APPLICATION OF SUPERFICIAL ELECTROMAGNETIC METHODS FOR LOCALIZATION AND INSPECTION OF OIL AND GAS PIPELINES' TECHNICAL CONDITION

Aleksandr Mousatov, *Mexican Petroleum Institute, Mexico E-mail: amousat@imp.mx*
V. Shevnin, Mexican Petroleum Institute, Mexico, E-mail: vshevnin@imp.mx
Omar Delgado-Rodríguez, Mexican Petroleum Institute, Mexico
Edgar Nakamura-Labastida, Mexican Petroleum Institute, Mexico
Abraham Mejía-Aguilar, Mexican Petroleum Institute, Mexico

Abstract

Superficial non-destructive inspection of oil and gas pipelines is performed using electromagnetic methods. For that an external AC generator connects to a control post of cathodic protection potentials to pass the current in the pipe system. To obtain the current distribution, the magnetic field on the earth surface is measured. Based on the approximation of metallic pipeline by transmission line we developed the electromagnetic (EM) technology for the control of pipeline technical conditions. This EM technology includes measurements of magnetic field, voltage on several cathodic protection posts and subsoil resistivity and allows determining the distributions of current along the pipes, leakage current, leakage resistance and resistance of insulating coating.

The practical studies of the technical condition of oil and gas pipelines have been realized at several places in urban areas of Mexico. For potential leveling, pipelines are frequently connected to a joint cathodic protection system using jumpers between pipes. The regional study applying the proposed EM technology characterizes the group trajectory and integral quality of the pipe insulating coating. Additionally, this technology reveals the amount of tubes including pipes out of operation and provides the individual information in each pipe about the variations of current and insulation resistance. The detailed survey in the detected anomalous zones allow estimating the positions of jumpers, and also separating the zones with damage of the pipe coating from the connection of pipes out of operation or other grounded constructions.

Introduction

The preventive control of oil and gas pipelines requires estimating a state of cathodic-protection system and grade of insulating coating damage. For these purposes, the pipeline inspection includes generally non-destructive surface techniques based on the measurements of electrical and electromagnetic field.

Such methods as Close Interval Pipe-to-Soil Potential (CIPS) and Direct Current Voltage Gradient (DCVG) give the distribution of the electric potential (or potential difference) along a pipeline by measuring direct-current electrical field produced by the cathodic protection (rectifier stations or sacrificed electrodes). The profiles of different electrical-field characteristics permit detecting anomalous zones with an insulation damage and low value of the cathodic potential. However, these data cannot reveal the cause of protection-potential dropping and do not provide the quantitative estimation of leakage resistance. Furthermore, the field technique for the pipeline electrical field study needs a galvanic grounding of electrode arrays and applying special reference electrodes.

To determine the pipeline position (in plan and depth) and quality of electrical insulation, other approach based on the measurement of magnetic field is frequently applied. The electrical current flowing in the pipeline exits the magnetic field. The sources of this current are the electrical stations for the cathodic protection or external generators. There are several techniques and equipments designed specially for the pipeline inspection: C-Scan instrumentation of the corporation Dynalog Electronics; Pipeline Current Mapper (PCM) of the corporation Radiodetection; the ERA - TRASS instrumentation of the "ERA" corporation (St.-Petersburg) and others. To calculate the pipeline depth and current from the magnetic field data, in the mentioned methods, it is assumed that the observed magnetic field is produced by the current in an infinite ideal insulated cable, placed in a resistive non-magnetic medium on the depth of the pipeline axis. At such a simplest model, the current variations related with its leakage in a surrounding medium through the coating with finite electrical resistance are not considered. In this case the conclusions about the insulating resistance and grade of insulation damage use the indirect but quantitative parameters: the leakage current defined as the current difference on the distance unit and logarithm of the current attenuation.

For direct estimation of leakage resistance we developed and experimentally tested the effective electromagnetic technology for pipeline inspection (EMPI technology) (Mousatov and Nakamura, 2001; Mousatov et al., 2002). We have approximated the metallic pipeline by a system with distributed electromagnetic parameters (transmission line - TL). The TL approach allows calculating the distributions of voltage, current and magnetic field along a pipeline as functions of the variable leakage resistance (piecewise uniform transmission line). The field operations consist in the measurements of the magnetic field above pipeline zone (2D mapping) and pipeline voltage only in 2-3 points on the posts that are directly connected to pipe. This technology admits the use of cathodic-protection sources or external generators. We have used the external generators of alternate current (low frequency range) and induction magnetic antenna. The cathodic-protection sources as the direct current component and second industrial frequency harmonic can be used also in this technology.

On the basis of theoretical calculations the fieldwork technology and data processing is updated. It is offered to supplement measurements of a magnetic field by measurements of a voltage with the help of an electric line, connected to the control posts of the pipeline and earthed in infinity. The distribution of a voltage along the pipeline is related basically with its integrated characteristics and is reflects weakly local heterogeneities of pipe insulation. For recovery of a voltage on all length of the pipeline with sufficient for the practical purposes accuracy it is enough to perform its measurements in one-two points using the control posts on the pipeline. On the basis of these measurements in each point of a profile above the pipeline the leakage resistance is calculated, which is equal to the ratio of an estimated voltage to a leakage current (the current difference on the unit of length).

In this report we propose the enhanced EMPI technology, which includes in situ estimation of the insulating-coating resistance of pipelines. This resistance characterizes completely the grade of tube-isolation damage and is obtained from the leakage resistance and resistivity of surrounding formations. To determine the rock resistivity, the resistivity survey should be incorporated in the PI technology.

We applied the considered technology for the practical inspection of the several oil and gas groups of pipelines in Mexico.

EMPI Technology

The principal concept of the pipeline inspection using surface electromagnetic observations consists in the determination of the current distribution along metallic tubes. The cathodic protection system or special external source can be used as a generator. One pole of a generator is connected to a conductive metal pipe and the other pole is grounded.

The cathodic protection source (sacrificed electrodes or rectifier unit) provides negative potential of a direct current (DC) on the pipeline with magnitude 1 - 2 V. When the rectifier substation is applied, the spectrum of a cathodic protection signal besides of DC component contains even harmonics of alternate current caused by an incomplete filtration of a rectified voltage of industrial frequency. The highest magnitude has the second harmonic with the frequency 120 Hz. Usually the operational frequencies of exterior generators correspond to low frequency range and do not exceed 1 kHz.

The remote determination of the current flowing into a pipeline is realized by measuring the magnetic field. To measure the magnetic component in a low-frequency interval, the inductive receiving antennas are generally used. The observation of the magnetic field on infra-low frequencies (close to DC) is performed with the fluxgate magnetometers.

Theoretical background

Let's suppose, that the generator of harmonically varying alternating current connected to the initial point of the pipeline produces the voltage $V(\omega, 0) = V_0 \exp(j\omega t)$ and current $I(\omega, 0) = I_0 \exp(j\omega t)$. These voltage and current should be decreased along pipeline with increasing the distance from the point of generator connection because the tube has the finite resistance and part of current leaks through the tube insulation (Fig. 1, A). Taking into account the high conductivity of a metal pipe and the presence of a resistive insulating coating, we approximated the pipeline by the transmission line with the distributed parameters (Mousatov and al., 2002). The equivalent scheme of the pipeline is presented in Fig. 1, B.

The pipeline with insulation damage (varied leakage resistance) can be analyzed as non-uniform transmission line that consists of piecewise homogeneous segments where the leakage resistance does not changes with distance. In each uniform interval i the complex amplitude of the voltage $V_i(\omega, x)$ and current $I_i(\omega, x)$ satisfy the following differential equations:

$$\frac{d^2 V_i(\omega, x)}{dx^2} - \gamma_i V_i(\omega, x) = 0 \qquad (1)$$

$$\frac{d^2 I_i(\omega, x)}{dx^2} - \gamma_i I_i(\omega, x) = 0\,, \qquad (2)$$

where $\gamma_i = \sqrt{ZY_i}$ - is the propagation parameter into the homogeneous interval i,

Z [Ohm / m] - is a linear complex pipe resistance on the unit of length (1 m),

Y_i [1/Ohm*м] - is linear complex leakage admittance on the unit of length of the homogeneous interval i.

The complex leakage conductance Y_i and pipe resistance Z (longitudinal resistance of the line) are determined by the ohmic resistance R [Ohm/m], inductance L [H/m], leakage conductance G_i [1/Ohm*m] and capacitance C_i [F/m] of a pipeline segment of single length 1 m:

$$Y_i = G_i + j\omega C_i \qquad (3)$$

$$Z = R + j\omega L \qquad (4)$$

The solutions of the equations (1) and (2) are:

$$V_i(\omega, x) = A_i e^{-\gamma_i x} + B_i e^{\gamma_i x} \qquad (5)$$

$$I_i(\omega, x) = \frac{\gamma_i}{Z}(-A_i e^{-\gamma_i x} + B_i e^{\gamma_i x}) \qquad (6)$$

The coefficients A_i and B_i are defined by using the boundary and source conditions. The terms with the positive and negative exponents correspond to outgoing and reflected components of a voltage and current.

Taking into account that G >>ωC for the

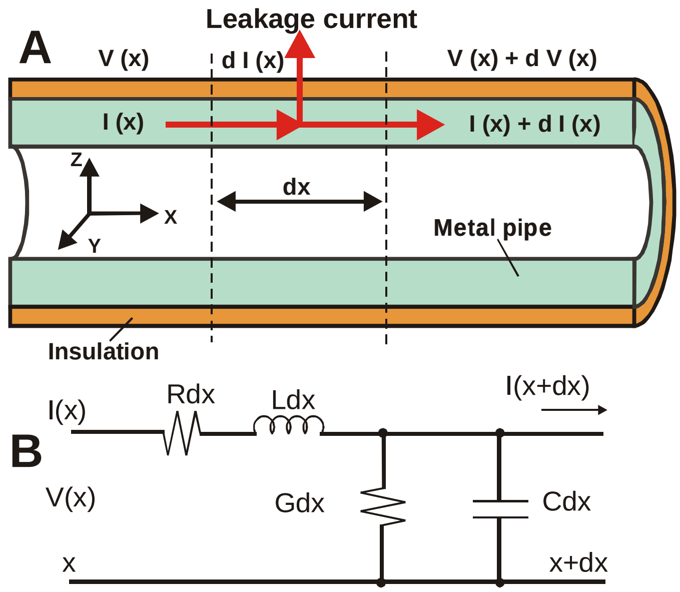

Figure 1.: A. Voltage and current variations in the pipeline's longitudinal section; **B.** An equivalent electrical scheme of the pipeline, where dx is a length element of the transmission line.

operating frequencies in the low range (0-10 kHz), the propagation parameter is expressed as:

$$\gamma = \sqrt{(R + j\omega L)G} \qquad (7)$$

For the frequencies ω>0, the resistance and inductance relate with a skin-layer thickness δ and when δ < Δd are given by following (Chipman, 1968) for $d_0/\delta>10$:

$$R = \frac{1}{2\pi d_0}\sqrt{\frac{\omega\mu}{2\sigma}} \qquad (8)$$

$$L = \frac{1}{2\pi d_0}\sqrt{\frac{\mu}{2\sigma\omega}} \qquad (9)$$

The leakage resistance T (T=1/G) can be estimated taking into account that the leakage current is radially directed (Mousatov and Nakamura, 2001) (Fig. 2):

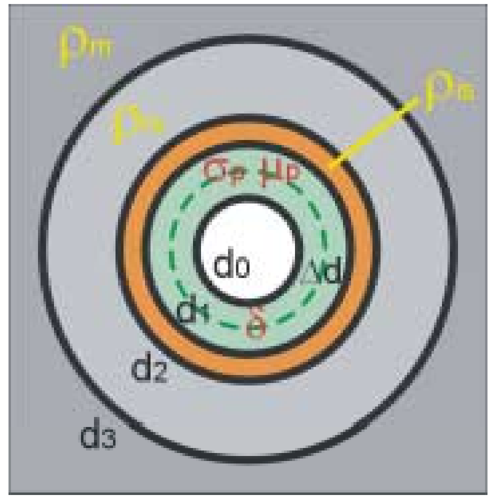

Figure 2.: The scheme for calculation of a leakage resistance

$$T = \frac{\rho_{is}}{2\pi}\ln\frac{d_2}{d_1} + \frac{\rho_m}{2\pi}\ln\frac{d_3}{d_2} \qquad (10)$$

where: ρ_{is} – is the insulation 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 assumed equal to zero (according to the needed accuracy $d_3 \approx (3 \div 20)\, d_2$).

For ω=0 the pipe resistance R is defined by the metal tube conductivity σ, the wall thickness Δd and the inner diameter d_0:

$$R = \frac{1}{\sigma 2\pi d_0 \Delta d} \qquad (11)$$

The complex amplitude of leakage current $dI_i(x)$ for a homogeneous interval i corresponds to the current difference on the interval dx:

$$\Delta I_i = \frac{dI_i(\omega, x)}{dx} \qquad (12)$$

and using (6) can be written as

$$\Delta I_i(x) = \frac{\gamma_i^2}{Z}\left(A_i e^{-\gamma_i x} + B_i e^{\gamma_i x}\right) \qquad (13)$$

If the current difference along pipeline (leakage current) and voltage are measured, the leakage resistance T (x) can be obtained from equation (4), (5), (7) and (13):

$$T(x) = \frac{V(\omega, x)}{\Delta I(\omega, x)} \qquad (14)$$

This parameter provides information about the grade of insulation damage in the point of measuring. The resolution of damage detection based on the leakage resistance is higher then using other parameters including

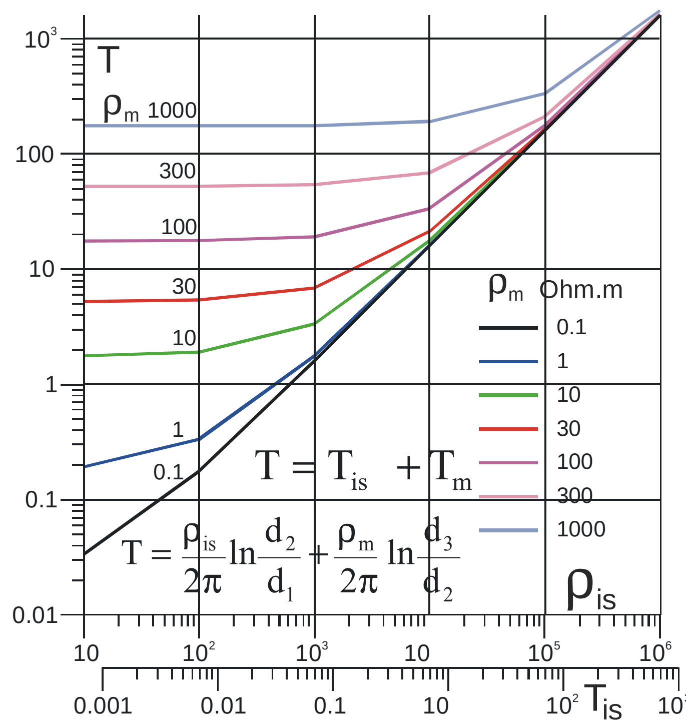

Figure 3.: The nomogram for separation of medium resistance T_m and leakage resistance T to estimate insulation resistance T_{is}

leakage current which additionally depends on the complex pipe resistance Z (frequency, pipe conductance and inductance) and current reflection from boundaries of leakage-resistance variations. It is necessary to mark, that at decreasing an insulating layer resistance T_{is} (x) in the case of its damage the influence of environmental resistivity on a leakage resistance increases (Fig. 3). To eliminate the surrounding-rock influence we proposed measuring the ground resistivity ρ_m around the pipeline and estimating the insulating-coating resistance T_{is} (x) from expression (10):

$$T_{is}(x) = T(x) - T_m(x)\,, \qquad (15)$$

where:

$$T_m(x) = \frac{\rho_m}{2\pi} \ln \frac{d_3}{d_2}\,. \qquad (16)$$

For calculation T_m (x) and insulating resistivity ρ_{is}, we assume that the pipe diameters $d_1$and d_2 are given.

The insulating-layer resistivity is free from environmental and measuring parameters and characterizes completely the technical pipeline condition.

Field operations and processing

The current distribution in the tubes is determined by measuring the magnetic field above the pipelines. We used the external current generator with operating frequency 625 Hz. The horizontal component of magnetic field is measured on the profiles that are perpendicular to the pipeline axis. The step between profiles relates with scale of observation and generally is about 25 m. When the medium is non magnetic and resistive for low frequency range, the magnetic field H_y from a current flowing in the non-uniform pipeline with insulation damage is calculated on the basis of Biot - Savart law (Mousatov and Nakamura, 2001):

$$H_y(\omega, x, y, h) = \frac{1}{4\pi} \int_{-\infty}^{\infty} \frac{I(\omega, x_p)\, h\, dx_p}{\left[h^2 + y^2 + (x - x_p)^2\right]^{3/2}}\,, \qquad (17)$$

where h is the distance from the pipeline axis to the earth surface.

When the current change in the integration interval (-a, a) is linear, and $a \geq 5\left[h^2 + y^2\right]^{1/2}$, then the magnetic field (with accuracy of 2 %) above the pipeline axis and along Y profile in the point x_p can be obtained using following expressions:

$$H_y(x, 0, h) = \frac{I(\omega, x)}{2\pi h}\,, \qquad (18)$$

$$H_y(x_p, y, h) = \frac{I(\omega, x_p) h}{2\pi (h^2 + y^2)}\,. \qquad (19)$$

The magnetic field correlates with pipeline current but depends also on the pipeline depth. To obtain current value we realized interactive inversion of the horizontal component of magnetic field on the profiles perpendicular to pipeline axis based on equations (17) or (19). For group of pipelines, we assume that the magnetic field is the simple superposition (without cross induction influence) of magnetic field of each pipe. When the distance between tubes is more than h it is possible to determine the plan position, depth and current for each pipeline separately. For close placed pipelines the total summarized current and position of equivalent axis can be found.

The alternate voltage on the pipeline (from external generator) can be practically (without special excavation) measured only in the control posts of the cathodic protection system. The voltage distribution has an integral character of its variation along the pipeline (Mousatov at al., 2003) and can be reconstructed using measured values in 1 - 2 points. In the case of the external generator (taking into account that the voltage and current tend to zero in infinite) the voltage along the pipeline with heterogeneous insulation is approximated by uniform transmission line with the apparent propagation parameter γ.

To estimate the resistivity of surrounding pipeline formations, the resistivity survey is performed. The rock resistivity is obtained from the apparent resistivity curve after geological noise filtering and interpretation.

Based on the current difference calculated from the magnetic field, reconstructed voltage distribution and measured rock resistivity we estimate the resistance of insulating coating along pipeline.

In the detected damage zones, the detailed study that includes the measurements of two horizontal components of the magnetic field H_x and H_y with the step 1 m is realized. The interpretation of detailed data allows more accurate estimating the size of damaged zone and specifying the character and cause of current leakage (efficiency of cathodic protection). After that these zones can be inspected with excavation.

Experimental Pipeline Inspection Using EMPI Technology

The experimental study was performed with the operating current of the external generator equal to 100 mA at the frequency 625 Hz. The horizontal component of AC magnetic field, perpendicular to pipeline axis (Hy), was measured by the inductive magnetic antenna with sensitivity 20 mV/(mA/m).

The regional magnetic measurements were fulfilled along Y profiles perpendicular to the pipeline axis X with a step 0.5 m. Spacing interval between profiles ΔX was 25, 50 or 100 m. An alternate voltage was only measured on 2 - 3 posts of cathodic protection for one generator position (the distance between posts is about 500 m). An environmental resistivity was estimated along the pipelines each 25 – 100 m. In the detected anomalous zones, we carried out detailed study of two magnetic field components (Hx and Hy) with the step 1 m and 0.5 m along X and Y axis correspondingly.

Area 1

The results for the pipeline section of 500 m length for generator position in X=0 are presented in figures 4-8. In this example the observations were performed above the group of 4 pipelines at the depth about 2 m with the distances between pipes about 80 sm. In such situation the group of pipes normally produces a single anomaly. The distribution of magnetic component Hy on the map and the graph of maximal Hy values above the pipe axis are presented in fig.4.

We interpreted the each Y profile of magnetic field (fig.5) to estimate of pipelines position, depth and current. The graph of current is displayed in fig.6, A. For each interval between two Y profiles the leakage current (current difference) was calculated (fig.6, B). Using the voltage measurements in three posts, the voltage distribution on the pipeline was found (fig.6, C). Then the leakage resistance along the pipe (fig.6, D) was calculated (14).

The difference between leakage resistance T and medium resistance T_m characterizes the quantity of insulation resistance (15,16), which is given in fig.6, E.

The damaged zones were found in four intervals X: 125-150; 275-300; 350-375; 450-475.

The interval X=200 - 250 is characterized by anomalously low values of leakage and insulation resistances that are smaller than environmental resistance.

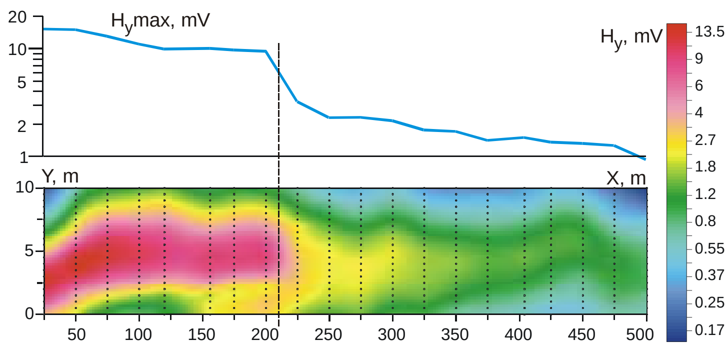

Figure 4.: Area 1. Map of magnetic field (Hy) and graph of maximal Hy values along the pipeline.

We made detailed studies to understand the cause of this anomaly (fig.7). The curves 1 (Hy) and 2 (Hx) are the detailed graphs along X profile above pipeline axis. The graph 3 presents Hx component on the parallel X profile shifted at the distance of 4 m. The presence of maximums on both X graph demonstrates that the leakage current is concentrated in same conductive channel (Fig.7, B). The value of channel current flowing in Y direction in point 209 m is equal to 10 mA. Such an anomaly results in the connection of pipelines to some additional object with a low grounding resistance. The control excavations found here the jumper connecting the pipes in operation to the old tube out of operation with practically destroyed insulation coating.

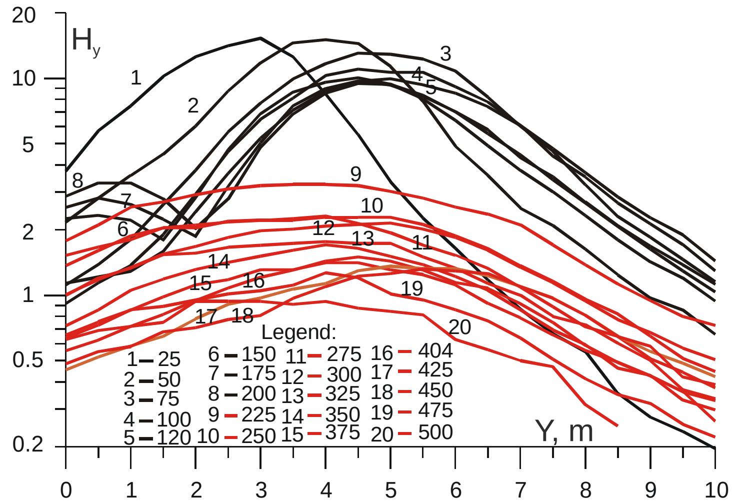

Figure 5.: Magnetic field (Hy) graphs across the pipelines group. X= 25-500 m. Generator position is in X=0 m.

In this zone we additionally detected the noticeable difference of Hy curves 1 and 5 (fig.8, A) for the same Y profile (X=200 m) at two generator positions (X=0 and X=470 m). The forward modeling (fig.9) shows that such a difference take place when the current in the pipe 1 with axis position at Y=0.5 m is

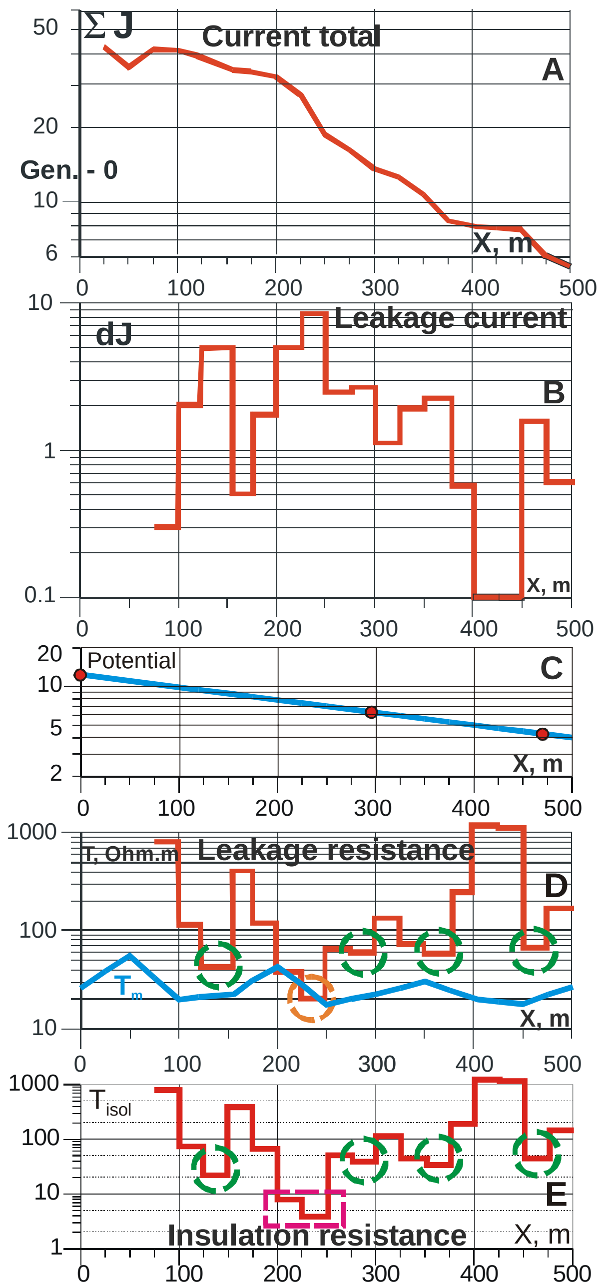

Figure 6.: Data processing for graphs in fig.5

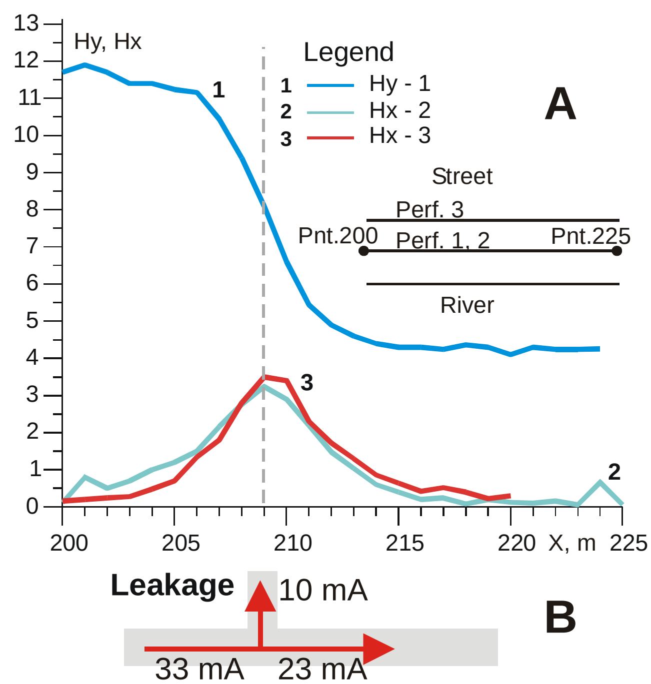

Figure 7.: Detailed measurements in the interval X=200-225 m

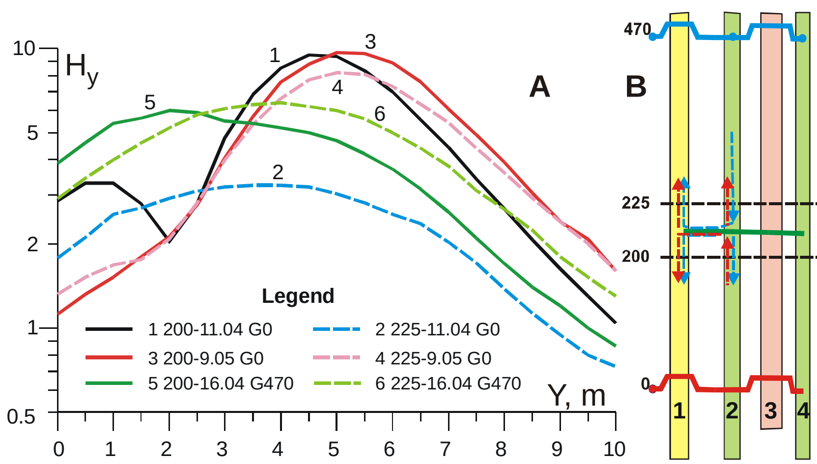

Figure 8.: Practical example with different phases of current

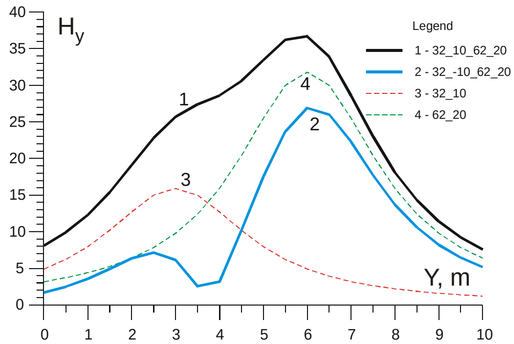

Figure 9.: Modeling with different phases of current. 3 and 4 – graphs for a single pipe, 1 – graph for two pipes with the same phases of current; 2 - two pipes with different phases

oriented in the opposite direction to the current in the other pipes 2-4 for the generator point X=0 m. When generator is connected to the post 470 m, the current in this pipe coincides with current direction in the pipeline group.

After the excavation and disconnecting the jumper between pipe 1 and group 2-4, the Hy curves 3-4 for X=200 m at generator positions in points 0 and 470 m are fitted.

Pipe 1 and pipes 2-4 (fig.8, B) belong to different organizations. We have been informed earlier that pipe 1 should have its own cathodic protection and should be disconnected from pipes 2-4. As we found in this case some connection existed.

The demonstrated examples convince that the determination of insulation resistance allows estimating more reliably zones of insulation damage and also detecting the pipe connections to grounded constructions with low resistance. The detailed observations of both Hy and Hx components provide the reconstruction of the current distribution scheme and location of jumpers. The obtained information should be taken into account for modeling the operation of a cathodic protection system and understanding its problems.

Area 2

The area of 2.5 km length is the other example of pipeline study. The basic problem of this area is that the cathodic protection potentials are below permissible minimum 0.85 V. This pipeline group consists of a number of pipes connected with jumpers.

In fig. 10 the graph of a Hy magnetic field component along a test Y profile. On this profile on official data indicate 7 tubes with known positions. The situation on this profile is favorable for separated determination of pipe position and depth, because the minimal distance between tubes is 3 m and their depths are about 1.3 m. In this case each tube has a proper anomaly in the magnetic field. The inversion of magnetic data for this and also all profiles in the studied area gives a stable determination of positions for at least 9 pipes. At the same time the detected situation is rather typical, when the official information about pipes

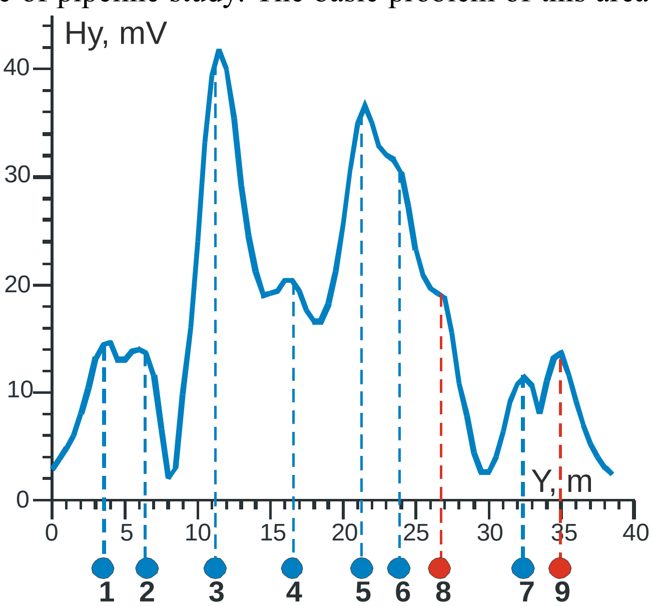

Figure10.: An estimation of pipelines' position

does not coincide the facts. That discrepancy can be explained by the connection to the group of several pipes out of operation.

In fig. 11 some graphs of magnetic field Hy along 14 Y profiles are displayed. These graphs despite of visible complexity have a good correlation that permits to draw the scheme of all pipelines position for the studied area. In fig. 12 the pipe positions (relatively the rectilinear pathway of pipe 5) are shown. The triangles on X-axis show positions of Y profiles. The lines G1, G2, G3 correspond to the points of the external generator connection. Thus the electrical station of cathodic protection is really connected to the 9-10 pipes instead of 7 ones. The additional pipes are out of operation and can consume significant part of the protection energy, especially; taking into account that the insulation of old pipes is probably destroyed.

We have found current distribution in the group of pipes according to procedure, described above. The current distributions for two points of generator G3 and G1 are displayed in fig. 13-14. The analysis of figures 13-14 demonstrates that the jumpers joint only several pipes (not all) in the group. The complex character of these figures indicates on the strong influence of jumper connections on the normal current distribution defined by the insulation quality.

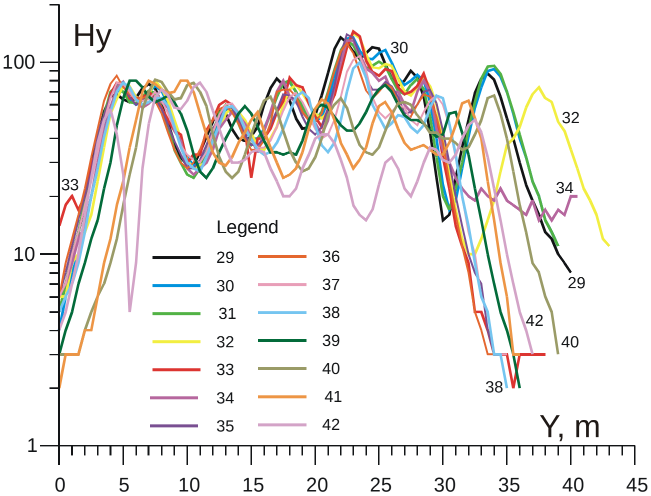

Figure 11.: Graphs for group of 10 pipes

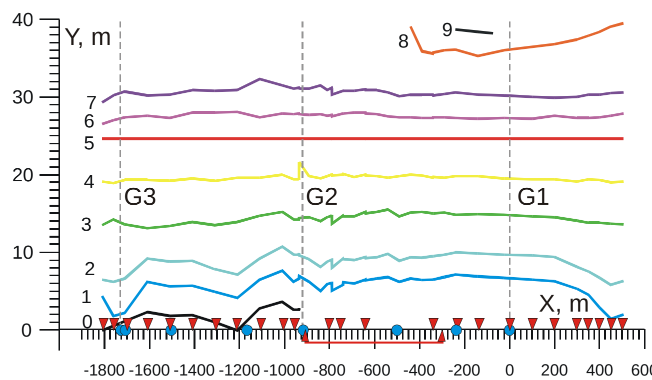

Figure 12.: Pipelines position along 2.5 km profile, relatively pipe 5

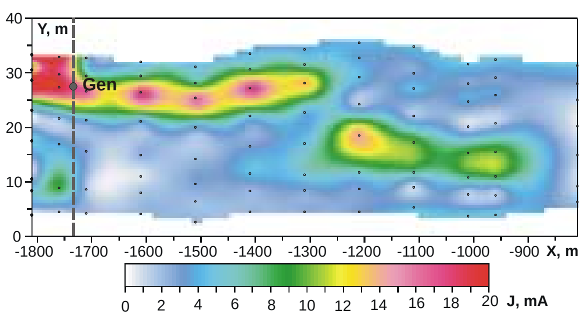

Figure 13.: Current in pipes distribution for generator in point G3

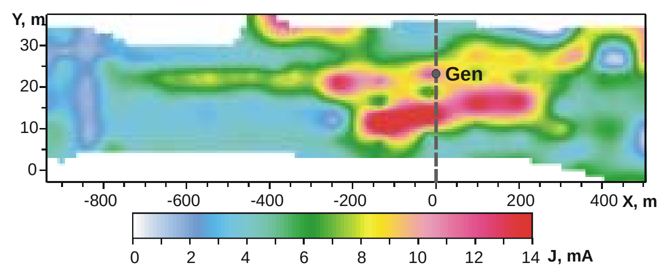

Figure 14.: Current in pipes distribution for generator in point G1

The leakage resistance of the pipeline group (normalized to the number of pipes) is shown in fig.15. This normalized leakage resistance T on each interval between jumpers is close to the leakage resistance of the pipe with the worst insulation because the pipelines are connected in parallel. To estimate the insulation quality we compare the leakage resistance T with the environmental resistance T_m. Its difference speaks about the insulation quality. Three zones with bad insulation (damaged coating) are detected in points X= -800, -240 and +400 m. In the point X=+500 the value of T is less than environmental resistance T_m. Such an anomalous behavior of leakage resistance graph reflects the connection of the pipeline group to a large metallic object, which has a very low grounding resistance.

The presence of this unexpected connection is the most probable reason of dropping the cathodic protection potentials below permissible level.

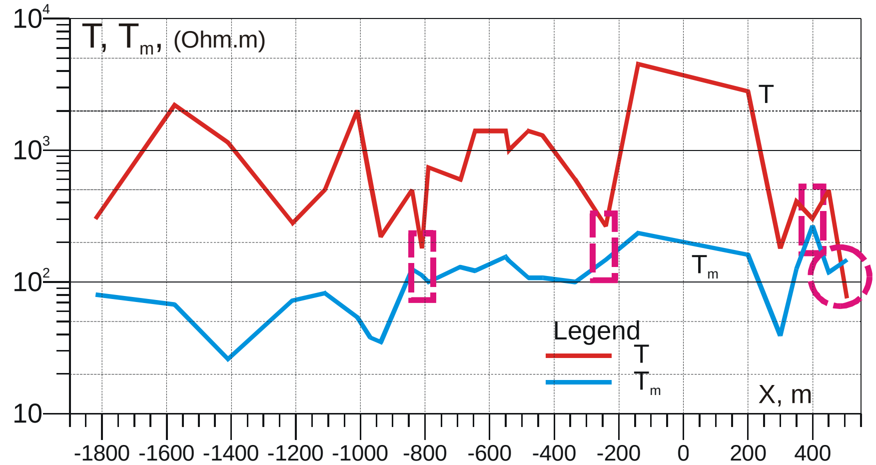

Figure 15.: Graphs of T and T_m

Conclusions

1. The enhanced EM technology for pipeline inspection was developed. This technology requires the following field measurements: the magnetic field above a group of pipelines, alternate voltage only on several posts of cathodic-protection system and environmental resistivity. The interpretation of obtained data allows determining the resistance of insulating coating. The insulation resistance depends certainly on the grade of coating damage and it is the best parameter for technical characterization of the pipeline condition.

2. The EMPI technology was successfully approved during the practical pipeline inspection in Mexico. The excavations realized in the detected zones with anomalous current distributions tested the results of technical condition's estimation.

3. The analysis of the current and insulation resistance distribution is better for understanding of cathodic protection problem than the potential observations. The potential only indicates the existence of same problem and EM allows seeing the cause of problem for example to separate the problem of coating damage and overcharging of cathodic protection with some low resistive grounding.

4. The measurements of magnetic field and developed processing allow seeing the current distribution and reconstructing the pipes net including jumper connections. This information helps to characterize efficiency of cathodic protection and clarify causes of the anomalous potential attenuation. The application of EMPI technology permits separating the problem with the insulation damage from the overcharging the cathodic protection system.

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. Mousatov A., Nakamura E. Transmission-line approximation of pipelines with cathodic protection. SAGEEP-2001 Proceedings, Denver, 7 p.
4. Mousatov A., Nakamura E., Shevnin V., Delgado O.. Application of electromagnetic methods for estimation of technical conditions of oil and gas pipelines in Mexico. SAGEEP-2002 Proceedings, Las Vegas, 9 p.
5. CIPS - Close Interval Potential Survey. www.corrpro.com
6. C-Scan - Dynalog Electronics Ltd. United Kingdom. http://www.dynalog.co.uk
7. DCVG - D. C. Voltage Gradient Technology. http://www.dcvg.com. United Kingdom.
8. ERA instrumentation. User Guide. Research & Production Enterprise “ERA”. St. Petersburg, Russia
9. PCM - Pipeline Current Mapper. User Guide. Radiodetection Ltd. www.radiodetection.com, 84 p.