APPLICATION OF ELECTROMAGNETIC METHODS FOR ESTIMATION OF TECHNICAL CONDITIONS OF OIL AND GAS PIPELINES IN MEXICO

Aleksandr Mousatov (amousat@imp.mx), Edgar Nakamura, Vladimir Shevnin, Omar Delgado (IMP, Mexico).

Abstract

The results of study of oil and gas pipeline's technical condition in Mexico are presented. The pipes system has some construction's peculiarities. The distances between pipes are small in comparison with their depth and all pipes in one group have the joint system of cathodic protection. This presents some difficulties at the study of pipes condition.

Some practical examples with results of interpretation at several places in urban areas of Mexico are showed: including studies with magnetic antenna for estimation of position and technical condition of pipelines at depths from 1 until 12 m, including an isolation damage and cathodic protection quality.

External AC generator at operating frequency 625 Hz was connected to pipelines through a control unit of cathodic protection potentials and horizontal component of magnetic field was measured, created by the current in pipes. For interpretation we recalculate AC magnetic field into value of current, flowing in the pipe. This allows localizing places of isolation damage and estimate isolation resistance and value of current leakage. The transmission line theory is the base of such interpretation.

Introduction

The superficial electrical and electromagnetic methods are widely applied for non-destructive control of pipeline condition. The pipeline inspection includes the determination of their position, depth, state of electrical isolation and quality of the cathodic protection. The effective electromagnetic pipeline inspection (EMPI) technology consists in the non-contact measurement of magnetic field created by the current, flowing in the pipeline (Geoecological inspection, 1999; Modin et al., 2000; Mousatov et al., 2001, Mousatov and Nakamura, 2001). An external generator or the cathodic protection station can be used as a current source.

The external AC generator is connected directly to the pipeline through a control unit of cathodic protection system and the other electrode, grounded in infinity. The inductive magnetic antenna generally measure the horizontal and vertical components of AC magnetic field. For this purpose the operating frequencies are selected in the low frequency range.

The electrical stations of the cathodic protection system use rectifiers of industrial frequency current and produce both the direct current and the alternative current of the frequency 120 Hz (the second industrial frequency harmonic). The magnetic field measurement in the infralow frequency range close to DC requires the use of special fluxgate magnetometer. In this case, to avoid technical problems, the pipeline inspection is realized by studying the magnetic field distribution of the alternative current (120 Hz) applying the inductive magnetic receivers.

In this paper we consider the theoretical basis and practical cases of the pipeline inspection using the AC magnetic field measuring technology.

The theory is based on the approximation of metallic pipeline by transmission line (TL). In this case the current distribution in the transmission line and the magnetic field above the pipeline are obtained. This approach for direct current has been proposed in Mousatov and Nakamura, 2001. In this report we extend the TL approximation of pipelines for the infralow-frequency band taking into account skin effect and leakage resistance variation.

The practical studies of the technical condition of oil and gas pipelines have been realized at several places in urban areas of Mexico. For pipeline inspection we used the magnetic field and self-potential observation. The pipes system has some construction's peculiarities. The distances between pipes are small in comparison with their depth and all pipes in one group have the joint system of cathodic protection that presents some difficulties for the experimental data analysis. At interpretation we recalculated AC magnetic field into value of current, flowing in the pipe. Based on TL theory, some zones of isolation damage and the leakage resistance have been determined.

Metallic pipeline approximation as a transmission line.

Let's allow, that the AC generator giving voltage V(ω, 0) is connected to the pipeline starting point. The origin of coordinate system with the x-axis directed along the pipeline is in this point. The equivalent electric scheme of the pipeline, as a transmission line with distributed parameters, is given in Fig. 1.Then in the pipe the variations of current I(ω, x) and voltage V(ω, x) are expressed by following equations, derived by application of Kirchhoff´s equations (Fig. 1).

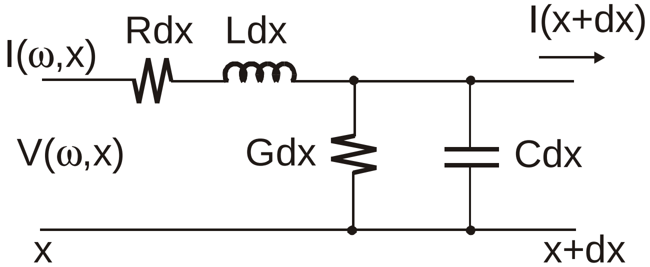

Fig.1. Equivalent electrical scheme of a pipeline as AC transmission line.

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

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

where: Z=R+jωL - is a pipe impedance per unit interval of 1 m.

Y=G+jωC- is a leakage admittance per unit interval of 1 m.

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 change of the current dI(x) along a pipeline takes place due to the current leakage through the pipe isolation into an environment. The voltage V(ω, x) corresponds to the electric potential for ω=0. For infralow-frequency band it is the voltage that is measured between a pipeline and an infinity point. To exclude the influence of inductive part of the electromagnetic field, the generator cables and the remote reference point have to be in the plane that is perpendicular to the pipeline axis.

By the differenciation of the expressions (1) and (2) we get the equations for the voltage and current:

$$\frac{d^2V(x)}{dx^2} - \gamma^2 V(x) = 0 \qquad (3)$$

$$\frac{d^2I(x)}{dx^2} - \gamma^2 I(x) = 0 \qquad (4)$$

where $\gamma = \sqrt{ZY}$ is propagation parameter.

The propagation parameter is a complex quantity that can be presented through an attenuation coefficient α and phase factor β, related with the wavelength λ as $\beta=2\pi/\lambda$: $\gamma=\alpha+j\beta$.

The solution of the equations (3) and (4) can be written as:

$$V(x)=Ae^{-\gamma x}+Be^{\gamma x}, \tag{5}$$

$$\mathrm{I(x)}=\mathrm{Ce}^{-\gamma x}+\mathrm{De}^{\gamma x}. \tag{6}$$

in those A, B, C, D coefficients are defining from the boundary and source conditions. The terms with the positive and negative exponents correspond to outgoing and reflected components of current and voltage. For infinite transmission line the reflected components disappear.

$$V(x)=Ae^{-\gamma x}, \tag{7}$$

$$I(x)=Ce^{-\gamma x}. \tag{8}$$

The current coefficient C can be expressed through voltage coefficient A using the equation (1):

$$I(x)=\frac{\gamma}{Z_0}ZAe^{-\gamma x}, \tag{9}$$

where: $Z_0=\sqrt{R+j\omega L/G+j\omega C}$ - is characteristic impedance.

The pipe resistance R for $\omega=0$ is defined by the pipe conductivity σ, the wall thickness $\Delta\mathrm{d}$ and the inner diameter d_0:

$$R=\frac{1}{\sigma 2\pi d_0\Delta d}. \tag{10}$$

The leakage conductance G can be estimated taking into account that the leakage current is radially directed (Mousatov and Nakamura, 2001):

$$T=\frac{\rho_{is}}{2\pi}ln\frac{d_2}{d_1}+\frac{\rho_m}{2\pi}ln\frac{d_3}{d_2}, \tag{11}$$

where: ρ_{is} – is the isolation resistivity,

ρ_{m} – is the environmental resistivity,

d_1 and d_2 - are internal and external diameters of an isolation layer,

d_3 - is an effective diameter of a cylindrical layer of environment, on which the voltage value can be accepted equal to zero (according to the needed accuracy).

The inductance of pipe according to Chipman, 1968, for $\omega=0$ and $\mathrm{d}_0 >> \Delta\mathrm{d}$ is given as

$$L=\frac{\mu}{8\pi}\left[\frac{4}{3}\left(\frac{\Delta d}{d_0}\right)-\frac{2}{15}\left(\frac{\Delta d}{d_0}\right)^2-\frac{1}{10}\left(\frac{\Delta d}{d_0}\right)^3\right], \tag{12}$$

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

Taking into account that $G \gg \omega C$ for the operating frequencies in the infralow range (0-10 kHz), the propagation parameter and characteristic impedance are expressed as

$$\gamma = \sqrt{(R + j\omega L)G}\ , \tag{13}$$

$$Z_0 = \sqrt{R + j\omega L/G}\ . \tag{14}$$

For the frequencies $\omega>0$, the resistance and inductance relate with a skin-layer thickness δ. When $\delta<\Delta d$ the equation (10) and (12) have to substitute for following (Chipman, 1968) for $d_0/\delta>10$:

$$R = \frac{1}{2\pi d_0}\sqrt{\frac{\omega\mu}{2\sigma}}\ , \tag{15}$$

$$L = \frac{1}{2\pi d_0}\sqrt{\frac{\mu}{2\sigma\omega}}\ . \tag{16}$$

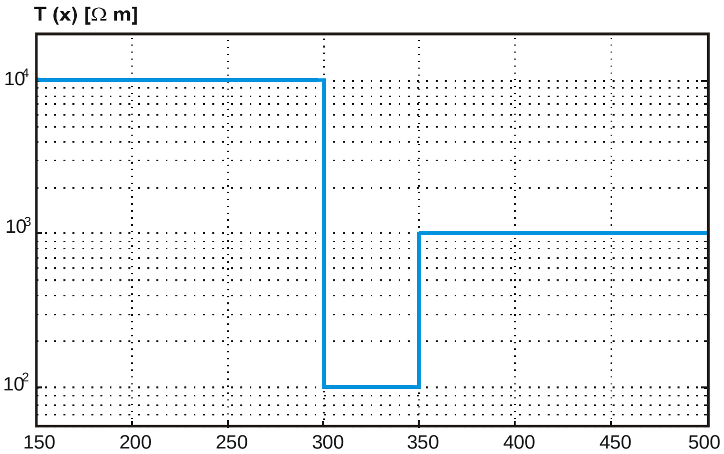

Fig.2. The model of leakage resistance distribution.

Based on the solutions (5,6) and equations (11, 13-16) we have simulated the current and voltage distributions along the pipeline with isolation damage. The model is the transmission line with a piecewise continuous variation of the leakage resistance. In the considered model (Fig. 2) the isolation resistance is supposed a piecewise constant in each of three zones. The value of $G=10^{-2}$ corresponds to the serious damage of the pipe isolation. The conditions on the zone boundaries, in infinity and in the source point for using the current generator with value I_0 are given as:

$I_1(\omega,0) = I_0$,
$I_1(\omega,l_1) = I_2(\omega,l_1)$,
$V_1(\omega,l_1) = V_2(\omega,l_1)$,
$I_2(\omega,l_2) = I_3(\omega,l_2)$,
$V_2(\omega,l_2) = V_3(\omega,l_2)$,
$I_3(\omega,x)\rightarrow 0,\ x\rightarrow\infty$,
$V_3(\omega,x)\rightarrow 0,\ x\rightarrow\infty$.

The distribution of voltage and current modulus are presented in the Fig.3, 4 for frequencies 120 Hz (second harmonic of rectified alternate current produced by the cathodic protection stations) and 625 Hz (operating frequency of ERA instrument, used for field measurements). The calculations have been realized for following properties of pipe material: $\sigma=2*10^7$, $\mu=50 – 500$.

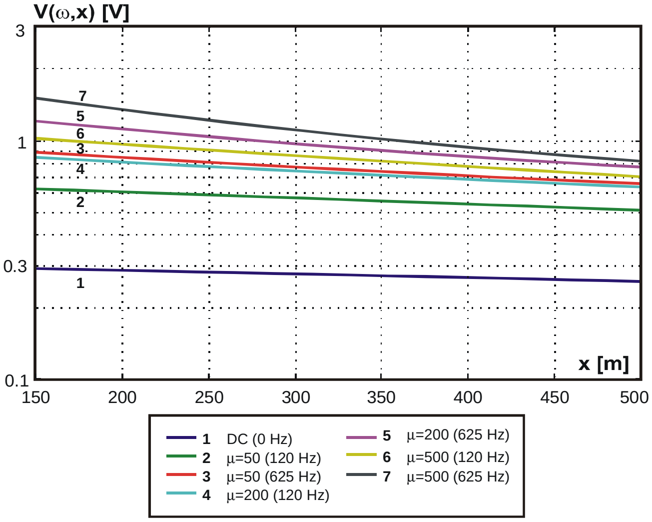

Fig.3. The potential (voltage) distribution for the model parameters from fig. 2.

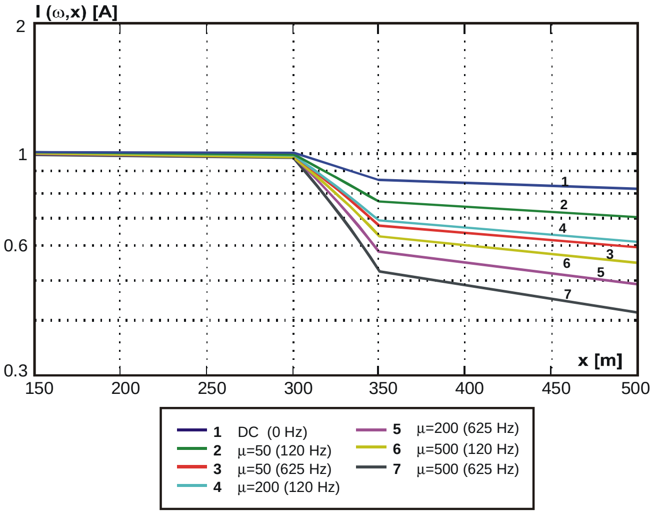

Fig.4. The current distribution for the model parameters from fig. 2.

The modeling results show that the voltage behavior (Fig.3) practically has no the spatial resolution. The curves of current (Fig.4) allow to detect the presence of zones with different leakage resistance and to determine their limits.

The derivative of the current flowing along the pipeline corresponds to the leakage current and using (6) and (9) can be expressed as

$$\Delta I(\omega,x)=\frac{\gamma^2}{Z_0}\left(Ae^{-\gamma x}+Be^{\gamma x}\right) \tag{17}$$

or simplifying

$$\Delta I(\omega,x)=G\left(Ae^{-\gamma x}+Be^{\gamma x}\right) \tag{18}$$

Thus, in compliance with the equation (2), the leakage resistance T (T=1/G) can be determined in every pipeline point:

$$T=\frac{V(\omega,x)}{\Delta I(\omega,x)} \tag{19}$$

The distribution of the leakage current, presented in Fig.5 allows detecting the zones with the isolation damage.

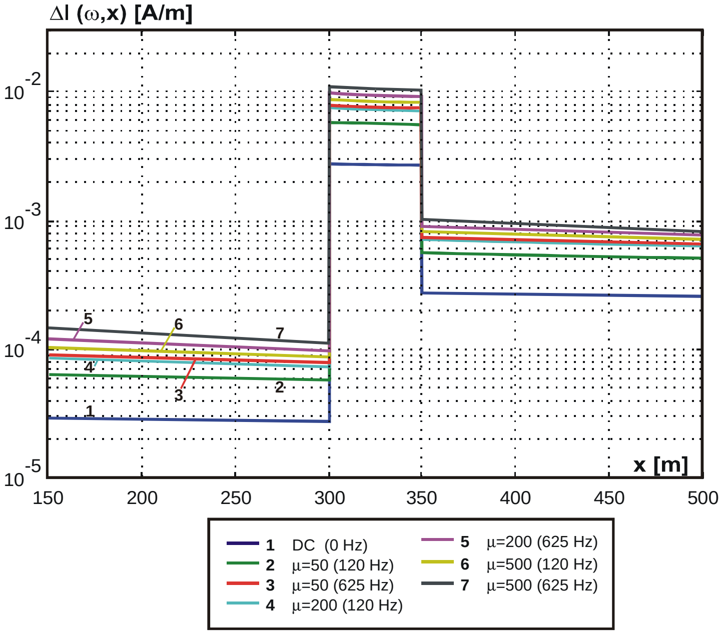

Fig.5. The leakage current distribution for the model parameters from fig. 2.

The measured at field studies horizontal component of magnetic field that is perpendicular to the pipeline axis, is calculated on the basis of Biot - Savart law (Mousatov and Nakamura, 2001)

$$H_y(\omega,x,y,h)=\frac{1}{4\pi}\int_{-\infty}^{\infty}\frac{I(\omega,x_p)hdx_p}{\left[h^2+y^2+\left(x-x_p\right)^2\right]^{3/2}} \tag{20}$$

When the current change in the integration interval (-a, a) is linear, and

$$a = 10\left[h^2 + y^2 + \left(x - x_p\right)^2\right]^{1/2},$$

then the magnetic field (with accuracy of 0.5 %) above the pipeline axis and along profile (perpendicular to pipeline) in the point x_p can be obtained using following expressions:

$$H_y(x,0,h) = \frac{I(\omega,x)}{2\pi h}, \qquad (21)$$

$$H_y(x_p,0,h) = \frac{I(\omega,x_p)h}{2\pi\left(h^2+y^2\right)}.$$

The calculated horizontal magnetic field has similar behavior as the current (Fig.6).

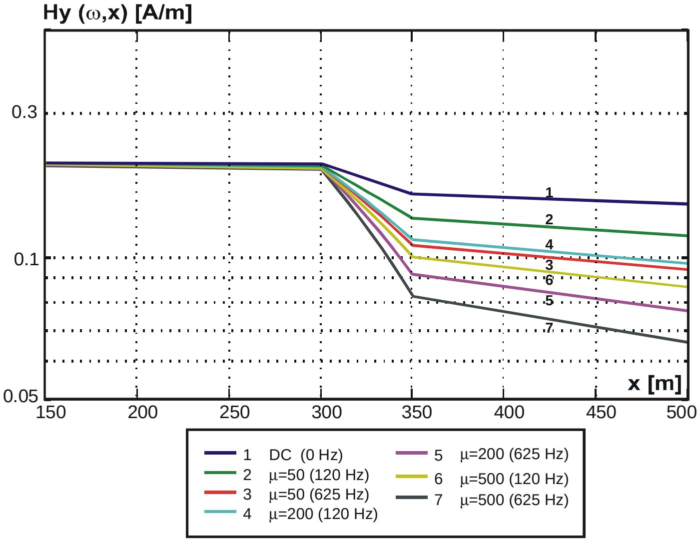

Fig.6. The horizontal component of magnetic field distribution for the model parameters from fig.2.

Experimental Pipeline Inspection Using EMPI Technology

The experimental studies of pipelines' technical condition were conducted with usage EMPI technology on several objects in Mexico City. These objects are characterized by a series of particular design features. The pipelines of different diameters and assignment (gas and oil pipelines) are placed at close-distances both in plan and depth from each other. Distances between parallel pipelines frequently do not exceed their depth. The group of close posed pipelines is aggregated by a joint cathodic protection system. The electrical connections between pipelines were conducted on different spacing intervals and the quality depends on time of pipelines construction. The depth range of pipelines' group is usually in limits 1.5 - 4.0 m, though there are areas, where depth reaches 10 m.

The field studies were made with ERA instrument (produced by ERA Ltd., St.-Petersburg, Russia) intended for geoelectrical studies and AC magnetic field measurements. On investigated objects only the cathodic protection with sacrificial anodes was used. That is why we applied external generator, which was connected to pipeline in some point of a cathodic protection control and to an electrode, grounded in infinity. The operating current of this generator was set equal to 100 mA at frequency 625 Hz. A horizontal component of AC magnetic field, perpendicular to pipeline axis, was measured with the help of an induction magnetic antenna with sensitivity 10 mV/(mA/m).

The measurements were fulfilled along profiles perpendicular to the pipeline axis with a step 0.5 - 1 m. Spacing interval between profiles was 25 m. In some special cases (zones of different pipelines crossing, areas with anomalous characteristics of magnetic field) more detailed measurements of a magnetic field were made. In zones of pipelines' isolation damage, found on magnetic field measurements, the studies were complemented by measurements of DC electric field potential produced by cathodic protection.

The obtained data were processed under the following technology:

- Drawing and analysis of graphs and maps of horizontal component of a magnetic field and DC cathodic protection potentials.
- Correlation of anomalies and estimation of pipeline axis position (or group of pipelines).

- Definition of depth of pipeline axis (or group of pipelines) and value of a current, flowing in it (or in them).
- Estimation of an apparent propagation factor γ_a and reconstruction of a voltage distribution.
- Calculation of a leakage current (a current difference along of pipeline axis) and estimation of a leakage resistance.
- Separation of pipelines areas with a different extent of an isolation damage and estimation of a cathodic protection state on the basis of integrated analysis of magnetic and electric measurements.

Two typical examples, illustrating opportunities of EMPI technology for determination of pipelines' position and depth and for estimation of zones with isolation damage, are presented below.

Case 1

The example of separation of two pipelines, situated at great depth with spacing interval between their axes, comparable with their depth, is given in Fig. 7. For determination of pipelines axes positions and values of currents, flowing in them, the interactive data inversion was used (theoretical and experimental curves fitting). The theoretical curve calculation can be done under the precise formula or utilizing an approximate solution. If the profile of magnetic field measurements is situated at the distance L from the source of current (and the distance in 15 times exceeds a pipeline depth h) and on a spacing (15h in both sides from a profile of measurements) the gradient of current variation is constant, then it is possible to use the formulas for approximate calculation with inaccuracy not exceeding 0.5 %.

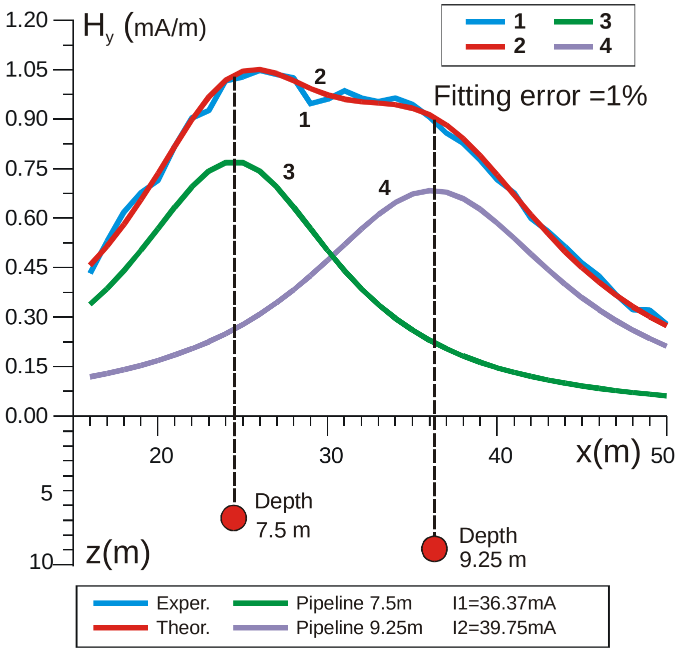

Fig.7. Determination of pipelines position and currents.

During iterations it is possible to achieve good fitting of theoretical and experimental curves up to rms error in 1%. It testifies to a small level of measuring and geologic noise and. relatively high sensitivity to variation of model parameters: current value, depth and distance between pipelines. So depth variation on 2-3 % results in rms error growth up to 2 %. This example shows, that with the help of EMPI technology and inversion it is possible to separate pipelines, spacing interval between those is comparable with their depth. Besides it is possible to estimate pipeline depth about 10 m with inaccuracy 3-5 %.

Case 2

The data processing of magnetic measurements for an estimation of isolation damage on the basis of current values and leakage resistance is shown in Fig. 8.

The pathway of pipelines group's axis (red dotted line in Fig. 8A) is traced on a map of horizontal magnetic component, obtained at connection of the generator to the potential control unit, placed in the point 0 of the coordinates origin. In the interval (-25) - (-100) there are some complications in magnetic field distribution, which are probably resulted from intersection of investigated pipelines group with other extended conductive object (black dotted line in Fig. 8A).

On horizontal magnetic component graphs (as it was shown in the example 1, on Fig. 7) were estimated pipeline depth and the current, flowing in it. The depths of pipelines group axis to the left and to the right from the current source (Fig. 8C) essentially differ, that can be explained by design features and quality of connection of separate pipelines to a joint cathodic protection system.

The magnetic field values (Fig. 8B), measured near to the source (points (-5) and 20) are reduced because the currents from the point of the generator connection spread in opposite directions. The reconstructed current values are indicated by a dotted line in Fig. 8D. The sum of spreading currents practically is equal to the current from generator (100 mA). By using a current distribution along pipelines, the values of an apparent propagation factor γ_a were obtained; those correspond to true values, if the conduction impedance and leakage resistance along the pipeline are constant. For currents, spreading towards positive and negative points of the study area, the apparent propagation factors are equal to: $\gamma_a = 1.7 \times 10^{-3}$ and $\gamma_a = 1.1 \times 10^{-3}$. The current difference along the pipeline being a current leakage in a surrounding medium, is given in Fig. 8E.

By using measured value of voltage V (ω, x) on the proximate control points of cathodic protection (V (-500) = 5.4 mV, V (+500) =3.3 mV) and apparent propagation factors, the voltage distribution along the pipeline was reconstructed. On the basis of the reconstructed voltage and obtained leakage current we have calculated a leakage resistance along the pipeline (Fig. 8F).

The values of a leakage resistance exceeding 0.8-1 kOhm.m correspond to a satisfactory state of isolation, taking into account, that some pipelines in group are connected in parallel. The areas of pipelines with reduced leakage resistance from 800 up to 100 Ohm.m are characterized by isolation damaged in a different extent. Values of resistances less than 100 Ohm.m mean a high scale of the isolation damage. In such zones with a high probability progressing corrosive processes are possible. The pipeline zones with the damaged isolation are considered as the most dangerous areas from the viewpoint of petroleum leakage. It is necessary to mark, that

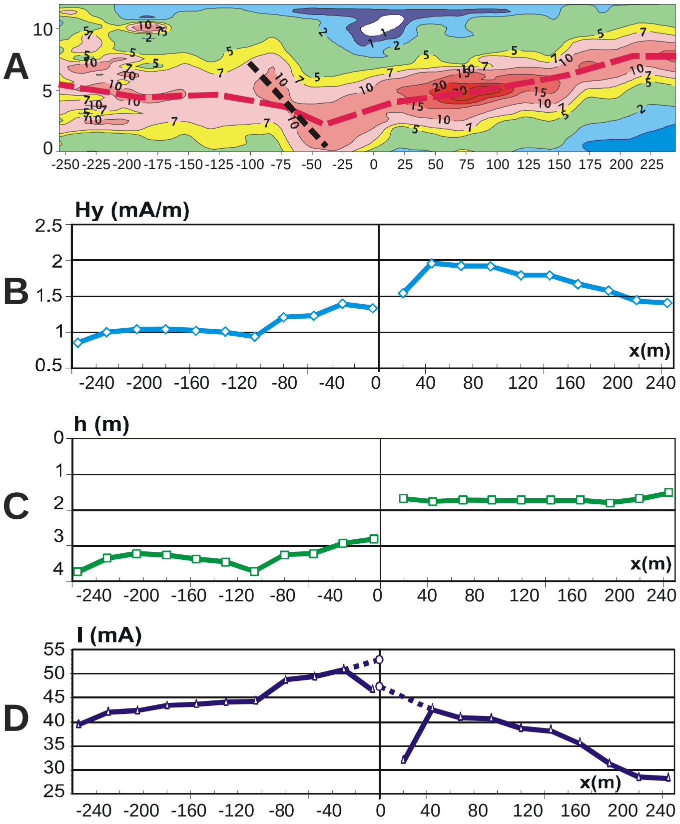

Fig.8. A, B, C, D. Estimation of leakage resistance on magnetic field distribution above pipeline. A - map of the measured magnetic field, B - a magnetic field graph along pipeline axis, C - depth of the pipeline axis, D – current, flowing in the pipeline.

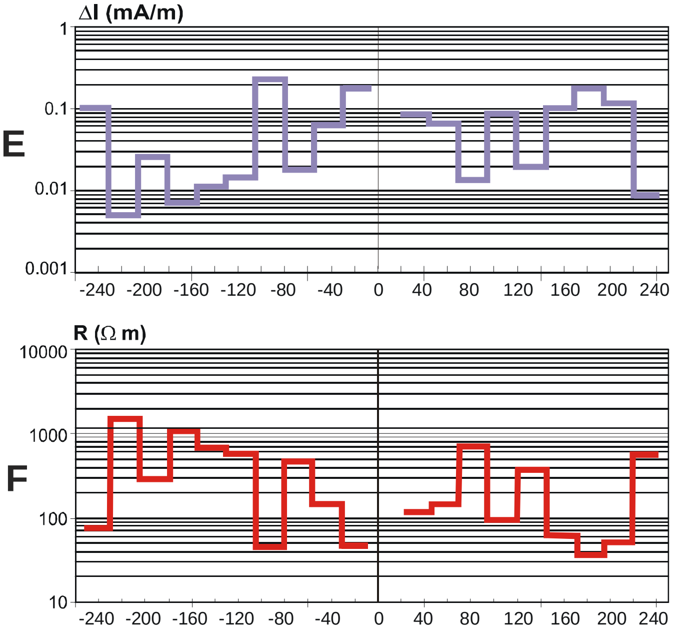

Fig. 8, E - current leakage from the pipeline in a surrounding medium, F - leakage resistance.

the obtained estimations of a leakage resistance are averaged on an interval 25 m between profiles of observation.

The low values of a leakage resistance and distortions, marked on the magnetic field map in the interval (-100 m) - (-20 m) testify to presence of galvanic connection between the investigated pipeline and some other extended object, crossing its axis. At a result of that crossing above the indicated object there is a magnetic field interfering with a field of the investigated pipeline. As the crossing takes place under an acute angle in 5-7°, that between those an inductive coupling is probable.

Conclusions

The theoretical basis for electromagnetic pipeline investigation (EMPI) technology has been developed. It is built on approximation of metallic pipelines by the transmission line with variable distributed parameters. This theory have been developed for the infralow-frequency band (0- 10 kHz) taking into account skin effect and leakage resistance variations along the pipelines. The examples of simulation of a magnetic field above pipelines with zones of different isolation damages are given.

On the basis of such approach the technology of field observations has been improved and the methodology of data interpretation of AC magnetic field above pipelines is developed. The proposed algorithm of interpretation allows estimating a leakage resistance along the pipeline to localize zones and estimate the extent of isolation damage.

The results of experimental studies on analysis of a state for groups of gas and oil pipelines in urban area of Mexico City have allowed to receive a series of practically important conclusions about pipeline position and zones of isolation damage. Besides the obtained results confirm the efficiency of the proposed theoretical and technological developments.

Acknowledgments

The authors consider as the pleasant debt to express gratitude to Mexican Petroleum Institute, department of Production Technology for the support of this study.

References

1. Chipman R. A., 1968, Theory and problems of transmission lines, *McGraw Hill book Company*.
2. Geoecological inspection of oil industrial enterprises, Editors: Shevnin V.A. and Modin I.N., 1999, Moscow, *RUSSO*, 511 pp. (In Russian).
3. Ivanov V.T., Spiridonov A.V., 1982. The solution of problem of current distribution in pipeline with damaged isolation. *Izvestia VUZov, Geologia i Razvedka, Electromechanics,* N 2, p.151-157 (in Russian).
4. Kaufman A.A. and Wightman W.E., 1993. A transmission – line model for electrical logging through casing. *Geophysics*. Vol.58, N 12, pp.1739-1747.
5. Modin I., Karinski A., Mousatov A., Pervago E., V. Shevnin. Electrical and electromagnetic methods to estimate position and technical conditions of pipelines and decision of ecological problems. *Proceedings of "5 Congreso y Expo Internacional de Ductos"*. Ciudad de Morelia, Michoacán, México, 18 - 20 October 2000. SI-09, 18 pp.
6. Morgan J., 1993. Cathodic Protection. (Second Edition), *NACE publication*, 519 pp.
7. Mousatov A., Nakamura E. Transmission-line approximation of pipelines with cathodic protection. *Proceedings of SAGEEP-2001 conference in Denver (March 2001).* ERP-5. 10 pp.
8. Mousatov A., Nakamura E., Shevnin V., Modin I. 2001. Inspección y control periódico de ductos aplicando mediciones del campo electromagnético producido por sistemas de protección catódica. 6th Congreso Internacional de Ductos. Merida. México. Memorias Tecnicas. DT-13.7p.