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ELECTROMAGNETIC SURFACE METHOD FOR THE PIPELINE PERIODICAL INSPECTION BASED ON THE HETEROGENEOUS TRANSMISSION LINE MODEL

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ABSTRACT

The superficial electromagnetic methods are widely applied for non-destructive control of pipeline technical condition. For this purpose we have developed the theory and field technology for the pipeline inspection that allows: 1) determining the pipeline trajectory (plane position and depth), 2) delimitation of pipeline intervals with an insulation coating damage, and 3) estimating the condition of a cathodic protection system.

The proposed method is based on the approximation of a metallic pipeline by a heterogeneous transmission line with variable distributed parameters: resistance and inductance along a tube (tube wall thickness) and leakage conductance. The field operations consist in measurements of magnetic field above a pipeline and voltage only on the control posts.

The interpretation process includes the iterative inversion of the magnetic component in order to determine the pipeline depth and current distribution along pipeline. The current difference corresponds to leakage current and allow estimate the leakage resistance. We illustrate the practical application of this method using the obtained results for pipeline inspections in Mexico.

Based on the voltage and current simulations for the infralow-frequency band (0-1kHz) we have evaluated the feasibility of the time lapse measurements of the magnetic field in some fixed points for the early prediction of an insulation damaging process.

KEYWORDS

Pipeline inspection, electromagnetic method, wall thickness, insulation damage, magnetic field.

INTRODUCTION

The pipeline inspection includes the determination of their position, depth, condition of insulated coating, and quality of cathodic protection. The effective inspection by superficial

electromagnetic methods consists in the non-contact measurement of magnetic field created by the current flowing in the pipeline [1-3].

This current is produced by the cathodic protection station or can be excited using an external generator. The external AC generator is connected directly to the pipeline through the control unit of cathodic protection system and an electrode grounded in a remote point ("infinity"). The operating frequencies are selected in low frequency range to apply an inductive magnetic antenna that allows measuring magnetic fields components.

The electrical stations of cathodic protection system use rectifiers of industrial frequency current and produce both the DC and AC components. Frequently, the magnetic-field observation carries out at frequency of 120 Hz, which corresponds to the second harmonic of the industrial frequency.

In this work we consider the pipeline inspection method based on the superficial measurements of electromagnetic field components. We treat a metallic pipeline as heterogeneous transmission line (TL). This approximation allows representing a pipeline with insulation damages and variable tube-wall thickness. Based on the transmission line approach we simulated the distributions of voltage, current and magnetic field along a pipeline as functions of the leakage resistance and tube impedance.

We present the results of this technique application to the practical inspection of pipeline condition. This example developed the field technology and the interpretation of the magnetic field measurements to determine the depth and position of the pipeline axis as well to delimitate the intervals with coating failure of different stages.

Taking into account that the voltage behavior is mainly defined by the integral pipeline parameters, we can reconstruct the voltage distribution along pipeline using observations only on several control posts. The leakage resistance is determined as the ratio of the voltage to the current difference per length unit (leakage current).

Additionally, we have considered the feasibility of use the time lapse measurements of the magnetic-field in several fixed points for monitoring the dropping of the pipeline insulation resistance.

NOMENCLATURE

- C - leakage capacitance per unit interval of 1 m $[\text{Fm}^{-1}]$.
G - leakage conductance per unit interval of 1 m $[\Omega^{-1}\text{m}^{-1}]$.
L - pipe inductance per unit interval of 1 m $[\text{Hm}^{-1}]$.
R - pipe resistance per unit interval of 1 m $[\Omega\text{m}^{-1}]$.
Y - leakage admittance per unit interval of 1 m $[\Omega^{-1}\text{m}^{-1}]$.
Z - pipe impedance per unit interval of 1 m $[\Omega\text{m}^{-1}]$.
 $dI(x)$ – change of current along the pipeline [A].
 $dV(x)$ – change of voltage along the pipeline [V].
 dx -length element of the transmission line [m].
 H_y - magnetic-field horizontal component $[\text{Am}^{-1}]$.
 $I_i(x)$ – current along the pipeline on an interval i [A].
 $I_i^1(x)$ - leakage current on an interval i [A/m]
 $T_i(x)$ - leakage resistance on an interval i $[\Omega\text{m}^{-1}]$.
 T_i^{env} – environmental resistance on an interval i $[\Omega\text{m}^{-1}]$.
 T_i^{ins} – insulation resistance on an interval i $[\Omega\text{m}^{-1}]$.
 $V_i(x)$ – voltage on an interval i [V].
h - depth of the pipeline axis [m].
t – time [s].
x - point of observation [m].
 δ - skin-layer thickness [m].
 μ - magnetic permeability of pipeline $[\text{Hm}^{-1}]$.
 μ_0 - permeability of free space and has a value of $4\pi \times 10^{-7} [\text{Hm}^{-1}]$
 α_i - attenuation constant for an interval i $[\text{m}^{-1}]$.
 β_i - phase constant for an interval i $[\text{m}^{-1}]$.
 γ_i - propagation constant for an interval i $[\text{m}^{-1}]$.
 λ_i – wavelength on interval i [m].
 σ_i - pipeline conductivity for an interval i $[\Omega^{-1}\text{m}^{-1}]$.
 ρ_m - environmental resistivity $[\Omega\text{m}]$
 ρ_{ins} – is the insulation resistivity $[\Omega\text{m}]$
 $\tau(x,t)$ - relative variation of the magnetic field in the measuring point
 $\delta(\Delta x,t)$ relative variation of magnetic field on the pipeline interval Δx .
 Δr - pipeline wall thickness [m].

HETEROGENEOUS TRANSMISSION LINE FOR METALLIC PIPELINE APPROXIMATION

The equivalent electric scheme of the pipeline as a transmission line with distributed parameters is given in Fig. 1.

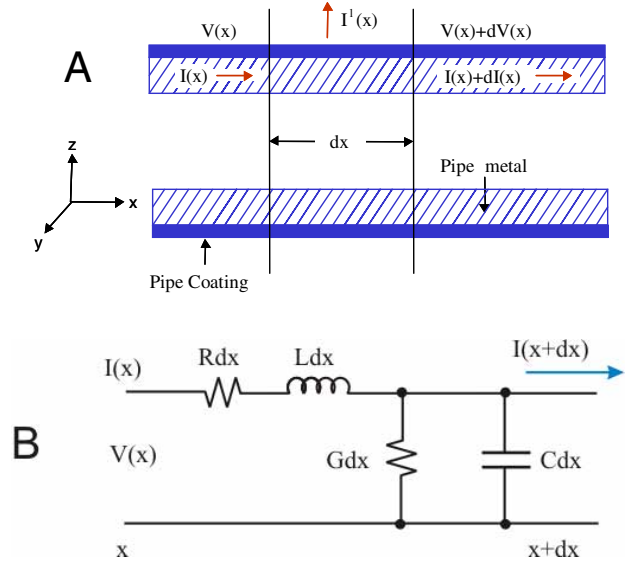


Fig 1. Transmission line model of a metallic pipeline. (A) Voltage and current variations in the longitudinal pipeline section. (B) Equivalent electrical scheme of transmission line.

In the frequency domain the variations of current $I(x)$ and voltage $V(x)$ in the pipeline are expressed by following equations:

$$\frac{dV(x)}{dx} = -ZI(x) \quad (1)$$

$$\frac{dI(x)}{dx} = -YV(x) \quad (2)$$

$$\text{where: } Z=R+j\omega L \\ Y=G+j\omega C$$

The pipe impedance Z and leakage admittance Y are defined by the next parameters, distributed per unit interval of 1 m: pipe resistance R , pipe inductance L , leakage conductance G and leakage capacitance C .

The decrease in current along a pipeline takes place due to the leakage of current through pipe insulation into an environment. Therefore this leakage current $I^1(x)$ in a point x can be defined as derivative of current $I(x)$ flowing along a pipeline for each i -th interval:

$$I_i^1(x) = -\frac{dI(x)}{dx} \quad (3)$$

Taking into account that the real pipeline has the variable wall thickness and insulation resistance we represented such pipeline as a heterogeneous transmission line composed by piecewise-uniform intervals [4-5].

For each i-th interval where the TL parameters are constant, from expressions (1) and (2) we can obtain

$$\frac{d^2 V_i(x)}{dx^2} - \gamma_i^2 V_i(x) = 0 \quad (4)$$

$$\frac{d^2 I_i(x)}{dx^2} - \gamma_i^2 I_i(x) = 0 \quad (5)$$

where: $\gamma_i = \sqrt{Z_i Y_i}$ - propagation constant for an interval i.

The propagation constant γ_i is a complex quantity that can be presented through an attenuation constant α_i and phase constant β_i , related with the wavelength λ_i as $\beta_i = 2\pi/\lambda_i$; $\gamma_i = \alpha_i + j\beta_i$.

The solution of equations (4) and (5) can be written for the i-th interval as following:

$$V_i(x) = A_i e^{-\gamma_i x} + B_i e^{\gamma_i x} \quad (6)$$

$$I_i(x) = \frac{\gamma_i}{Z_i} (A_i e^{-\gamma_i x} - B_i e^{\gamma_i x}) \quad (7)$$

The terms with the positive and negative exponents correspond to the outgoing and reflected components of voltage and current.

The unknown coefficients A_i and B_i are found from the system of equations obtained by using the boundary conditions between homogeneous intervals and conditions in the source. In the points of homogeneous interval connection the voltage and current functions are continuous

$$V_i(d_i) = V_{i+1}(d_{i+1}) \quad (8)$$

$$I_i(d_i) = I_{i+1}(d_{i+1}) \quad (9)$$

The source conditions for the voltage or current generator are

$$V_i(0) = V_0 \quad (10)$$

$$I_i(0) = I_0 \quad (11)$$

In the last interval, when the distance from the source point tends to infinity the voltage and current go to zero.

$$V_i(x) \rightarrow 0 \quad x \rightarrow \infty \quad (12)$$

$$I_i(x) \rightarrow 0 \quad x \rightarrow \infty \quad (13)$$

Transmission line parameters

The pipe resistance R_i according to Chipman [6], for $\omega=0$ is defined by the pipe conductivity σ_i , the wall thickness Δr and the inner radius r_0 :

$$R_{i dc} = \frac{1}{\sigma_i 2\pi r_0 \Delta r} \quad (14)$$

The inductance of pipe, for $\omega=0$ and $r_0 \gg \Delta r$ [6] is given as

$$L_{i dc} = \frac{\mu}{8\pi} \left[\frac{4}{3} \left(\frac{\Delta r}{r_0} \right) - \frac{2}{15} \left(\frac{\Delta r}{r_0} \right)^2 - \frac{1}{10} \left(\frac{\Delta r}{r_0} \right)^3 \right] \quad (15)$$

where: μ - is the magnetic permeability of pipe material.

For the frequencies $\omega > 0$, the resistance and inductance relate to a skin-layer thickness δ . When $\delta < \Delta r$ and $r_0/\delta > 10$, the equations (14) and (15) have to be substituted by following:

$$R_{i ac} = \frac{1}{2\pi r_0} \sqrt{\frac{\omega \mu}{2\sigma_i}} \quad (16)$$

$$L_{i ac} = \frac{1}{2\pi r_0} \sqrt{\frac{\mu}{2\sigma_i \omega}} \quad (17)$$

For operating frequencies in the low range (0-10 kHz) we can neglect the influence of leakage capacitance because the leakage conductance $G \gg \omega C$. The leakage resistance T ($T=1/G$) can be presented as a sum of the insulation T^{ins} and environmental T^m resistances

$$T = T^{ins} + T^m \quad (18)$$

The resistance of the insulation coating is calculated taking into account that the leakage current is radially directed from a tube surface [1]:

$$T^{ins} = \frac{\rho_{ins}}{2\pi} \ln \frac{d_2}{d_1} \quad (19)$$

where: ρ_{ins} - is the insulation resistivity, d_1 and d_2 - are internal and external diameters of an isolation layer.

The environmental resistance for the small pipeline depth (about a few meters) can be estimated using the expression for the current line on the surface of a half-space with the environmental resistivity ρ_m

$$T^m = \frac{\rho_m}{\pi} \ln \frac{d_3}{d_2} \quad (20)$$

The quantity d_3 is the effective radius in an environment, on which the voltage value can be assumed equal to zero (according to accuracy needed for the practical application $d_3 \approx 10^3 d_2$).

Magnetic field

The magnetic field created by the current flowing in the pipeline can be calculated on the basis of Biot - Savart law. The magnetic-field component that is perpendicular to the pipeline axis is expressed through the convolution integral [1]:

$$H_y(\omega, x, y, h) = \frac{1}{4\pi} \int_{-\infty}^{\infty} \frac{I(\omega, x_p) h dx_p}{[h^2 + y^2 + (x - x_p)^2]^{3/2}} \quad (21)$$

where h is the depth of pipeline axis and x is the point of magnetic field measurement.

When the current change in the finite integration interval $(-a, a)$ is close to be linear and $a > 10\sqrt{h^2 + y^2}$, the horizontal component H_y along the profile perpendicular to the pipeline axis can be calculated with accuracy better than 0.5 % from expression

$$H_y(\omega, x, 0, h) = \frac{I(\omega, x)h}{2\pi(h^2 + y^2)} \quad (22)$$

This equation shows that the horizontal magnetic field corresponds to the current value in the measuring point and its distribution has the similar behavior as current flowing along pipeline.

DISTRIBUTIOS OF THE ELECTROMAGNETIC-FIELD CHARACTERISTICS ALONG PIPELINE

To study the influence of the insulation damages and changes of the tube wall thickness we have calculated the distribution of the electromagnetic-field characteristic along a pipeline with variable parameters. We treated such pipelines as a heterogeneous transmission line and performed simulation solving system of equations (6-13). The transmission line parameters were evaluated from equations (16-17) for the operating frequencies of 625 Hz. We used the following pipe electromagnetic properties: electrical conductivity $\sigma=10^6$ and magnetic permeability $\mu=50\mu_0$. We considered two cases of the electromagnetic-field excitations by a voltage and current generators. The generator was connected to the pipeline in the point $x=0$. The magnetic field was calculated at the altitude 1 m above the pipeline axis.

Insulation damage.

The model of the pipeline with insulation coating variations consists of three zones with different leakage conductance (fig. 2). In the first zone the presence of undamaged insulation with a leakage conductance $G_1=10^{-4}$ is supposed. The second zone introduces a part of the pipeline with strong damage of insulation and it is characterized by a high leakage conductance $G_2=10^{-2}$. Center of this zone is in a point 250 m. Its width is variable and equal to 10, 30 and 100 m. In the third zone the leakage conductance $G_3=10^{-3}$ corresponds to medium grade of the insulation change.

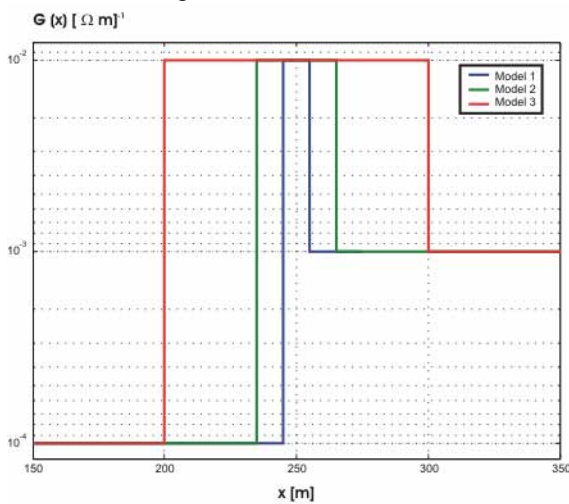


Fig. 2. Model of a leakage resistance distribution for different length of a zone of strong insulation damage: Model 1 - 100 m.; Model 2 - 30 m.; Model 3 - 10 m. Center of a zone is in the point $X=250$ m.

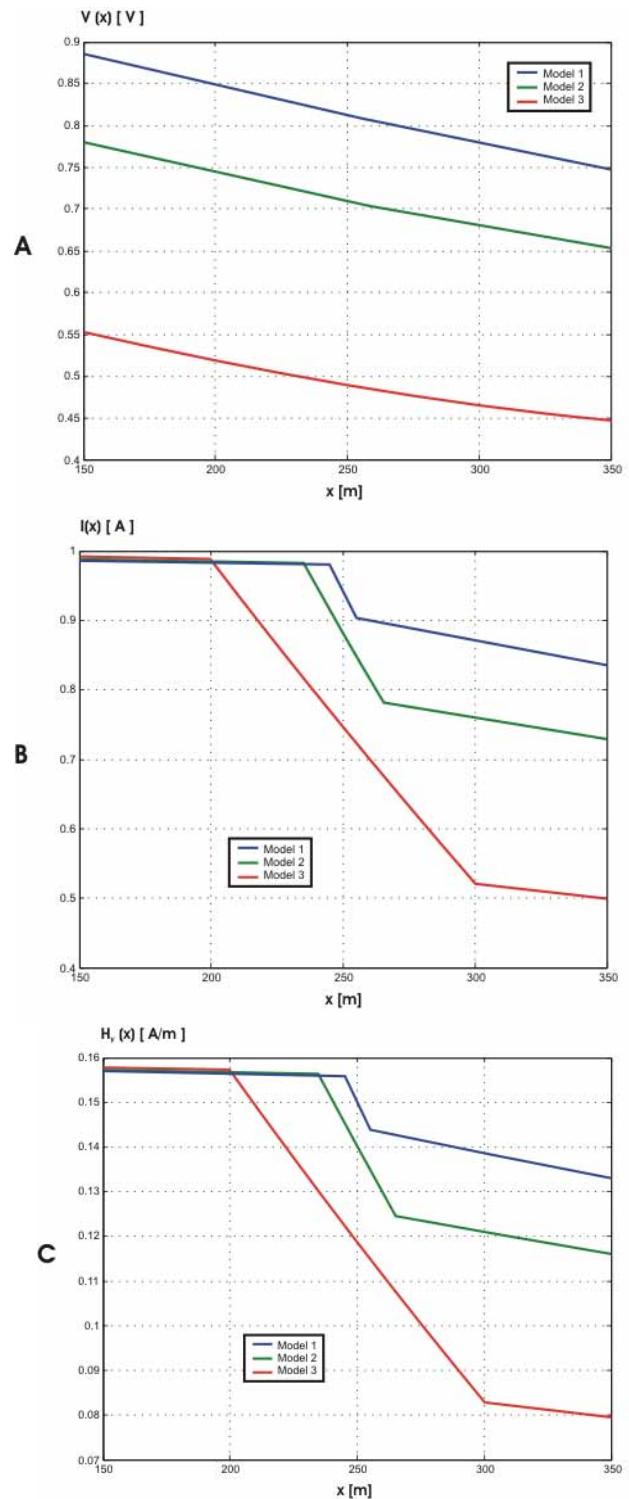


Fig.3. Distribution of voltage (A), and current (B) on the interval 150-350m(C). Distribution of magnetic field on the interval 150-350m for the model from fig. 2. (Current generator).

For current generator the voltage graphs for three models have a similar behavior and low sensitivity to the zone of the high leakage conductance (Fig. 3A). The presence of the zone with strong insulation damage affects only the absolute value of voltage that vary on 10% when the length of the second zone is changed in one order. The voltage is characterized by integral propagation factor of the whole pipeline.

The current distribution reflects clearly the variations of the leakage conductance (Fig. 3B). The breakpoints in the current curves correspond to the contacts of three zones with a different leakage resistance. The current distribution in the non-uniform pipeline is defined by the local characteristic of the transmission line in the measurement point. The behavior of the horizontal component of the magnetic field along pipeline axis is similar to the current distribution (Fig. 3C).

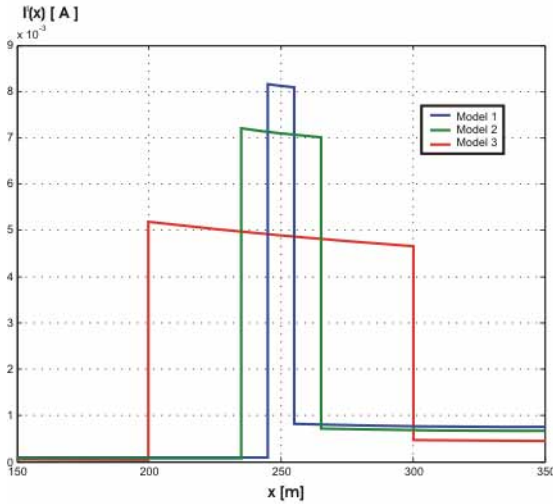


Fig. 4. The graphs of a leakage current $I^1(x)$ for model from fig. 2. (Current generator).

The leakage current (Fig. 4) is the piecewise continuous function that practically repeats the variations of a leakage conductance. We consider this parameter as the most adequate characteristic to separate the zones of insulation damages and estimate the relative variation of the leakage resistance.

The magnitude of leakage current $I_i^1(x)$ for a homogeneous pipeline, according to equation (7), is:

$$I_i^1(x) = \frac{\gamma_i^2}{Z_i} (A_i e^{-\gamma_i x} + B_i e^{\gamma_i x}), \quad (23)$$

$$\text{where } \frac{\gamma_i^2}{Z_i} = \frac{1}{T_i}.$$

For the non uniform pipeline with variable parameters the ratio of voltage (6) to a leakage current (23) on the basis of the Eq. (3) corresponds to magnitude of a leakage resistance to a current difference on an interval i .

$$T_i(x) = \frac{V_i(x)}{I_i^1(x)} \quad (24)$$

From here follows, that it is possible to receive high resolution in estimation of a leakage resistance, which in fact is restricted by the accuracy of finding a current difference on a magnetic field. It is necessary to mark, that the measured magnetic field smoothes variations of a current depending on depth.

Wall thickness variations

The changes of the tube wall thickness can be a consequence of erosion produced by products carried into the pipeline. To simulate this situation we considered the pipeline characterized by two zones with the same leakage conductivity ($G=10^{-4}$) and different wall thickness. In terms of transmission lines parameters that changes represents variations on its impedance (Resistance and inductance).

By the first zone ($0m \leq x < 250m$) the wall thickness is equal 8mm, 6mm, and 4mm while in the second zones ($250m \leq x \leq 500m$) this parameter maintains constant (10mm). It means that impedance on first zone is bigger than second zone ($Z_1 > Z_2$). The external tube radius is 10 cm.

The results of numerical simulations using a voltage generator are showed on figs 5-6 and are represented by continues lines. The inverse situation on wall thickness is presented in the same figures by dotted lines: 10mm of wall thickness on zone ($0m \leq x < 250m$) and 8mm, 6mm and 4mm in the second zone ($250m \leq x \leq 500m$).

The voltage distribution is sensitive and reflects the pipeline wall thickness variations (Fig 5) and does not depend on the generator type (voltage or current). The contact of two zones with different wall thickness reflects a breakpoint on voltage curves. In this case the voltage distribution is defined by the local characteristics of the transmission line on the measurement point.

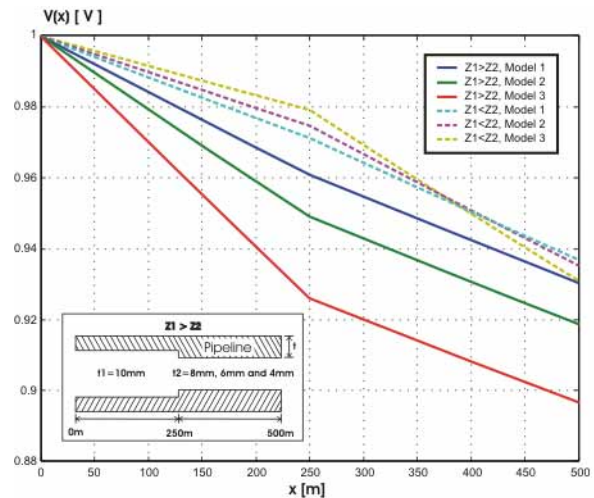


Fig. 5. Voltage distribution along the pipeline with wall thickness variation using a voltage generator.

However, measurements of voltage only are possible between control posts because it directly corresponds to the voltage along the pipeline. Thus, an electric field measurement on the surface will not be correct.

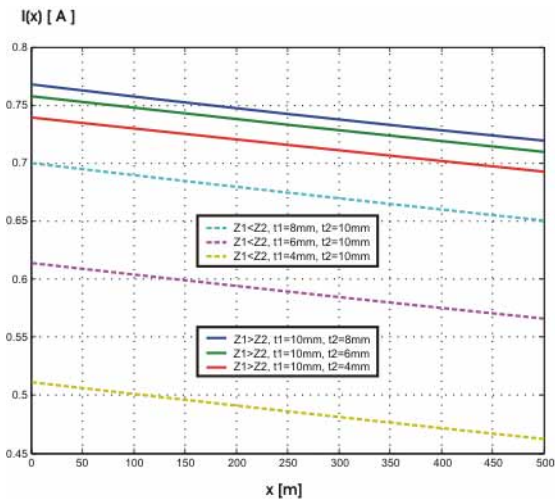


Fig. 6. Current distribution along the pipeline with wall thickness variation using a voltage generator.

The current distribution for all models has a similar behavior and reflects a low sensitive to the pipeline wall thickness variation (Fig 6). This variation affects the absolute value of current distribution and no breaks are presented, this is a reason for which voltage generator is optimal for wall thickness changes. The measurements of voltage between two control post letting us to detect the absolute variations of the pipeline thickness change.

So, the joint analysis of electromagnetic distributions along the pipeline allows to estimate and to distinguish variations on insulation damage and wall thickness.

Example of pipeline inspection

We have applied the method presented above to study technical condition of various pipelines in different areas of Mexico including urban zones [4-5]. Here we consider one example to illustrate the field operations and processing steps.

The field observations have consisted in the measurements of the horizontal component of the magnetic field. We have used the external generator with current of 100 mA at the frequency of 625 Hz. (The point of the generator connection to the pipeline is considered as the coordinate origin). The measuring system have consisted of the induction magnetic antenna with sensitivity 10 mV/(mA/m) and the amplifier with a high selective filter. The observations were carried out along profiles of 20m length perpendicular to the pipeline axis with the step 1 m. The selection of an interval between profiles depends on the investigation resolution required and time of measurements. In this case the interval was 25m. The measurements on one profile have taken about 3-4 minutes. Such a magnetic-field mapping can be performed at any time of the year and its efficiency is determined by accessibility of a survey area.

The processing of magnetic-field data for estimating isolation damages on the basis of current values and leakage resistance [7-8] has included the following steps:

1. Analysis of graphs and maps of the horizontal magnetic-field component. Correlation of anomalies to trace the pipeline axis position (red dotted line in Fig. 7A). The magnetic-field profile above the axis is shown in Fig. 7B.

2. Inversion of the magnetic field data obtained along the profiles perpendicular to pipeline axis using the equation (21) to determine the pipeline axis depth (Fig. 7C) and the value of current that flow along the pipeline (Fig. 7D).

3. Calculation of the leakage current per length unit (1 m) as the difference of current along of pipeline axis (Fig. 7E).

4. Reconstruction of the voltage distribution using values measured on the proximate control points of cathodic protection and the apparent propagation constant. The apparent propagation constant γ_a is defined as propagation constant on homogeneous transmission line. In this case the voltage values were $V(-500) = 5.4$ mV, $V(0) = 8.5$ mV, $V(+500) = 3.3$ mV and the propagation constants corresponded to $\gamma_a = 1.1 \times 10^{-3}$ (for negative points) and $\gamma_a = 1.7 \times 10^{-3}$ (for positive points).

5. Evaluation of the leakage resistance along of the pipeline (Fig.7F) based on equation (24)

The values of a leakage resistance exceeding 0.8-1 kOhm.m correspond to the satisfactory state of isolation coating. The pipeline intervals with reduced leakage resistance from 800 up to 100 Ohm.m characterize the isolation with different grades of damages. Values of resistances less than 100 Ohm.m indicate a high grade of the isolation destruction. In such zones the corrosive processes can be progressed with high probability. The pipeline zones with the damaged isolation are potentially the most dangerous areas from the viewpoint of petroleum leakage.

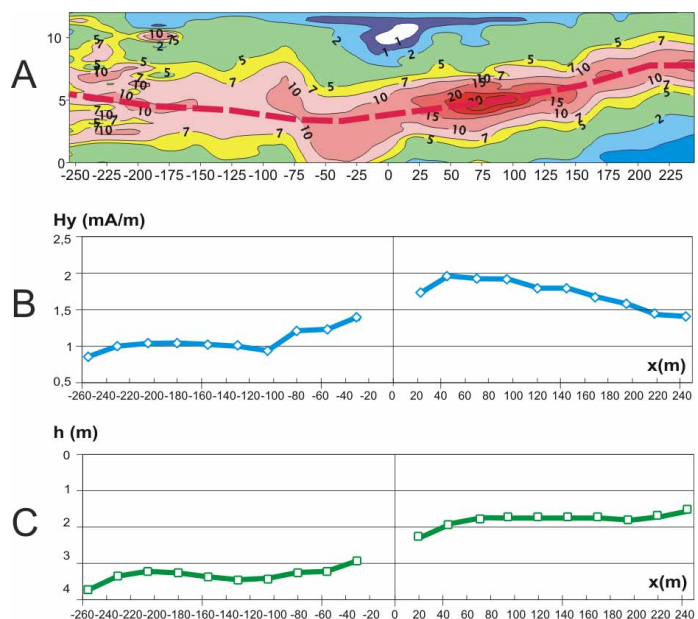


Fig. 7. A, B, C Estimation of leakage resistance on magnetic field distribution above pipeline. (A)- map of the measured magnetic field, (B) - a magnetic field graph along pipeline axis, (C) - depth of the pipeline axis.

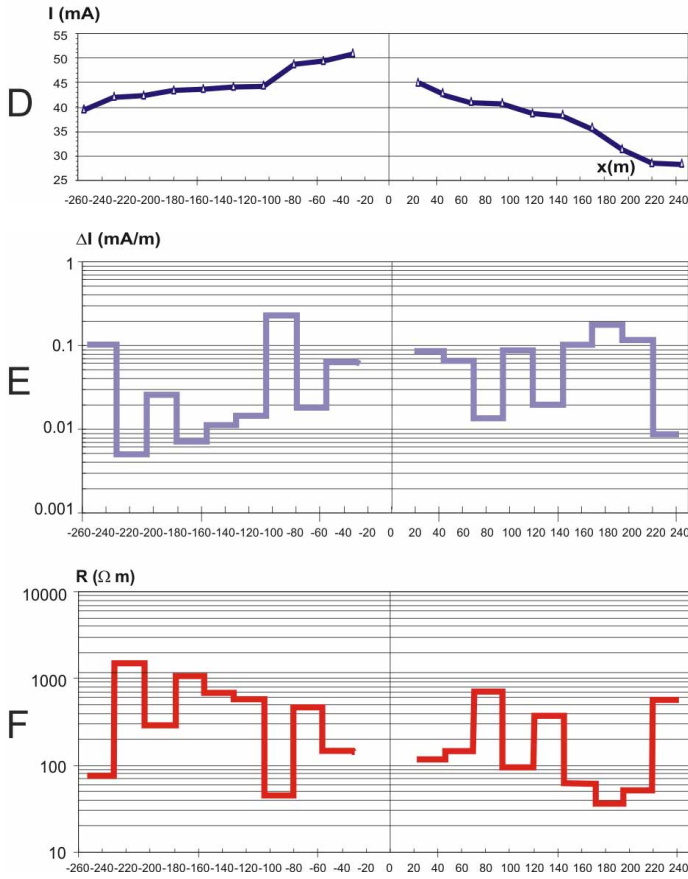


Fig. 7. D,E,F. Estimation of leakage resistance on magnetic field distribution above pipeline. (A)- map of the measured magnetic field, (B) - a magnetic field graph along pipeline axis, (C) - depth of the pipeline axis, (D) – current, flowing in the pipeline, (E) - current leakage from the pipeline in a surrounding medium, (F) - leakage resistance.

FEASIBILITY OF PERIODICAL INSPECTION

Based on the voltage and current calculations for the infralow frequency band we have estimated the feasibility of early predicting the process of insulation damage. In this case the time lapse measurements of the magnetic field are performed in several fixed points along pipeline.

To simulate this situation we considered the pipeline model composed by three zones. The wall thickness (10 mm) and external radius (10cm) are assumed constant along the pipeline for all periodical measurements. The tube conductivity and magnetic permeability are $\sigma=10^6$ and $\mu=50\mu_0$. We considered two cases of the electromagnetic-field excitations: voltage and current generators. The generator was connected to the pipeline in the point $x=0$. The magnetic field was calculated at the altitude 1 m above the pipeline axis.

In the first zone ($0 \leq x < 225$ m) and third ($275 < x$) zones the leakage conductivity $G_0=10^{-4}$ corresponds to a pipeline with the non-damaged insulation. The second zone ($225 \leq x \leq 275$ m) represents the pipeline interval where the insulation coating varies with time. In this interval the leakage conductance increases consequently on 20% ($G_1=1.25 \times 10^{-4}$), 100% ($G_2=2 \times 10^{-4}$), and 200% ($G_3=4 \times 10^{-4}$).

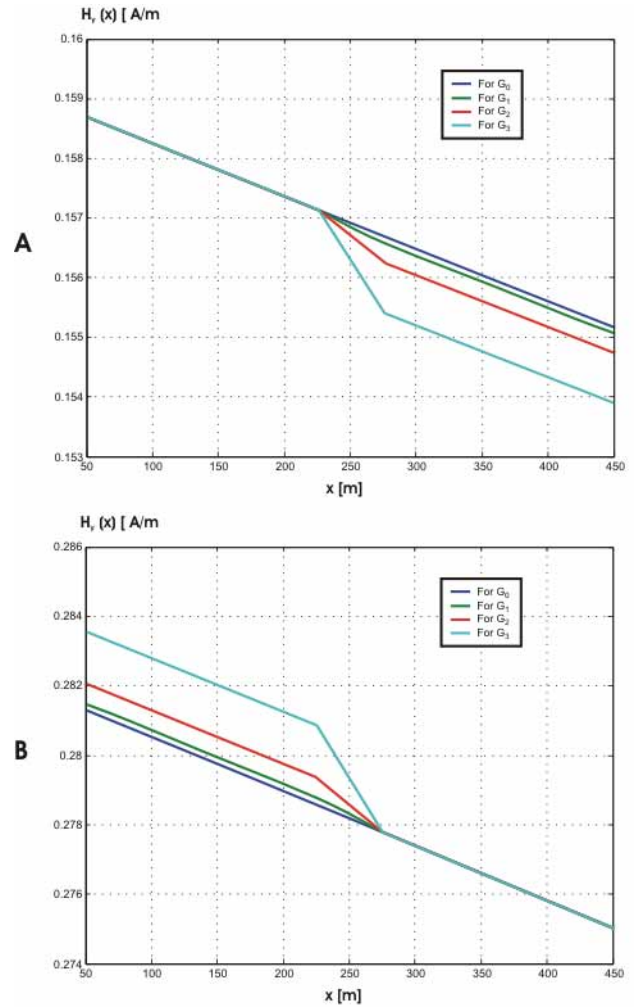


Fig. 8. Horizontal component of the magnetic field for the model with variable leakage conductance. (A) - DC current generator, (B) - DC voltage generator.

Taking into account that the horizontal magnetic-field component is directly proportional to the current value in the point of observation we can use this characteristic measured in fixed points along pipeline for monitoring the change of pipeline technical parameters during exploitation. The graphs of the H_y time-lapse measurements are sensitive to the variation of the leakage conductance in the central model zone (Fig. 8A-B).

To evaluate the pipeline insulation changing we have calculated the relative variation of magnetic field on the pipeline interval Δx :

$$\delta(\Delta x, t) = \frac{\Delta H_y(\Delta x, 0) - \Delta H_y(\Delta x, t)}{\Delta H_y(\Delta x, 0)} \times 100\% \quad (25)$$

where: $\Delta H_y(\Delta x, 0) = H_y(x, 0) - H_y(x + \Delta x, 0)$ is the initial difference of the magnetic field in the interval Δx , $\Delta H_y(\Delta x, t) = H_y(x, t) - H_y(x + \Delta x, t)$ is the difference of the magnetic field in the same interval at the moment t that correspond the different value of the leakage resistance.

The ΔH_y difference is the linear function of the conductance G at the moment of measurements and so the $\delta(\Delta x, t)$ represents the relative leakage resistance variations. Thus, the estimation of the relative time variations of the pipeline parameters does not require the magnetic field inversion for determining the pipeline depth and current.

To simplify the field operations it is convenient to carry out periodical measurements only in the points which are close to control unit of cathodic protection system. For this purpose we have estimated the sensitivity of the $\delta(\Delta x, t)$ function (Table 1) for the large interval $\Delta x=400$ m ($x=50$ m).

Table 1

PERCENTAGE OF INSULATION DAMAGE	CURRENT GENERATOR		VOLTAGE GENERATOR	
	$\delta H_y(x,t)$ (%) FOR DC	$\delta H_y(x,t)$ (%) FOR 625HZ	$\delta H_y(x,t)$ (%) FOR DC	$\delta H_y(x,t)$ (%) FOR 625HZ
20%	3	2.8	3.12	3.1
100%	12.2	11.2	12.5	12.4
200%	36.3	33	37.5	37.2

The rise of the leakage conductance on 20% only in the central zone of the 50 m length results in the relative variation $\delta(\Delta x, t)$ about 3% in interval 400m. Such sensitivity of magnetic field difference to the leakage conductance increment is sufficient to detect the initial phase of the insulation coating destruction.

To localize the anomalous pipeline parts with time variable properties the density of observation points can be incremented. For example, we can use the binary search technique in the anomalous zone to increase both the spatial resolution and value of the $\delta(\Delta x, t)$. This methodology allows optimizing field operations for pipeline monitoring.

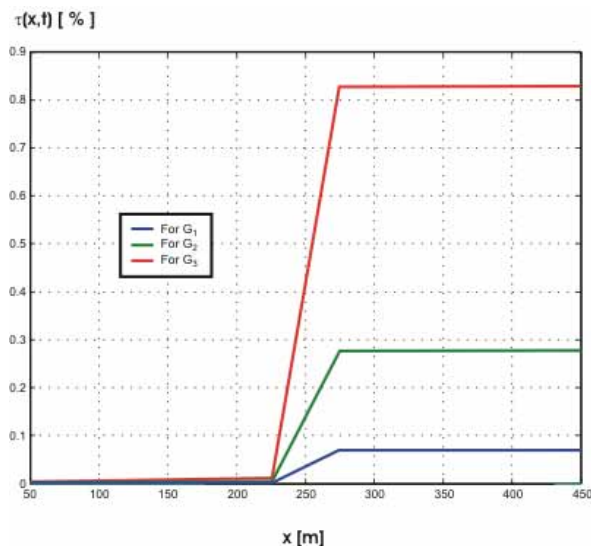


Fig 9. Relative variation of the magnetic field in the measuring point for the model with the variable leakage conductance (current generator).

Other characteristic that can be applied for the periodical inspection and delimitation of zone with anomalous time behavior is proportional to the relative current variations in the measuring point

$$\tau(x, t) = \left(\frac{H_y(x, 0) - H_y(x, t)}{H_y(x, 0)} \right) \times 100 \quad (26)$$

The $\tau(x, t)$ graphs for the model considered reflect the local change in the pipeline insulation coating (fig. 9).

CONCLUSIONS

We have presented the superficial electromagnetic method for the pipeline inspection based on the approximation of pipelines by heterogeneous transmission line. The developed theory allows fast simulating as the distributions of current and voltage along a pipeline as well in the surrounding environment.

This approximation provides the inversion of the magnetic-field data measured above a pipeline into technical characteristics as a pipeline position, depth and resistance of the insulation coating. The last parameter allows estimating the grade of insulation damage.

The modeling results demonstrate that the technique proposed is sensitive to the wall thicknesses of pipelines and can be used to estimate the integral wall thinning during the exploitation process.

We have demonstrated the feasibility of the time lapse measurements of the magnetic fields in several fixed points along the pipeline for the early prediction of an insulation-damage process.

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