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AC Corrosion on Pipelines: Influence of the Surface Layer Soil Resistivity in Evaluating the Current Density by a Probabilistic Approach

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Abstract—The context of the paper is the 50–60 Hz electromagnetic interference between AC power lines/electrified railway lines and pipelines; we present here an algorithm for the evaluation of the AC induced current density, flowing through the holidays (defects) in the pipeline insulating coating, from pipe to soil by modelling this last one as a two-layer structure. Moreover, the value of holidays area is treated as a random variable (as actually is from field experience) so allowing to associate a certain level of probability to the event of exceeding the AC current density limit, established by standards, for AC corrosion risk. The results show that the surface layer soil resistivity is a very significant factor influencing the level of AC induced current density.

1. INTRODUCTION

It is well known that when a pipeline or a metallic duct is under the electromagnetic influence of an AC power line or electrified railway line (typically 50–60 Hz), induced voltages and currents appear on it; depending on the level of those quantities, one may have problems of electrical safety for personnel or damages/malfunctioning of apparatuses installed along the pipeline. For such a reason, in many countries suitable standards have been published with the indication of limits to be respected in order to ensure safety for people and correct functioning of apparatuses; nevertheless in the last decades, starting from the field experience, a further problem, again originating from the electromagnetic influence on the pipeline, has been recognized: the AC corrosion even on cathodically protected pipelines [1, 2].

Within the community of pipelines corrosion experts, it is commonly accepted that the AC current density exchanged between a pipeline and soil through the holidays (defects) present in the pipe insulating coating is a meaningful parameter in order to assess the AC corrosion risk; in particular, the value of $30\,\mathrm{A/m^2}$, besides a level of induced AC voltage greater than 15 V, are considered a threshold that, if exceeded, leads to corrosive effects for any type of soil [3]. Thus, from this point of view, especially at the design stage of new plants, it is useful to predict the level of induced voltage and induced current density in different point along the pipeline so that the AC corrosion risk could be assessed. Moreover, also in case of already existing plants, the use of simulation programs can be a complementary tool to be used besides the field measurements.

The algorithms, on which such simulation tools are based, are essentially the same successfully adopted since a long time, to calculate voltages and currents induced on telecommunication cables and pipelines under the influence of power or electrified railway lines [4–9]. These algorithms are mainly based on the transmission line model for both inducing and induced plants. Afterwards, other algorithms based on Finite Element Method (FEM) have been proposed [10–13], and more recently, some theoretical evaluations of the AC induced corrosion risk have been presented in [14, 15].

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The models above mentioned are generally based on the assumption of homogeneous soil, but such a hypothesis is questionable because it neglects the presence of the surface layer soil, that, in many cases, has electrical characteristics quite different from the ones of the bottom soil. On the other hand, the surface layer soil has significant influence on the AC corrosion phenomena; in fact, in order to calculate the AC induced current density through a holiday present in the insulating coating, it is necessary to determine the resistance to remote earth (also named *spread resistance*) of the holiday itself which, as we shall show in the following, strongly depends on the resistivity of the surface layer soil. Thus, a two-layer earth model seems, in our opinion, more adequate than a homogeneous earth model, to estimate the AC induced current density; therefore, in the article, we propose an analytical formulation to calculate the earth resistance of a holiday in the pipeline coating in case of a two-layer soil model and we present a sensitivity analysis by varying the values of the most important parameters involved in the phenomenon. Thus, the first main aspect of novelty of the paper is the application of the two-layer earth model to the AC induced current density calculation instead of the homogeneous soil model as in the above mentioned literature.

The second important aspect relevant to this paper is related to the probabilistic approach adopted in estimating the exceeding of the limit for the AC induced current density; such an approach is based on the hypotheses of treating the holidays area as random variable instead of deterministic variable as usually assumed in literature.

2. SURFACE LAYER SOIL RESISTIVITY

For our purposes, by surface layer soil we mean a horizontal layer soil with thickness of about 1–2 meters and having electrical parameters largely determined not only by the soil characteristics, such as type of soil, chemical composition and concentration of salts dissolved in the contained water, grain size of the material, and compactness but also by the moisture content and temperature that of course depend on the seasonal and meteorological conditions [16–18].

Hill et al. [19] reported some empirical formulas correlating measured values of earth conductivity and permittivity to frequency and moisture content for various soil types; as far as the conductivity is concerned, the following empirical formula is proposed:

$$\sigma = 0.082 w^{1.435} f^{0.072} \tag{1}$$

where f is the frequency in Hz, w the per cent moisture content in the soil, and σ the conductivity in mS/m.

By means of Eq. (1), we plot in Fig. 1 the soil resistivity versus the per cent moisture content at the frequency of 50 Hz. In the same figure we also add some data reported in [17] and [18]; we can notice that there is a good agreement between the two curves.

Figure 1 shows, as expected, the strong dependence of soil resistivity with respect to the water content. This is the reason that the surface layer soil resistivity may vary appreciably between a long dry and a long wet season.

On the contrary, the soil characteristics below the surface layer do not depend upon weather and season; so, if one adopts a two-layer model, the second layer is represented by an infinite and homogeneous medium characterized by a constant resistivity generally having a different value with respect to the one of the surface layer. For practical applications, as an alternative to measurements, it is possible to deduce such a value from suitable maps that relate the prevalent geological formations, relevant to the geographical area of interest, to the electrical resistivity.

It is worthwhile to add that the ratio ρ_1/ρ_2 (being ρ_1 and ρ_2 the resistivity of the top and bottom soil respectively) lies, according to [9], in the range $[0.02, 100]$.

As a general remark, it is important to notice that the presence of the surface layer soil greatly influences the value of the earthing resistance of any kind of electrode especially if buried in the surface layer itself.

This has a direct consequence on the evaluation of the AC induced current density, flowing through a defect in the pipeline insulating coating, from pipe to soil; in fact, the earthing resistance of the pipe to remote earth at the holiday location, which is directly related to the current density, can be modelled as a very small electrode having the shape of a circular disk of area A in contact with the soil as sketched in Fig. 2.

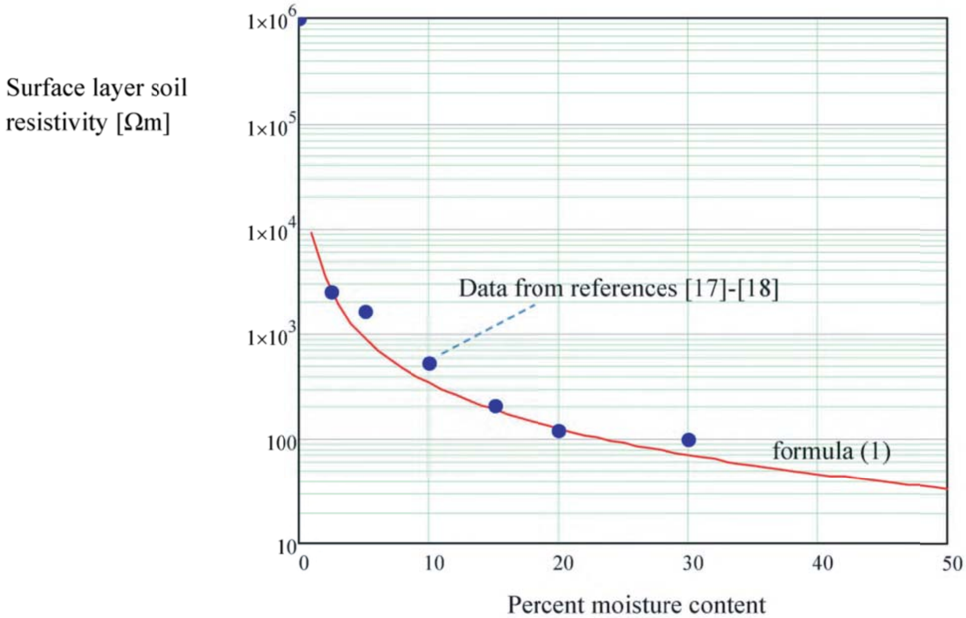

Figure 1. Surface layer soil resistivity versus per cent moisture content; $f = 50\,\mathrm{Hz}$.

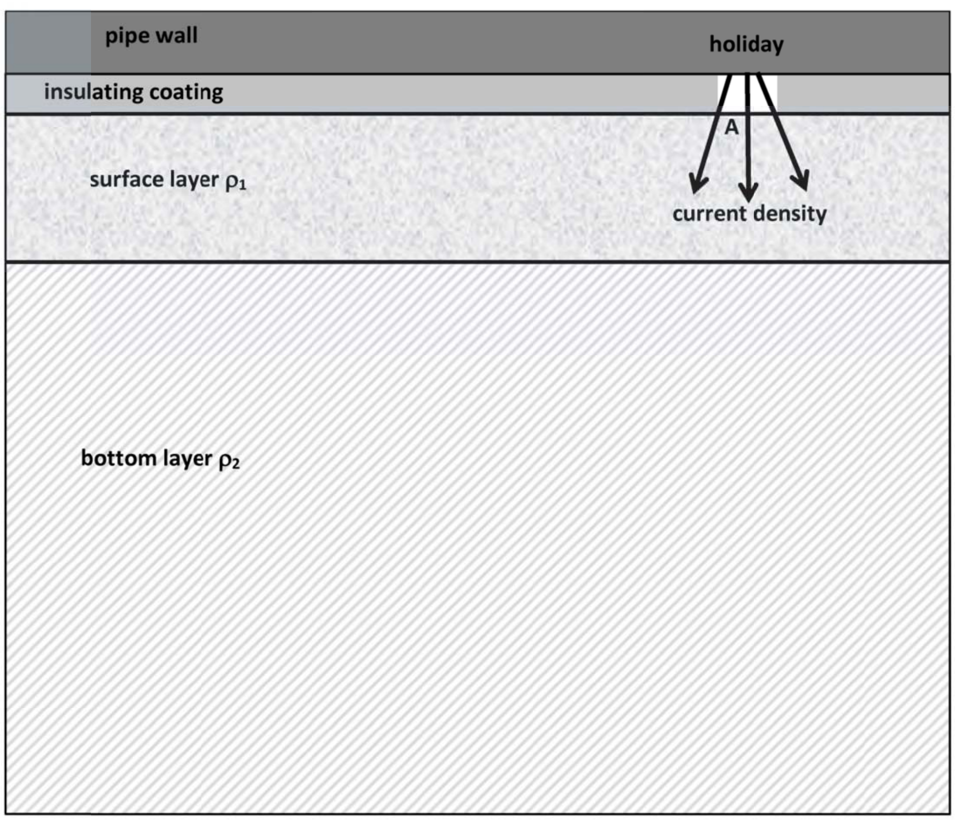

Figure 2. Sketch of a holiday in the insulating coating of a pipeline buried in a two-layer soil.

In the next paragraph we present analytical formulas for evaluating such a resistance in function of the resistivities ρ_1 and ρ_2 of the two-layer soil and of the area A of the holiday in the insulating coating.

3. EARTH RESISTANCE OF A HOLIDAY IN CASE OF A TWO-LAYER SOIL

As mentioned before, by modelling the holiday in the pipeline coating as a circular disk of area A placed at the air-soil interface, according to [20, 21], its resistance to remote earth is given by:

$$R = \frac{\rho_1}{4b}\left[1 + 2\sum_{k=1}^{\infty}\frac{\left(\frac{\rho_2-\rho_1}{\rho_2+\rho_1}\right)^k}{\sqrt{1+\left(\frac{2kD}{b}\right)^2}}\right] \tag{2}$$

ρ_1 and D being respectively the resistivity and thickness of surface layer soil, ρ_2 the bottom soil resistivity, and $b = (A/\pi)^{1/2}$ the radius of the holiday of area A.

It is convenient to rewrite formula (2) in function of the holiday area A and of the ratio η of the two resistivities, i.e., $\eta = \rho_1/\rho_2$:

$$R = \frac{\rho_2\eta}{4\sqrt{\frac{A}{\pi}}}\left[1 + 2\sum_{k=1}^{\infty}\frac{\left(\frac{1-\eta}{1+\eta}\right)^k}{\sqrt{1+\left(\frac{2kD}{\sqrt{\frac{A}{\pi}}}\right)^2}}\right] \tag{3}$$

In Fig. 3, we plot some curves representing the value of the earth resistance of a holiday versus the parameter η for different values of the resistivity ρ_2 of the bottom soil under the hypothesis that A has the typical value of $1\,\text{cm}^2$.

As one can notice, by looking at Fig. 3, the values of R are very high even for small values of the parameter η; consequently, the presence of the holidays has practically no influence in the determination of AC induced voltage and current along the pipeline-earth circuit; that can be readily verified by using

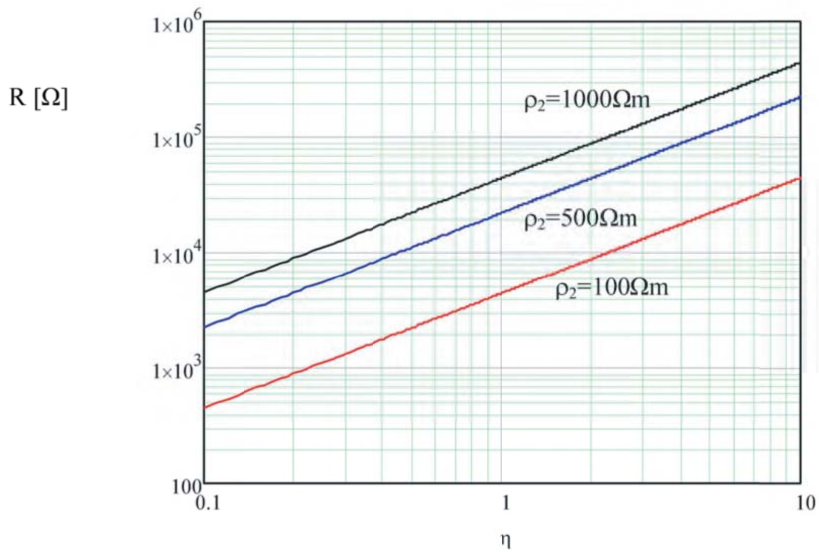

Figure 3. Holiday resistance to remote earth versus η for different values of bottom soil resistivity; $A = 1\,\text{cm}^2$, $D = 1\,\text{m}$.

the models described in [4–9]. In fact, we remind that the presence of earthing electrodes installed along the pipeline route is able to significantly influence the voltage and current profiles only when the value of their resistance to earth is low; i.e., in the range of some ohms.

On the contrary, as we show in the next paragraph, the value of the AC induced current density is strongly determined by the value of the holidays earthing resistance and, more specifically, by the two-layer soil characteristics.

4. CURRENT DENSITY THROUGH A HOLIDAY IN CASE OF A TWO-LAYER SOIL

Let us define by s the curvilinear abscissa along the pipeline route, and let $V(s)$ be the AC induced voltage calculated in function of such an abscissa by means of the methods described in [4–9]. Let us also suppose that a holiday of area A is present at the position, corresponding to abscissa s, along the pipeline route.

The current density $J(s)$ through the holiday is given by:

$$J\left(s, A\right) = \frac{V\left(s\right)}{RA} \tag{4}$$

By substituting Eq. (3) into Eq. (4) one gets:

$$J\left(s, A\right) = \frac{4V\left(s\right)}{\rho_2 \eta \sqrt{\pi A}\left(1 + 2\sum_{k=1}^{\infty} \frac{\left(\frac{1-\eta}{1+\eta}\right)^k}{\sqrt{1 + \left(\frac{2kD}{\sqrt{\frac{A}{\pi}}}\right)^2}}\right)} \tag{5}$$

Therefore, from the knowledge of the AC induced voltage profile along the pipeline route it is possible to determine the value of the AC current density at a given position provided that a holiday of known area A is present there.

Due to the linearity of $J(s, A)$ with respect to $V(s)$, it may be useful to also introduce the AC induced current density $J'(A)$ per unit AC induced voltage that we can define as:

$$J'\left(A\right) = \frac{4}{\rho_2 \eta \sqrt{\pi A}\left(1 + 2\sum_{k=1}^{\infty} \frac{\left(\frac{1-\eta}{1+\eta}\right)^k}{\sqrt{1 + \left(\frac{2kD}{\sqrt{\frac{A}{\pi}}}\right)^2}}\right)} \tag{6}$$

Note that, for given values of ρ_1 and ρ_2, the value of $J'(A)$ does not depend on the abscissa s but only on holiday area A; so, the quantity $J'(A)$ can be considered as a scale factor between $J(s, A)$ and $V(s)$.

In Fig. 4, we plot the AC induced current density versus the dimensionless parameter η by supposing a 50 Hz induced voltage of 15 V (i.e., the induced voltage limit prescribed by [3]) for different values of the bottom soil resistivity ρ_2. The area of the holiday has been supposed equal to $1\,\mathrm{cm}^2$. For convenience, in Fig. 4 we also add the $30\,\mathrm{A/m}^2$ limit for the AC induced current density as prescribed by [3].

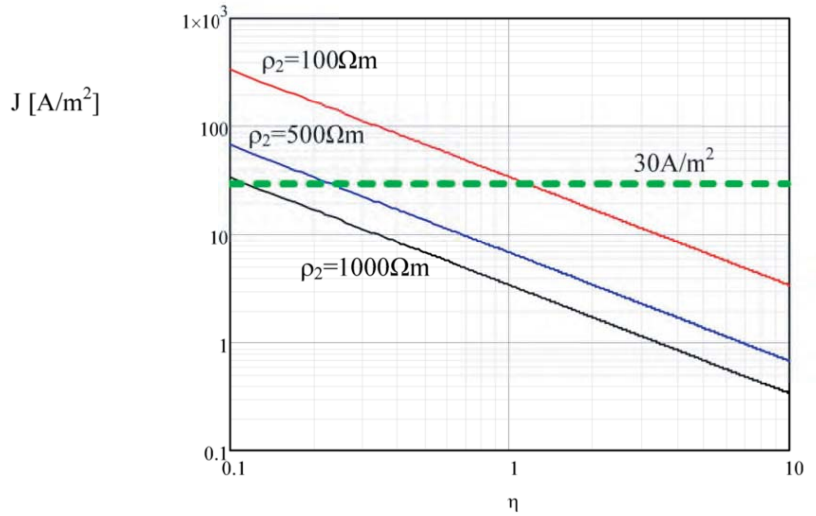

Figure 4. AC induced current density versus η for different values of bottom soil resistivity; $A = 1\,\mathrm{cm}^2$, $D = 1\,\mathrm{m}$, $V = 15\,\mathrm{V}$.

Figure 4 clearly shows the role played by the surface layer soil: in fact, for a given value of AC induced voltage, the smaller ρ_1 is, the higher the current density is, and the stronger this trend is, the lower the bottom soil resistivity is.

In Fig. 5, we plot the current density versus the dimensionless parameter η by supposing a 50 Hz induced voltage of 15 V for different values of the holiday area A. The bottom soil resistivity ρ_2 has been supposed equal to $200\,\Omega$m.

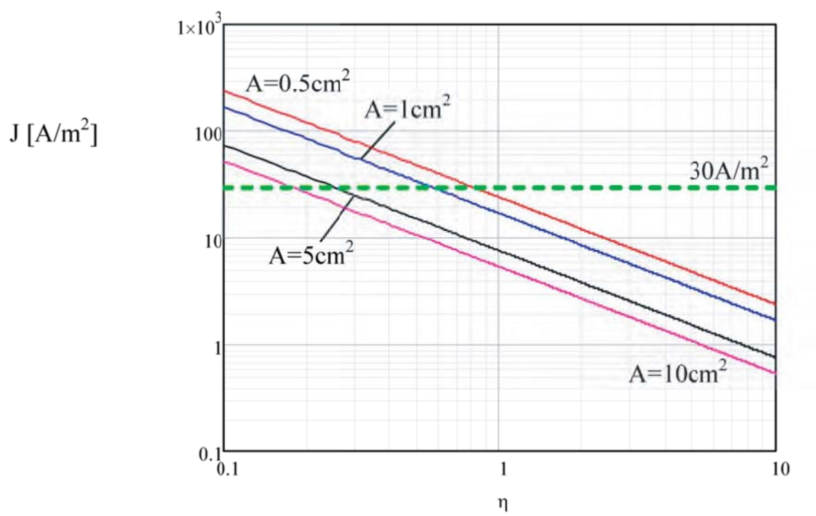

Figure 5. AC induced current density versus η for different values of holiday area; $\rho_2 = 200\,\Omega\mathrm{m}$, $D = 1\,\mathrm{m}$, $V = 15\,\mathrm{V}$.

As expected, Fig. 5 shows that, for a given value of the induced voltage, the smaller the holiday area is, the higher the current density is; also in this case, the stronger this trend is, the lower the value of the surface layer soil resistivity is.

In both Figs. 4 and 5 one can notice the significant differences between the results for the case with $\eta = 1$ (i.e., homogeneous soil) and the cases with $\eta \neq 1$ (i.e., two-layer soil).

It is important to remark that, if a holiday is present at abscissa s along the pipeline and $V(s)$ is the value of AC induced voltage at the same location, a given value of current density limit J_{lim} (e.g., the one established from the standards) can be exceeded only if the holiday area is smaller than a certain limit value A_{lim}. Such a value is solution of the following equation:

$$J'(A)\,V(s) = J_{\text{lim}} \tag{7}$$

It is also worthwhile to notice that, for each value of A fulfilling the condition $A \leq A_{\text{lim}}$, the inequality $J \geq J_{\text{lim}}$ holds.

This concept can be explained also by means of the example shown in Fig. 6 where we plot the current density $J(A, s)$ by supposing that, at abscissa s along the pipeline, where the holiday is present, one has an induced voltage of 15 V, (i.e., from (7) $J(A, s) = 15J'(A)$).

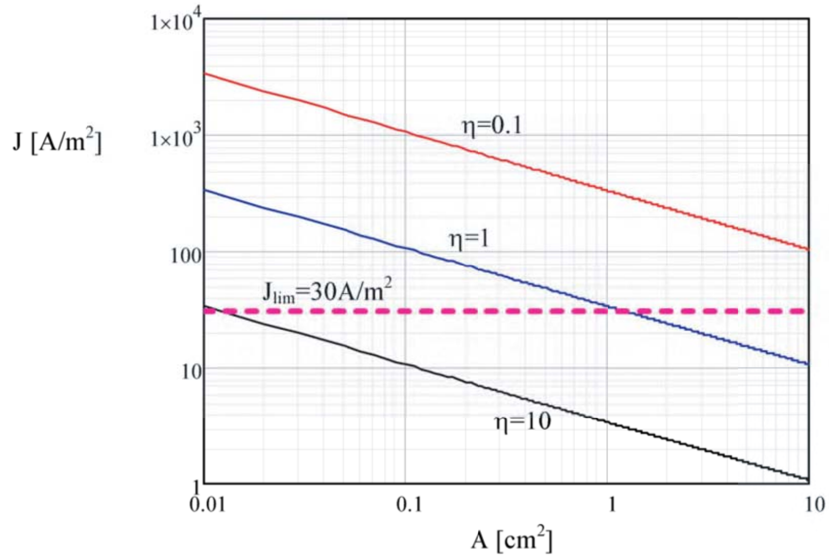

Figure 6. AC induced current density versus the holiday area A for different values of the ratio η; $\rho_2 = 100\,\Omega\text{m}$, $D = 1\,\text{m}$, $V = 15\,\text{V}$.

Figure 6 shows the current density versus the holiday area A for different values of the ratio η; the value A_{lim} is the abscissa corresponding to the intersection of the curve $J(A, s)$ with the horizontal line identified by the value J_{lim}.

5. A PROBABILISTIC APPROACH FOR THE CURRENT DENSITY CALCULATION

The approach followed till now is purely deterministic, i.e., it is based on the assumption of a known value concerning the holidays size; typically, in literature and standards, one finds $A = 1\,\text{cm}^2$ which is considered as a mean and representative value. Nevertheless, field experience shows that the holiday area size statistically lies in an interval ranging from few mm^2 to some tens of cm^2; thus, a probabilistic approach that takes into account of the random nature of the holiday area size seems more adequate for calculating the levels of AC induced current density.

To this aim, in a previous work [22], we inferred, from experimental data coming from the field, that the empirical statistical distribution of the holidays area is sufficiently well fitted by a log-normal distribution having the probability density $w(A)$ given by the expression:

$$w(A) = \frac{1}{A\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\frac{(lnA-\mu)^2}{\sigma^2}} \tag{8}$$

where parameters μ and σ, characterizing the distribution, have the values $\mu = -8.207$ and $\sigma = 1.419$.

On the basis of this hypothesis and by assuming the actual presence of a holiday at a point of abscissa s along the pipeline route, the probability that the AC induced current density, at the holiday location, exceeds the limit J_{lim} is given by:

$$P\left(J\left(V\left(s\right)\right) \geq J_{\mathrm{lim}}\right) = P\left(A \leq A_{\mathrm{lim}}\left(V\left(s\right)\right)\right) = \int_{0}^{A_{\mathrm{lim}}(V(s))} \frac{1}{A\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\frac{(lnA-\mu)^2}{\sigma^2}} dA \quad (9)$$

Formula (9) allows to associate, to any point of abscissa s along the pipeline route, the corresponding level of probability of exceeding the current density limit J_{lim}. Thus, the knowledge of such a probability profile $P = P(s)$, along the pipeline besides the AC induced voltage profile $V = V(s)$, gives us a more complete information in order to quantify the AC corrosion risk.

In Fig. 7, we plot the per cent probability $P_{\%}$ of exceeding the current density limit of 30 A/m^2 versus the parameter η for a given value of AC induced voltage of 15 V and for different values of bottom soil resistivity. It is useful to notice that the bottom soil resistivity ρ_2 is involved because the AC induced current density is also a function of ρ_2 (see formula (5)).

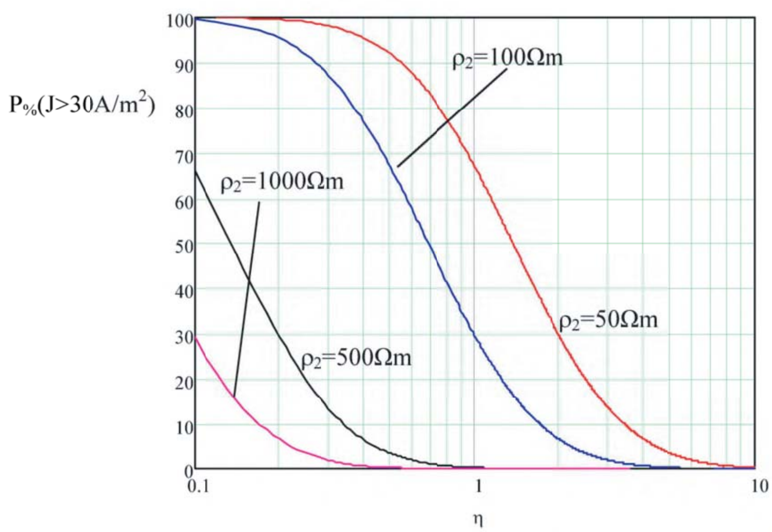

Figure 7. Per cent probability of exceeding the limit of 30 A/m^2 versus η for different values of bottom soil resistivity; $D = 1$ m, $V = 15$ V.

From the plots in Fig. 7, one immediately notices that, for a given value of induced AC voltage, the per cent probability of exceeding the current density limit is high when the bottom soil resistivity value is low and the ratio η is much smaller than 1.

Also in Fig. 7, one can notice the significant differences between the results for the case with $\eta = 1$ (i.e., homogeneous soil) and the cases with $\eta < 1$ (i.e., two-layer soil with $\rho_1 < \rho_2$).

6. EXAMPLE OF APPLICATION

We consider in this example a pipeline 16.34 km long that is induced by a 380 kV–50 Hz power line, 6.225 km long in normal operating conditions. The layouts of both the plants are shown in Fig. 8.

The power line, provided with two shield wires, carries a tri-phase current of 2310 A and one of the phases has a 2.5% imbalance. The steel pipeline has diameter 400 mm, thickness 11 mm it is provided by a polyethylene coating and no earthing points exist along its route.

By applying the calculation methods quoted in the References one can determine the 50 Hz induced voltage profile $V(s)$ along the pipeline route; in Fig. 9 we plot such a quantity for different values of surface soil resistivity ρ_1 and of the bottom soil resistivity ρ_2.

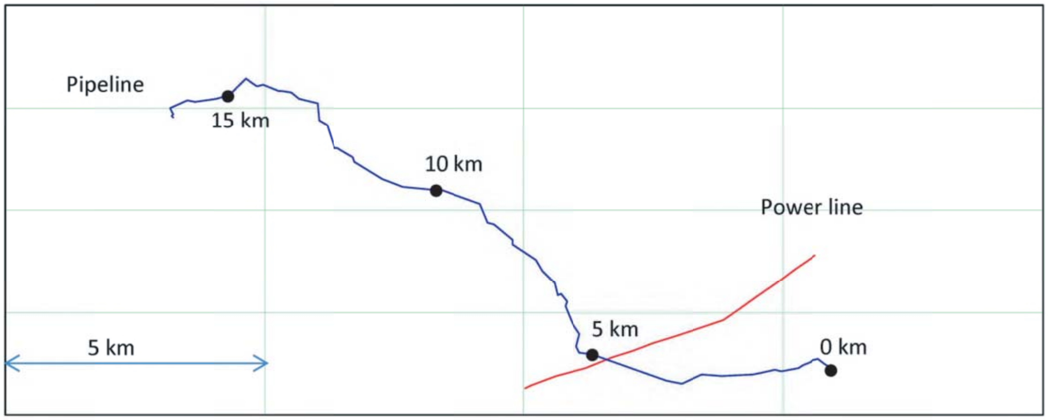

Figure 8. Layouts of power line and pipeline.

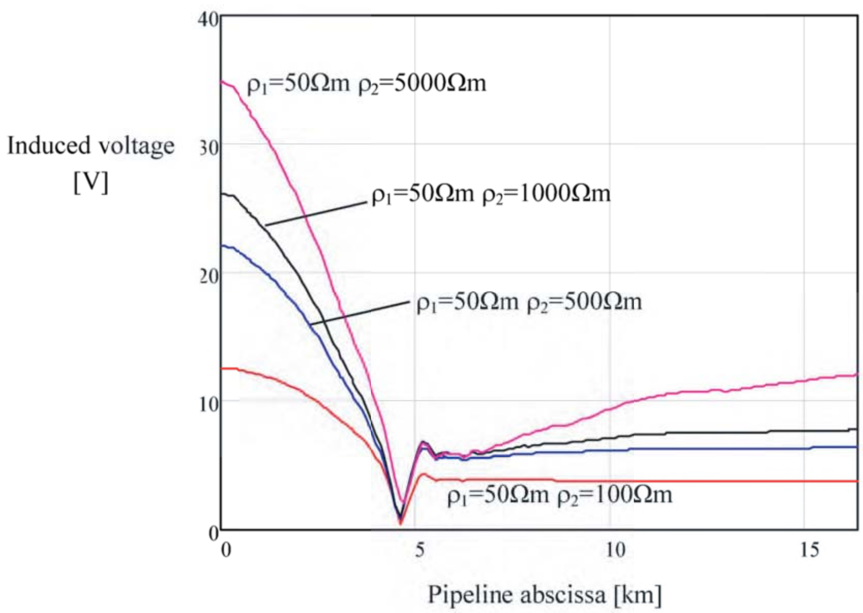

Figure 9. Induced voltage along the pipeline for different values of soil resistivities ρ_1 and ρ_2; $D = 1\,\mathrm{m}$.

We can notice that the higher the bottom soil resistivity is, the higher the level of induced voltage is along the pipeline; we can explain this result by remembering that, due to the small thickness of the surface layer soil ($D = 1\,\mathrm{m}$), both inductive and conductive influences, from the power line on the pipeline, mainly depend on the bottom soil resistivity; in fact, they both increase, by increasing ρ_2.

In correspondence with the profile voltages shown in Fig. 9, we also plot the per cent probability curves of exceeding the current density limit of $30\,\mathrm{A/m^2}$ (see Fig. 10).

By looking at Fig. 10, one can notice the larger influence of the surface layer soil resistivity in determining the probability of exceeding the current density limit than the influence that the same parameter has in determining level of induced voltage along the pipeline.

To conclude, it may be useful to explain the shape of the plots in Fig. 9. To this aim, it is necessary to remember that in the case of uniform induction along a pipeline with no earthing points, as a consequence of the second Kirchhoff law, the modulus of the induced voltage profile has the typical shape of a V where the vertex is located at the pipeline route midpoint.

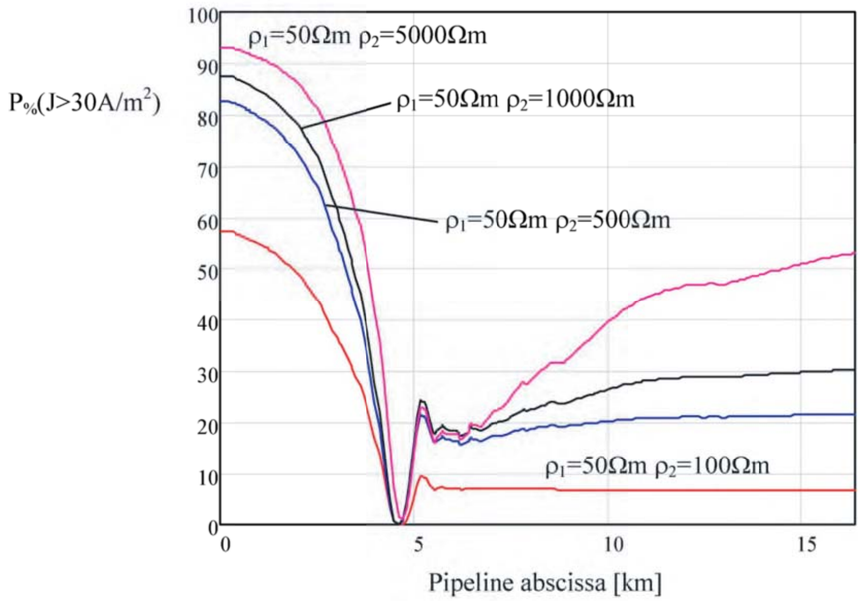

Figure 10. Per cent probability of exceeding the limit of $30\,\mathrm{A/m^2}$ along the pipeline, for different values of soil resistivities ρ_1 and ρ_2; $D = 1\,\mathrm{m}$.

In our case, the pipeline, as already said, has no earthing points, but it is not uniformly induced because most of the induction is concentrated in the first 5–6 kilometers due to the greater proximity with the inducing power line (see Fig. 8); thus, the consequence is an induced voltage profile having the shape of an unsymmetrical and distorted V where the highest values are reached in the first part of the pipeline route.

The plots of Fig. 10 are qualitatively similar to those of Fig. 9 because the probability of exceeding the AC induced current density limit in a certain point along the pipeline route is proportional to the value of AC induced voltage in the same point.

7. CONCLUSIONS

In the frame of the 50–60 Hz electromagnetic interference between power lines/electrified railway lines and pipelines, this paper proposes a model for evaluating the AC induced current density exchanged between pipeline and soil through the holidays present in the pipe insulating coating.

Three main points are put into evidence:

1. The AC induced current density is evaluated under the hypothesis of a two-layer soil so improving the simpler assumption based on homogeneous soil adopted in most of literature.
2. The area of holidays present in the pipe insulating coating is, more realistically, treated as a random variable instead of deterministic; this allows to make a probabilistic evaluation of the AC induced current density.
3. The surface layer soil resistivity has noticeable influence on the level of AC induced current density exchanged between pipe and soil and the results in many cases are very different with respect to the ones obtained by adopting a homogeneous soil model.

To conclude, we think that the two-layer soil model, combined with a probabilistic model for the evaluation of the induced AC current density can represent a useful approach for assessing the AC corrosion risk for pipelines subjected to 50–60 Hz interference from power lines and electrified railway lines.

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