A Theoretical Model for Corrosion Assessment in Overhead Line Conductors

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Abstract—This paper presents an electromagnetic model for assessing the zinc layer thickness of galvanized steel strands that form cables used in overhead power lines, i.e., aluminum conductor steel-reinforced (ACSR) and overhead ground-wire (OHGW). The status of the steel galvanization provides an important indication of remaining cable life. The model is based on the evaluation of eddy currents induced in the zinc layer and its influence on a test coil impedance that has the cable as part of its core. The theoretical results of the model agreed well with results of experiments, both for a cable containing only steel strands (e.g., OHGW) and a complete ACSR cable. This model was applied in the analysis of data collected by an inspection robot to be used in overhead power lines.

Index Terms—ACSR cable, corrosion detection, galvanization, overhead line, eddy currents.

I. INTRODUCTION

The overhead power lines are usually made of aluminum conductors steel reinforced (ACSR), where the inner steel strands provide the desired mechanical strength and the outer aluminum strands conduct the line current. One important factor that limits the service life of these conductors is internal corrosion, which is initiated by the loss of the zinc layer that covers the internal steel strands. When this layer is lost, the corrosion process between aluminum and zinc strands progresses fast, compromising the integrity of the conductor. As this corrosion takes place inside the conductor, it is not detectable by visual or infra-red inspections, except when the corrosion products are large enough to bulge the conductor but, at this stage, the conductor’s failure may be imminent.

In order to detect the corrosion of ACSR conductors in its early stages, an inspection system based on the eddy currents induced in the zinc layer was developed in the 80’s [1, 2]. This system is based on a remote-controlled robot that sweeps the surrounding the cable. The theoretical results are compared with outputs from reference samples of the same conductor, but with known flaws. Therefore, the aim of this paper is to provide a theoretical model for the corrosion assessment of overhead line conductors based on the eddy current method. This model is intended to provide the zinc layer thickness from the signal picked-up by a sensing coil surrounding the cable. The theoretical results are compared with experimental data obtained from samples produced in laboratory, which support the proposed model.

II. THE GALVANIZED STEEL STRAND

A. Theoretical Model

This section analyzes the response of a steel strand when it is subjected to a time-varying longitudinal magnetic field. Let us consider a strand of length $s$, as shown in Fig. 1. The steel core is a cylinder of radius $r$, covered by a zinc layer of thickness $d$. It is considered that the zinc has conductivity $\sigma$ and permeability $\mu_0$, while the steel permeability is

$$\bar{\mu} = \mu_0 (\mu' - j \mu'') ,$$  \hspace{1cm} (1)

where $\mu_0$ is the free-space permeability, $\mu'$ and $\mu''$, are the real and imaginary parts of the relative permeability, respectively, and the dash above the symbol denotes a complex variable. The steel permeability takes into account the eddy currents within the steel, so that it may be regarded as an effective permeability. As the intensity and frequency of the applied magnetic field are kept constant in an inspection system, the effective steel permeability is assumed to remain constant.
For a current $i$ flowing in the zinc layer around the steel core of length $s$, the corresponding magnetic field in the steel is:

$$H = \frac{i}{s}.$$  

(2)

Considering that the current has a harmonic time-dependence, the magnetic flux in the steel is:

$$\Phi = H \pi r^2 \mu.$$  

(3)

Substituting (2) into (3), dividing by the current, and multiplying by the angular frequency $\omega$ gives the frequency-dependent impedance of the zinc layer:

$$X = \frac{j \pi \omega r^2 \mu}{s}.$$  

(4)

The resistance of the zinc layer is given by:

$$R = \frac{2 \pi r}{s d \sigma}.$$  

(5)

The total zinc layer impedance is obtained from (4) and (5):

$$Z = \pi r \left( \frac{2}{d \sigma} + j \omega r \mu \right).$$  

(6)

If the steel core is excited with a harmonic longitudinal magnetic field $H_0$, the corresponding flux in the steel core is:

$$\Phi_0 = H_0 \pi r^2 \mu.$$  

(7)

and the induced voltage in the zinc layer is:

$$V = -\frac{\partial \Phi_0}{\partial t} = -j H_0 \pi r^2 \mu \omega.$$  

(8)

This voltage will drive a current in the zinc layer that, by its turn, will give rise to a magnetic field given by:

$$H_R = \frac{V}{s Z}.$$  

(9)

Substituting (6) and (8) into (9) gives:

$$H_R = \frac{-j H_0 r \mu \omega d \sigma}{2 + j r \mu \omega d \sigma}.$$  

(10)

The total magnetic field $H_T$ in the steel core is given by the superposition of the incident field $H_0$ and the reaction field $H_R$:

$$H_T = H_0 + H_R = \frac{2 H_0}{2 + j r \mu \omega d \sigma}.$$  

(11)

Substituting $\omega = 2 \pi f$ in (11), where $f$ is the frequency, and dividing by $H_0$ leads to the normalized total field:

$$H_N = \left( 1 + j \pi f r \mu d \sigma \right)^{-1}.$$  

(12)

Equation (12) gives the total normalized magnetic field in a steel strand. Fig. 2 shows the dependency of $H_N$ modulus with the zinc layer thickness, for representative values of the relevant parameters. As the output of a sensing device is a function of $H_N$, it is clear from Fig. 2 that zinc layer thickness in the range of interest (e.g., from 0 to 80 µm) can be assessed from the total magnetic field.

![Fig. 2. Total normalized magnetic field in a steel strand according to (12) as a function of zinc layer thickness.](image)

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$$H_N = \left( 1 + j \pi f r \mu d \sigma \right)^{-1}.$$  

(12)

A key parameter in the use of (12) is the magnetic permeability of a steel strand. This permeability is defined in (1) as a complex variable, where the real part ($\mu'$) is related to the energy stored in the magnetic field and the imaginary part ($\mu''$) is related to the losses.

In order to obtain experimentally the steel strand permeability, some samples of strands were taken from different ACSR conductors and also from galvanized steel conductors used as OHGW. The test procedure consisted in selecting a strand sample of about 0.5 m in length and removing the galvanization by means of acid attack. A test coil was applied in the middle of the sample, wrapping tightly a thin insulated copper wire (0.16 mm diameter) around the strand, in order to obtain a coil with 120 turns. The real and imaginary parts of this coil was measured with a precision LRC meter (HP 4284A). In order to have reference values, a similar coil was built by wrapping the wire around a plastic core having the same diameter as the steel strand. The steel permeability components were obtained as follows:

$$\mu' = \frac{X_s}{X_p},$$  

(13)

$$\mu'' = \frac{R_s - R_p}{X_p},$$  

(14)

where $X_s$ and $X_p$ are the reactances of the steel-core and plastic-core coils, and $R_s$ and $R_p$ are the resistances of the steel-core and plastic-core coils, respectively.
Fig. 3 shows the values obtained for the steel strands from a 3/8” diameter OHGW. It can be seen that the real component ($\mu'$) falls fast as the frequency increases, and then goes asymptotically to 1. The imaginary component ($\mu''$) reaches a maximum value around 2 kHz and then also falls close to the real component. These measurements were carried out at ambient temperature (23 °C) and with an applied magnetic field equal to 45 A/m.

In order to assess the dependency of the permeability with the intensity of the exciting magnetic field, some results are shown in Fig. 4, for the frequency of 40 kHz. It can be seen that the permeability is relatively stable in a wide range of magnetic field intensity. It is important to highlight that in a detection device the frequency and the applied magnetic field intensity are kept constant.

$$P = H_N \mu' + H_N \mu'' - 1,$$

$$Q = H_N \mu' - H_N \mu'' ,$$

$$k = \frac{A_s}{A_c} ,$$

$H_N'$ and $H_N''$ are the real and imaginary parts of the normalized magnetic field, respectively, and $A_s$ and $A_c$ are the cross-section areas of the steel strand and the test coil, respectively. For the test coil considered, $A_c = 46 \text{mm}^2$.

As $H_N$ is function of the zinc layer thickness, the measurement of $\bar{Z}_c$ for steel strands with zinc layers of different thicknesses can provide a verification of (12). Therefore, a set of steel strands was prepared taking a 0.15 m sample from the core of different ACSR cables. Each strand was weighted in a precision scale. The galvanization was completely removed from one strand of each core, and the respective zinc layer thickness was calculated from the strand diameter and its mass reduction. The other strands were subjected to the same chemical treatment to remove the zinc, but the process was interrupted at different stages. The remaining zinc layer thickness was calculated from the mass reduction and the assumption that all strands of the same cable core had the same original zinc layer thickness.

Fig. 5 shows the modulus of the coil impedance as a function of zinc layer thickness for steel strands taken from the core of an ACSR 556.5 MCM cable. Continuous line: calculated from (15) and (12); Dots: experimental data obtained from treated samples. It can be seen that the correlation between theoretical and experimental data is very good, which supports the electromagnetic model contained in (12).

$$\bar{Z}_c = (R_0 - X_0 k Q) + j X_0 (1 + k P) ,$$

where:

$$P = H_N \mu' + H_N \mu'' - 1,$$

$$Q = H_N \mu' - H_N \mu'' ,$$

$$k = \frac{A_s}{A_c} .$$
In the calculation shown in Figs. 5 and 6, the zinc conductivity considered is $\sigma = 11.7$ MS/m. This value was obtained experimentally and it is somewhat lower than the conductivity of pure zinc ($\sigma = 16.9$ MS/m). This difference is likely to be due to impurities in the zinc used in the galvanization process. The zinc conductivity was obtained by weighting a 1 m sample of galvanized steel strand and also measuring its DC resistance with a milliohmmeter (HP 4328A). The sample was subjected to a chemical treatment to remove all the galvanization and its weight and resistance were measured again. Based on the strand dimensions (length and diameter), mass loss and increase of resistance, it was possible to obtain the zinc conductivity.

This experimental investigation was carried out for steel wires from the following cables: ACSR 1113.0 MCM (Blue Jay), ACSR 795.0 MCM (Drake), ACSR 556.5 MCM (Dove), and galvanized steel cable (3/8” OHGW). The results were similar to the ones shown in Figs. 5 and 6, which validate (12).

### III. The ACSR Cable

The behavior of a galvanized steel strand was investigated in the previous section. This section analyzes the behavior of a group of steel strands joined together to form a cable core, as well as the effect of the aluminum strands of an ACSR cable.

#### A. Joining Steel Strands

Excepting the smaller ACSR cables that have only a single steel strand, most of ACSR cables have several steel strands in the core. A common formation is seven strands, with one in the center and six strands twisted around the central one, as shown in Fig. 7. For a longitudinal inducing magnetic field, it is possible to identify two modes of induced currents: the intra-strand and the inter-strand modes, as shown in Fig. 7. If the inter-strand currents are neglected, the effect of having several strands inside a sensing coil may be modeled the superposition of the effect of each strand. Assuming that the strands are identical, (18) can be adapted in order to consider $n$ strands in the coil:

$$k = n \frac{A_s}{A_i}.$$  \hspace{1cm} (19)

The validity of (19) was verified experimentally using a test coil of 180 turns, 67 mm length, and 13 mm diameter. The coil impedance with air core at 40 kHz is $R_0 = 1.74$ Ω and $X_0 = 19.76$ Ω. A seven-strand steel core sample was introduced into the coil and the coil impedance was measured. Then one strand was removed from the steel core and the six-strand core was measured. This process was repeated, until only the central strand remained. The obtained data shows the coil impedance as a function of the number of steel strands. Fig. 8 shows the experimental data and the theoretical values calculated from (15) and (19). It can be seen that an excellent agreement was obtained, which supports the approximations used in the development of (19).

#### B. The Aluminum Strands

Equation (15) gives the response of a galvanized steel cable that is commonly used for OHGW. However, an ACSR cable has also one or more layers of aluminum strands around the steel core. Therefore, it is necessary to model the effect of the aluminum strands on the response of a sensing coil.

The inter-strand induced current on the aluminum layers could provide some shielding effect to the steel core. In order to assess this effect, some experiments were carried out with samples of typical ACSR cables. Each sample had its strands held tightly by using plastic straps and the inner steel strands were removed. The hollowed sample was placed inside a coil excited with alternating current. A small probe coil was inserted inside the sample, and the voltage induced in this probe was measured. The experiment was repeated without the cable sample, for the same current in the inducing coil.
The results obtained for different types of cables show that the hollowed cable does not change significantly the magnetic field intensity inside the coil. The presence of the aluminum strands produced a reduction on the magnetic field of less than 2% of the field measured without the hollowed cable. This result shows that the shielding effect provided by the inter-strand currents can be neglected. One possible explanation is that the contact resistance between the strands is large enough to prevent the flow of significant currents among the strands.

However, the currents induced inside the aluminum strands need to be taken into account (see the intra-strand current if Fig. 7). This phenomenon can be modeled by the same approach used in Section II, assuming that the current in the aluminum strand is confined in a layer defined by the skin depth \( \delta \). For a non-magnetic conductor, the skin depth is [17]:

\[
\delta = \left( \frac{\pi}{f} \sigma \mu_0 \right)^{-1/2}.
\]  

For instance, considering the frequency \( f = 60 \) kHz and the aluminum conductivity (\( \sigma = 35.5 \) MS/m), the skin depth is 345 \( \mu \)m. As the skin depth is not much shorter than the strand radius, an approximate assumption is necessary in order to obtain an effective strand radius for the application of (12). It is assumed that 50% of the induced eddy currents flow between the effective radius \( r_e \) and the real strand radius \( r \) and, of course, the remaining 50% flows within \( r_e \). It is easy to show that this condition leads to:

\[
r_e = r - 0.69 \delta.
\]  

The validity of this approximation can be assessed by measuring the response of a test coil with aluminum strands. In order to do so, the steel core was removed from samples of Grosbeak (ACSR 636.0 MCM) and Partridge (ACSR 266.8 MCM) cables. The resulting hollowed cables were introduced, one at a time, in a 32 mm diameter test coil. The coil impedance was measured for different frequencies with and without the hollowed sample.

Fig. 9 shows the impedances measured, as well as those calculated by (15) and (21). It can be seen a good agreement between the theoretical and experimental results, which supports the proposed model for the aluminum strands.

Fig. 9 also gives the coil impedance without the cable, showing that the aluminum strands actually reduce the coil impedance. A closer look into the real and imaginary data shows that the resistance increases due to the losses in the aluminum and the inductance decreases due to the neutralization of the magnetic field within the strands.

C. The Complete ACSR Cable

Once the effects of the steel and aluminum strands have been modeled, (15) may be adapted in order to provide the sensing coil impedance for a complete ACSR cable:

\[
\bar{Z}_c = R_0 - X_0 \left( k_s Q_s + k_a Q_a \right) + j X_0 \left( 1 + k_s P_s + k_a P_a \right),
\]  

where \( P, Q, \) and \( k \) are given by (16), (17), and (18), respectively, using the data for the relevant strand, i.e., the subscripts \( s \) and \( a \) apply to the steel and aluminum strands, respectively. It is worth to remember that, for aluminum strands, \( \mu'_a = 1 \) and \( \mu''_a = 0 \).

In order to verify (22) experimentally, two ACSR cables were used. For each cable, two samples were prepared: one remained intact and the other had its galvanization totally removed. The zinc layer thickness was calculated based on the mass variation, as explained before. The samples were introduced into sensing coils and the resulting impedances were measured. Fig. 10.a shows the experimental values obtained for the cables considered, while Fig. 10.b shows the corresponding theoretical values. It can be seen a good agreement between the experimental and theoretical values; the difference remained below 1% for the steel strands without galvanization and below 2% for the galvanized strands. The higher difference for the galvanized strands is likely due to the uncertainties related to the assessment of the zinc layer thickness by the loss-of-mass process. Fig. 10 also shows the results for a 3/8” (9.2 mm) galvanized-steel overhead ground wire (OHGW), for comparison.
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Fig. 10. Impedance of a coil containing a complete ACSR or OHGW cable. Bars with dashes: new galvanization; Bars with bricks: no galvanization; (a) Experimental data; (b) Theoretical data from (22).

IV. CONCLUSION

The electromagnetic model described in this paper allows the assessment of the zinc layer thickness of galvanized steel strands that form ACSR or OHGW cables, in order to provide an indication of the remaining conductor life. The theoretical results agreed well with results of experiments, which can be easily reproduced.

A technique employing this model has been successfully applied to a remote-controlled robot to inspect overhead conductors. The field trials have been carried out in de-energized and energized overhead lines, with consistent results. In order to apply the eddy current inspection in energized lines, the acquired data had to be processed in order to remove the power current influence on the steel strand permeability. This data processing technique will be subject of a future publication.

REFERENCES