Numerical Simulation of Currents Induced by Geomagnetic Storms on Buried Pipelines: An Application to the Tierra del Fuego, Argentina, Gas Transmission Route

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Abstract—Varying currents, superimposed on the normal cathodic protection have been observed for many years in pipelines. These telluric currents are generally associated with variations in the earth’s magnetic field and present a continuing problem in establishing and monitoring cathodic protection systems. This problem is enhanced when magnetic storms occur. In a previous paper, a method to calculate the induction over buried pipelines associated with an external source was developed and this effect was quantified as a function of the intensity and frequency of the external field. In the present work, we present the experimental tests. Simultaneous measurements of currents and natural fields are interpreted using this method, and a numerical simulation of the current induced by a magnetic storm is performed. The results show that, even for those storms considered to be of moderate intensity, the current geomagnetically induced in the buried pipeline may increase to 1000%, which suggests that this effect may represent an amount of risk high enough to justify a continuous evaluation and control.

Index Terms—Cathodic protection, corrosion in pipelines.

I. INTRODUCTION

THE PRESENCE of time-varying currents superimposed on the cathodic protection was detected several years ago. These telluric currents are generally associated with earth magnetic variations and may contribute to corrosion of buried pipelines and modify electrical devices connected to them (see, e.g., [1]). These fluctuations that highly exceed levels imposed by cathodic protection should be controlled since current values of about 1 A produce a significant increase in corrosion rates.

Our previous paper, based on observations in gas transmission lines and numerical simulations from earth models, showed the presence of geomagnetically induced currents that could reach tenths of Amperes during disturbed days. A method to calculate the currents induced by external fields on buried pipelines was developed, and this effect was also quantified as a function of intensity and frequency of the inducing field [2]. Theoretical calculations showed that the induced currents tend to follow the pattern of the inducing field, with intensities high enough to increase corrosion rates. These currents are not easily controlled by usual protection systems. In fact, Martin [3] observed this effect in a pipeline in northern Australia.

To verify those theoretical results experimentally, a survey throughout the Tierra del Fuego, Argentina, gas transmission line was performed. We measured the currents on the buried pipelines and the geomagnetic field components, and we used those simultaneous records to determine a correlation between solar activity and the pipeline currents. Finally, we applied the theoretical model and carried out a numerical simulation with the experimental results to estimate the current geomagnetically induced by a magnetic storm. If we take into account that these magnetic episodes occur frequently, in spite of the short duration of each storm, the accumulative effect can be risky from the point of view of increasing chances of corrosion, with a consequent reduction of the pipeline-safe useful life.

II. DATA

A Flux-Gate magnetometer was installed to measure the natural magnetic field. This instrument allows the measurement of the three field components, for periods approximately over 40 s, with a resolution of 10 mV/nT. To measure the current, it was allowed to drain from the pipeline to a reference copper electrode.

Simultaneous measurements of current and magnetic field components were recorded using a Data Logging Keithley, model 576/2 with 16 bits, with a microprocessor with 128 Kilobytes of RAM memory. This system supplies data logging with a resolution of 0.33 μV.

Usually, those sectors of the pipes are protected by batteries with the negative terminal connected to the pipe and the positive terminal to a supplementary anode. The current is made to circulate through this anode with the purpose of diminishing the amount of current that circulates on the pipe.

During the present study, the records were collected with the protection system both disconnected and connected. Simultaneous registrations of magnetic field and electric current were taken during 15 days. Time series 24–48 h long were...
Fig. 1. Time series 24 h long, with a sampling time of 10 s, of the (a) horizontal magnetic field component, (b) current drained from the pipe to a reference electrode, taken with the protection system disconnected, and (c) theoretical estimation of the current induced by the external field (a).

Fig. 2. Time series showed in Fig. 1 filtered in the 100–2000-s band. (a) Horizontal magnetic field component, (b) current drained from the pipe to a reference electrode, and (c) theoretical estimation of the current induced by the external field (a).

Fig. 3. (a) Time series of the (a) horizontal magnetic field component and (b) current drained from the pipe to a reference electrode, taken with the protection system connected.

From simultaneous measurements of the magnetic field and the electric current that circulates through the buried pipelines, we obtained the following results.

1) High correlation was observed between the natural magnetic field and the current circulating through the pipe with all the batteries disconnected. This high correlation was clearly found in the 100–2000-s band.

2) From measurements taken with the protection system connected, a change of level was observed, but the alternating variations were still present, and the correlation between the magnetic field and the current in the pipe held. Batteries were able to compensate a certain amount of direct and long period currents, but spectral components of short periods did not show modifications.
The proposed model is shown in Fig. 4(a). We modified the geometry described by Ogunade [4] to consider three cylinders, the external one \( C_1 \) with radius \( a_1 \), and the internal ones \( C_2 \) and \( C_3 \) with radius \( a_2 \) and \( a_3 \), respectively, defining four regions: the free space (0), the medium in which the body is embedded (1), the pipeline cylinders, medium (2), having a wall thickness of \( a_2 - a_3 \), and its inside occupied by the gas medium (3). The electrical and magnetic properties of each region are identified through the corresponding electrical conductivity \( \sigma_j \), magnetic permeability \( \mu_j \), and dielectric constant \( \varepsilon_j \), with \( j = 0 \ldots 3 \). The external field is created by a current line parallel to the cylinder, given by \( I_{\text{ext}} \), located at \((r_0, \varphi_0)\) measured from the center of \( C_2 \). For simplicity, we considered the TE mode only, but it is well known that this mode generates the main induction contribution since the one corresponding to the TM mode is comparatively smaller in the presence of large conductors and produces a channelling effect (see, e.g., [5] and [2]).

We solved the problem using separation of variables first considering the earth as the cylinder \( C_1 \) and then making \( a_1 \to \infty \) with \( h \) remaining constant [Fig. 4(b)].

Two cylindrical coordinate systems were used: \( O(r, \varphi, z) \), where the \( x \) coordinate coincides with the \( C_2 \) and \( C_3 \) axes, and the system \( O'(r', \Phi, x') \), where \( x \) coordinate coincides with the \( C_1 \) axis. Having made those assumptions, the electric field along the cylinder \( E_{\text{ext}}(r, \varphi) \) is found by applying Maxwell equations with the corresponding boundary conditions on each interface. The solution resulted in combinations of modified Bessel functions of the first and second kind

\[
\begin{align*}
I_n(k_2 r') \left\{ \frac{\cos n(\varphi - \varphi_0)}{\sin n(\varphi - \varphi_0)} \right\}, & \quad I_m(k_3 R) \left\{ \frac{\cos m(\Phi - \Phi_0)}{\sin m(\Phi - \Phi_0)} \right\} \\
K_n(k_2 r') \left\{ \frac{\cos n(\varphi - \varphi_0)}{\sin n(\varphi - \varphi_0)} \right\}, & \quad K_m(k_3 R) \left\{ \frac{\cos m(\Phi - \Phi_0)}{\sin m(\Phi - \Phi_0)} \right\}
\end{align*}
\]

(1)

with \( m \) and \( n \) integers and \( k_j^2 = (j \omega \mu_j \sigma_j - \varepsilon_j j \omega \varepsilon_j) \), with \( j \) indicating the cylinder \((j = 1)\) or the hostess layer \((j = 2)\). The electric field is expressed as

\[
E_{\text{ext}}^1 = -i \omega \sum_{n=0}^{\infty} A_{1n} I_n(k_2 r') \cos n(\varphi - \varphi_0) \\
+ \sum_{n=0}^{\infty} B_{1n} K_n(k_3 r') \cos n(\varphi - \varphi_0)
\]

where

\[
B_{1n} = -Q_n A_{1n}
\]

(3)

\[
Q_n = -\frac{k_1 I_n(k_1 a_2) [I_n(k_2 a_2) + K_n(k_2 a_2) Q_{2n}] - I_n(k_1 a_2) [k_2 K_n(k_2 a_2) + k_2 K_n'(k_2 a_2) Q_{2n}] - k_1 K_n'(k_1 a_2) [I_n(k_2 a_2) + k_n(k_2 a_2) Q_{2n}]}{K_n(k_2 a_2) [k_2 K_n(k_2 a_2) + k_2 K_n'(k_2 a_2) Q_{2n}] - k_1 K_n'(k_1 a_2) [I_n(k_2 a_2) + k_n(k_2 a_2) Q_{2n}]}
\]

(4)
located at a depth $h_1 = 1$ m in a half-space of conductivity $\sigma_1 = 0.001$ S/m.

Finally, we rebuilt the series with the spectral amplitudes to obtain the induced current as a function of time.

The theoretically estimated current is shown in Fig. 1(c), to be compared to the measured current shown in Fig. 1(b) and the horizontal external field component shown in Fig. 1(a). A correlation can be seen between both currents, and the different amplitudes could be explained comparing the model hypothesis and the actual conditions.

If the pipe were buried without isolation cover material, and no leakage were present along the line, we should get a resulting current, as the one given in Fig. 1(c), but due to the measuring procedure, the current must circulate to earth, then the amplitude should certainly be lower than the value of intensity that is actually circulating through the pipe. The decrease in the intensity of the measured currents suggests also that some extra drain could be present in this line.

The result of our measurements shows that, even with protection activated, the effect is present with an amplitude attenuation.

Fig. 2(c) also shows the theoretical estimation for the filtered series in the 100–2000-s band, where the correlation between measured currents and currents calculated using the geomagnetic horizontal field is clearly seen.

IV. Numerical Simulation During a Geomagnetic Storm

A. Geomagnetic Storms

The main geomagnetic field, which has a similar pattern to a dipolar distribution, presents temporal and spatial variations both of external and internal origin. The intensities of these variations are almost inverse to frequency and depend strongly on the solar activity. In fact, during disturbed days, magnetograms present fluctuations in the horizontal component of the magnetic field that may reach values of $-2000$ nT. These events are called geomagnetic storms and usually considered to be of two different kinds, depending on their statistical behavior: recurrent and sporadic.

Recurrent storms are weaker and typically present gradual onsets, while sporadic geomagnetic storms are usually preceded by a sudden commencement, their intensities are larger and, though having a nonrandom behavior, they tend to occur more frequently near solar maxima. Though the temporal distribution of geomagnetic variations cannot be predicted, it depends on a number of factors, including mainly the 11-year solar cycle and the seasonal effect (see, e.g., [9]). With regard to the solar cycle, the activity is higher for cycles with large sunspot number and frequency is larger during the increasing phase. These geomagnetic storms are recognized over the greatest part of the world by an unmistakable decrease of the intensity and the subsequent recovery of the horizontal geomagnetic field. They last approximately from one to two days, though it takes several days to recover the normal level, and their intensity often increases with latitude.
Fig. 5. (a) Horizontal magnetic field component (H) corresponding to the geomagnetic storm registered on February 21, 1994, in Trelew Observatory (Argentina). (b) Numerical simulation of the current induced in the pipeline by the field showed in (a).

Fig. 6. Occurrence of intense storms from 1957 to 1979.

From the simultaneous measurements of the geomagnetic field and currents that circulate through the pipe we can arrive at the results below.

An undeniable correlation between the field and the current circulating along the pipe is shown together with the correlation with the theoretical model that supports the hypothesis of the natural-field significant influence. This correlation can also be found in the series filtered in the 100–2000-s band, as shown in Fig. 2.

1) These currents can be reproduced from the model previously developed, which certainly gives an upper boundary to the possible measured values.

2) In the presence of magnetic storms, the external field can increase in more than one order of magnitude. The numerical simulation, using measured records corresponding to a moderate storm, show the currents that should be induced for such conditions, as discussed in Section III with reference to Fig. 5.

3) Two things are worth being discussed. The first is that low-frequency variations give, in long intervals, significant changes in the base values. The other, is that for higher frequencies the induced currents reach values of several Amperes, a result found previously in records of gas pipelines at other latitudes.

4) Finally, we can conclude that this procedure is a helpful tool to predict the currents that could circulate through the pipeline. The current estimation depends on the size of the pipe section, the electrical conductivity of the soil, the intensity of the external field, the electrical health of the pipe, and the occurrence of magnetic storms. Depending on the results, the protection could be improved in regions where a higher risk of corrosion is found.

REFERENCES

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