 microscope. This could be attributed to the alumina layer generated when aluminum comes in contact with an oxidizing medium, like oxygen and water. It is worth mentioning that galvanized steel, which is part of the ACSR, did show important surface deterioration because the zinc layer used as corrosion protector was affected. Without this zinc layer and with more hours of exposure to the saline fog, it is likely that due to the effect of the galvanic couple between the aluminum and the steel, the steel corrodes at a higher rate.

The input and output voltage, as well as the input and output current, had excellent correlation; this means that although the values were not equal, their deviations were not sufficiently significant to alter the tests.

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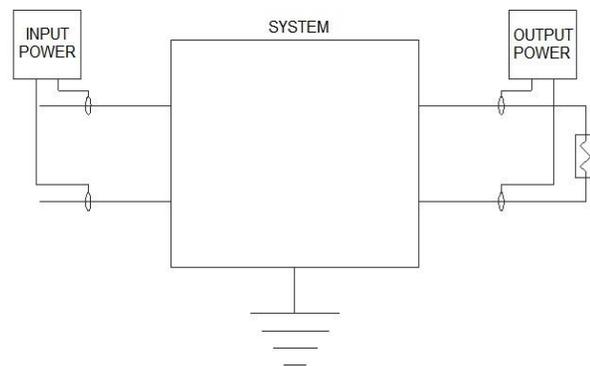
Figure 11 Power distribution

Regarding the general aim of this work, no clear evidence indicates that, in this test, corrosion affects electric power losses, probably due to the time the specimen was energized in non-continuous manner during the two weeks the samples were exposed.
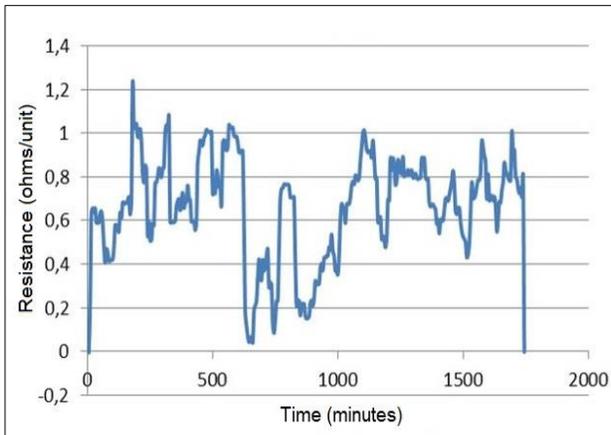
Figure 14 "mr" slope distribution of the A phase.
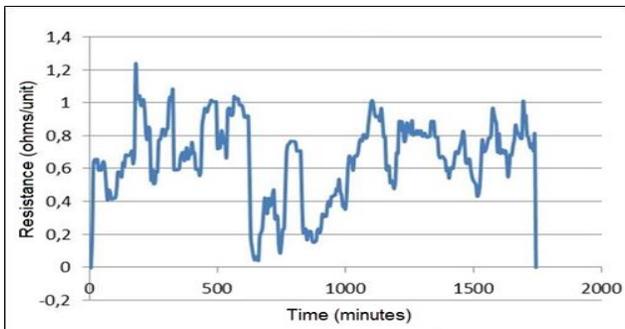
Figure 15 "mr" slope distribution of the B phase.
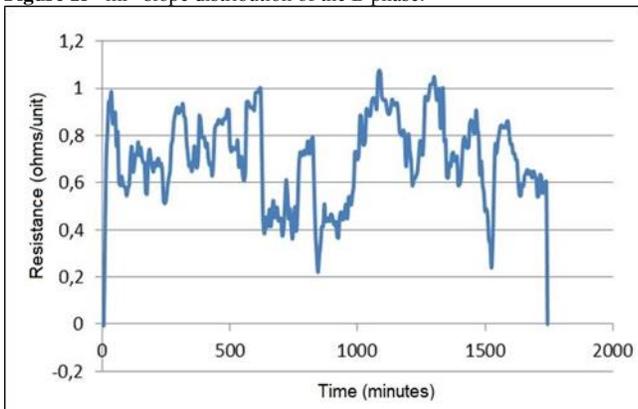
Figure 16 "mr" slope distribution of the C phase

Also, not having a daily resistance record sheds doubt on whether the phenomenon observed through the graphics with respect to the resistance slope calculated "per unit" is

sufficiently consistent to be attributed as characteristic of corrosion damage, given that electric power losses are directly related to conductor resistance, in this case the ACSR cable.

It is fundamental to ensure prolonged exposure times of the samples in the saline fog chamber, not below 720 h, to obtain samples with a higher degree of representativeness of the corrosion phenomenon as a factor of incidence in the electric power losses.

High-resolution scanning electron microscopy (SEM) was used to obtain more detailed information of the layer formed by the corrosion products, given that the pits and fissures on the material are often too small for the BX45 microscope to register.

Given that the tests performed for this research work used high-gauge cables that withstand at least 140 amps, we may implement one of the wires that make up the aluminum cable with steel core to analyze the incidence of the corrosion phenomenon and the electric power losses in areas with lesser surface through where current can cross. Likewise, the nominal current capacity may be delivered to one of the previously mentioned wires to increase its temperature.

Electric power measuring equipment should be used with one more degree of precision than that used in this experiment to lower the margin of error while measuring.

During the 1-h period when drying takes place of the SFC exposure cycle, a daily record of the sample's resistance could be taken to determine its variation and correlate it to the electric power loss phenomenon.

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