Estimating harmful effect of dynamic stray currents on pipeline by simultaneous multiparametric field measurements, continuous wavelet cross-correlation analysis, and frequency plots

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This paper presents the detection method and analysis methodology of dynamic stray current effects on underground pipelines based on simultaneous multiparametric measurements in combination with continuous wavelet cross-correlation and frequency plots. Measurements presented within this paper were conducted at two locations experiencing tram induced dynamic stray currents, in the first case, on unprotected pipeline and in the second case, on pipeline under cathodic protection. On both pipelines, measurements of pipe-to-soil potential, lateral potential gradient, corrosion probe current, and pipeline current were simultaneously done for time period of 20 min. For both locations, the two wavelet cross-correlation spectrograms for the quantities: lateral potential gradient and probe current versus pipe-to-soil potential show that 5% statistical significance levels are in periods between 16 and 128 s. Time spans and period lengths of observed cross-correlations on spectrograms reflect the stray current influence that may be linked to specific events, such as passing of trams. On the other hand, frequency plots of the measured quantities give clear visual representation of the time that pipeline spends in a certain state related to the possible harmful effect of stray current and also show the degree of cathodic protection beneficial effect.

KEYWORDS

cathodic protection, continuous wavelet cross-correlation (XWT), corrosion, dynamic stray currents, frequency plots

INTRODUCTION

Stray currents represent a great danger to the underground metallic pipeline integrity[1]. Problems with the integrity of pipelines that can cause stray currents are stray current corrosion, cathodic disbonding, and reduction of the cathodic protection efficiency.[2] These problems are particularly pronounced in urban environments due to the possible existence of several different stray current sources as well as the proximity of the stray current sources to underground metal installations, such as pipelines. From pipeline integrity point of view, electric DC traction systems, such as tram and train, are the main sources of the dynamic stray currents.[3]

Electric DC traction systems use running rails as the return path of the current to the supply substation.[4] Due to
the rails design and inadequate insulation of rails from surrounding soil, part of return current will leak into the ground. In order to complete the electrical circuit, this current will flow through the ground and/or neighboring underground metallic installations to the supply substation. The magnitude and direction of the stray currents depends on many factors such as the value of rail-to-soil resistivity, the longitudinal rail resistance, the surrounding soil electric resistivity, traction load, and position of vehicles in relation to the supply substation. Also, the operation of the vehicles such as acceleration and braking has an impact on the magnitude and direction of the stray current. In extreme cases, the intensity of the current that leaks from rails can reach up to 70–80% of the traction system current intensity.

When pipeline is placed in the field of the stray current, the corrosion macro cell can be established on the pipeline. On surfaces where cathodic protection current and/or stray current enters the pipeline, cathodic polarization takes place i.e., reaction of oxygen reduction and hydrogen evolution enhanced with respect to those at free corrosion potential. These surfaces of the pipeline are not under threat of stray current corrosion, but the problem of cathodic disbonding may occur if potential is low enough to cause a reaction of hydrogen evolution. Once stray currents enter the pipeline, they can flow through pipeline or a network of galvanically connected pipelines from several hundred meters to several tens of kilometres and this current flow is relatively harmless to the pipeline integrity. The corrosion problem occurs on the pipeline surfaces where the stray current exits the pipeline. On those surfaces, the process of metal dissolution occurs, usually provoking rapid localized corrosion and the ultimate result is perforation of the pipeline wall and loss of containment. The velocity as well as the amount of lost metal in the process of stray current corrosion is directly proportional to the intensity of the stray current.

It is well known that one of the most effective protection techniques for buried metallic pipelines is cathodic protection applied along with the passive protection by protective coating or lining. In order to assess efficiency of existing cathodic protection system or to establish the proper cathodic protection system on unprotected pipelines, it is necessary to measure pipe-to-soil potential. Under the dynamic stray current interference this potential fluctuates over the time. Therefore, measurement of the pipe-to-soil potential versus reference Cu/CuSO₄ (copper/copper sulphate) electrode under the influence of the dynamic stray current does not give true pipe-to-soil potential. Also, measured pipe-to-soil potential is affected by strong IR component. Because of the inability of exclusion of the stray current source, standard on/off technique that is used for the cathodic protection inspection cannot be used to eliminate IR component. To assess the hazard of pipeline corrosion caused by stray currents, probe current measurement can be used. Direction of the stray current through the pipeline as well as stray current intensity can be measured by stray current mapper (SCM).

Different methods are available in the literature for the analysis and interpretation of measurement results of different parameters with the purpose of detecting anodic surfaces on the pipeline and/or determining the efficiency of applied protective measures against dynamic stray currents. Since dynamic stray currents causes the non-stationary signals on measuring instruments, it is convenient to analyze their effect in time-frequency domain.

Research presented in this paper is based on the multiparametric field measurement on both cathodically protected and unprotected gas pipeline which were subject of dynamic stray current interference. Data analysis and visualization presented, is based on continues wavelet cross-correlations and frequency plots in order to develop reliable method for estimation of harmful effects of dynamic stray current and of cathodic protection beneficial action in complex urban infrastructure environment.

## 2 | EXPERIMENTAL

Dynamic stray current was detected by simultaneous measurement of: pipe-to-soil potential, lateral potential gradient, probe current, and pipeline current. In order to present benefits of application of the cathodic protection system in the presence of dynamic stray current, measurements were conducted on two pipelines coated by polyethylene coating, the first one being unprotected and second one being protected by the impressed current cathodic protection system. On both locations, source of dynamic stray current was DC tram system with operating voltage of 600 V and operating current of thousands amperes in peak periods. On both analysed pipelines, measurements were carried out for 20 mins. Both analysed pipelines are buried at depth of 80–120 cm below ground surface. The equivalent scheme of the field measuring circuit is given on the Figure 1.

As it can be noted from the Figure 1 multiparametric field measurements were done by using two reference Cu/CuSO₄ electrodes, one corrosion probe, one multichannel data logger, and a stray current mapper. Pipe-to-soil potential was measured with regard to Cu/CuSO₄ reference electrode which was set on the ground surface above the analysed pipeline. Lateral potential gradient was measured by using two portable Cu/CuSO₄ reference electrodes spaced apart by approximately 7 m and placed on the ground surface. For probe current measurement, corrosion probe was buried at an approximate pipeline depth in close proximity of analysed pipelines and connected with the
pipeline by wire. Probe current was measured by measuring current that flowed through the wire connection to the pipeline. Measurement of the pipe-to-soil potential, lateral potential gradient, and probe current was recorded by a multichannel data logger. All previously listed quantities were measured simultaneously by sampling frequency of 3.33 Hz. Measurement circuit was set up in such way that the current flowing towards pipeline caused positive sign of lateral potential gradient and positive sign of probe current, denoting cathodic current entering the probe. For pipeline current measurement non-contact technique by stray current mapper was used. During the measurements, the SCM sampling frequency was 20 Hz. [1]

3 | MEASUREMENT RESULTS

Results of the simultaneous multiparametric field measurement on unprotected pipeline are given on Figure 2 and on cathodically protected pipeline are given on Figure 3. The measured parameters are pipeline current by SCM device (Figures 2a and 3a), pipe-to-soil potential (Figures 2b and 3b), lateral potential gradient (Figures 2c and 3c) and probe current (Figures 2d and 3d). On both locations, measurements were recorded during a 20 min period in the period of day when tram passes are most frequent. [1] During the measurements on both locations the time between two tram vehicle passes was between 1 min 30 s and 5 min.

From measurement results on both locations it can be noted that variation in time of lateral potential gradient and probe current are similar and have the same sign, while pipe-to-soil potential follows the previous quantities but had the opposite sign, as the current entering the probe caused negative potential shift. Dynamic stray currents caused by tram passing caused erratic variation of the pipe-to-soil potential, lateral potential gradient, and probe current and these variations have both positive and negative sign in comparison to the baseline values. Therefore, in both

![FIGURE 1](equivalent_scheme.png)  
**FIGURE 1** Equivalent scheme of the field measuring circuit. [Color figure can be viewed at wileyonlinelibrary.com]

![FIGURE 2](measurement_results.png)  
**FIGURE 2** Measurement results on unprotected pipeline: a) pipe current, b) pipe-to-soil potential, c) lateral potential gradient, d) probe current. [Color figure can be viewed at wileyonlinelibrary.com]
analysed cases, dynamic stray currents caused both anodic and cathodic shifts of pipe-to-soil potential. Intensity of the dynamic stray current that enters or leaves pipeline is measured by SCM device. From diagrams of pipeline current, on both locations, it can be noted that tram passing causes peaks on pipeline current diagram and that these peaks have different values. By comparing the diagrams of pipe-to-soil potential, lateral potential gradient and probe current with pipeline current, it can be noted that shift of pipe-to-soil potential, lateral potential gradient, and probe current are not proportional to the pipeline current alternation. The pipeline current in Figure 2, shows no visible signs of tram passing, as the location of measurement was away from the current pick-up point. The visible current oscillations are due to passing of cars that interfere with SCM measurements. The pipeline current in Figure 3, shows visible signs of tram passing at approximately 200, 310, 500, 610, 700, 790, and 1100 s, observed as negative peaks. As the location of measurement was close to the current pick-up point, the pipeline current had no possibility of dispersing in the underground network of metallic installations.

4 | CONTINUOUS WAVELET CROSS-CORRELATION ANALYSIS

In this section of the paper results of the cross-correlation calculation between measured quantities are presented. The aforementioned calculations were performed on the measurement results that were carried out at two locations. For both locations, the cross-correlations of lateral potentials gradient versus pipe-to-soil and, probe current versus pipe-to-soil were performed. Calculation of cross-correlations between individual measured quantities were performed by using continuous wavelet cross-correlation transformation (XWT). Using XWT, the calculation of the cross-wavelet spectrum of two time series (measured quantities) in the time-frequency domain is performed.

4.1 | Mathematical background

The cross-correlation calculation procedure between the measured time varying quantities \( x(t) \) and \( y(t) \) using continuous wavelet cross-correlation (XWT) can be represented by the following three steps:

**Step 1:** Calculation of continuous wavelet transformation (CWT) of measured time-varying quantities \( x(t) \) and \( y(t) \). The CWT of the measured quantity \( x(t) \) can be given the following expression:

\[
W_x(\tau, s) = \frac{1}{\sqrt{s}} \int_{-\infty}^{\infty} x(t) \psi^*(\frac{t-\tau}{s}) dt
\]

where the \( W_x(\tau, s) \) is a continuous wavelet transform of the measured quantity \( x(t) \), \( s \) is the scaling parameter, \( \tau \) is the translation parameter, \( \psi(t) \) is the base function of the wavelet transformation (in the literature known as the wavelet mother function), symbol * represents a conjugated complex value. In this paper, the complex Morlet wavelet was used as the base function for the CWT calculation of the measured quantity, which is given with the following expression:

\[
\psi(t) = \pi^{-\frac{1}{4}} e^{-\omega_0^2 t^2} e^{-\frac{t^2}{2}}
\]
where $\pi^{-1/4}$ represents the factor of normalization, and $\omega_0$ is dimensionless frequency parameter.\cite{18}

**Step 2**: Calculation of the cross-wavelet power spectrum over $W_s(r,s)$ and $W_t(r,s)$, representing the continuous wavelet transformation of the measured quantities $x(t)$ and $y(t)$. The cross-wavelet power spectrum calculation was carried out using the following expression:

$$W_{xy}(r,s) = W_x(r,s)W^*_y(r,s)$$  \hspace{1cm} (3)

where $W_{xy}(r,s)$ represents the cross wavelet power spectrum of measured quantities $x(t)$ and $y(t)$.

**Step 3**: Calculation of the phase shift between the measured quantities $x(t)$ and $y(t)$ in the time-frequency domain, was carried out using the following expression:

$$\varphi_{xy} = \tan^{-1} \left( \frac{\Im W_{xy}(r,s)}{\Re W_{xy}(r,s)} \right)$$  \hspace{1cm} (4)

where $\varphi_{xy}$ is the phase shift between the measured time varying quantities $x(t)$ and $y(t)$. $\Re(W_{xy}(r,s))$ and $\Im(W_{xy}(r,s))$ represent the real and imaginary part of the complex function $W_{xy}(r,s)$, respectively.

The results of the calculation of the correlation between the measured time varying quantities are typically shown on the spectrograms. The abscissa of spectrogram represents the time while the ordinate represents a period.\cite{17} On given spectrograms, the magnitude of the cross-wavelet power spectrum $|W_{xy}(r,s)|$ is represented by appropriate colors. High magnitude values of the cross-wavelet power spectrum are represented in yellow color, while low values are represented in blue color. In other words, areas in which a high level of cross-correlation is registered between the measured quantities are indicated in yellow, while the areas with low cross-correlation levels are indicated in blue. Areas in the spectrogram with a value of 95% of the maximum value $|W_{xy}(r,s)|$, i.e., areas with 5% statistical significance are shown by the appropriate contours.

The phase shift between the measured quantities $x(t)$ and $y(t)$ are represented by arrows on given spectrograms. Depending on the orientation of the arrows, the obtained results can be interpreted in one of the following ways:\cite{19}:

1. $\varphi_{xy} = 0$ – the measured quantities $x(t)$ and $y(t)$ are in phase;
2. $\varphi_{xy} \in (0, \pi/2)$ – the measured quantities $x(t)$ and $y(t)$ are in phase, where $x(t)$ is leading;
3. $\varphi_{xy} = \pi/2$ – the measured quantity $x(t)$ is leading;
4. $\varphi_{xy} \in (\pi/2, \pi)$ – the measured quantities $x(t)$ and $y(t)$ are out of phase, where $y(t)$ is leading;
5. $\varphi_{xy} = \pi$ – measured quantities $x(t)$ and $y(t)$ are out of phase;
6. $\varphi_{xy} \in (\pi, 3\pi/2)$ – the measured quantities $x(t)$ and $y(t)$ are out of phase, where $x(t)$ is leading;
7. $\varphi_{xy} = 3\pi/2$ – the measured quantity $y(t)$ is leading;
8. $\varphi_{xy} \in (3\pi/2, 0)$ – the measured quantities $x(t)$ and $y(t)$ are in phase where $y(t)$ is leading.

**4.2 | Results of cross-correlation calculation and discussion**

The results of the calculation of the cross-correlation between the individual measured quantities for unprotected and cathodically protected pipeline, are given in Figures 4 and 5, respectively. High degree of correlation between signals is seen only for certain periods, as relatively fast sampling of pipeline potential under dynamic interference may reflect both IR drop without significant pipeline polarization and with significant pipeline polarization. Only

**FIGURE 4** Spectrogram of continuous wavelet cross-correlation for case of unprotected pipe: a) lateral potential gradient versus pipe-to-soil potential, b) probe current versus pipe-to-soil potential. [Color figure can be viewed at wileyonlinelibrary.com]
significant polarization effects lead to high correlation of the measured quantities which is generally observed for certain sampling intervals and may be linked to tram passages and CP current fluctuations due to automatic regulation.

From the previously given spectrograms, for both pipelines, it can be noticed that at low periods in the range from 0 to 8 s, there is no significant cross-correlation between measured quantities. High degree of cross-correlation between measured quantities for all considered cases is noticeable for periods of 16 s and higher.

By analyzing the spectrograms given on Figure 4 it can be noted that all 5% statistical significance levels are in periods from 16 s up to 128 sec. Time spans and period lengths of 5% statistical significance of the two spectrograms on Figure 4 correspond to each other. The time positions and magnitude of the 5% statistical significance levels on the spectrograms shown on Figure 4a and b, cannot be linked to the pipeline current observed by SCM.

On the other hand, the spectrograms on Figure 5a and b show a 5% statistical significance level in periods from 16 s up to 64 s. It may be noticed that 5% statistical significance levels on Figure 5a and b can be linked to the pipeline current measured by SCM, and they correspond to the tram passing times shown in Figure 3.

From the spectrograms of lateral potential gradient versus pipe-to-soil potential in Figures 4a and 5a and probe current versus pipe-to-soil potential on Figures 4b and 5b, it is noticeable that measured quantities are out-of-phase, meaning that a positive change of the lateral potential gradient and the probe current simultaneously cause a negative change of the pipe-to-soil potential to the negative side indicating entrance of current into the probe.

With respect to stray current induced corrosion, correlation of the pipe-to-soil potential to the probe current is of particular significance as it is often argued that pipe-to-soil potential shifts due to dynamic stray currents mainly reflect the IR drop contribution of the measurements.

By comparing spectrograms for unprotected (Figure 4) and pipeline protected by cathodic protection system (Figure 5) it can be noted that, between the pipe-to-soil potential and the probe current, there is less highly significant correlation and that the correlations are in lower time periods for the cathodically protected pipeline. Therefore, it can be concluded that cathodically protected pipeline is more immune to dynamic stray currents.

5 | FREQUENCY PLOTS

Frequency plots of the pipe-to-soil potential, probe current, and pipeline current versus time for both analyzed pipelines are given in Figure 6. These frequency plots are constructed based on the measurement data. Based on the given frequency plots one can clearly note state of considered pipeline during analyzed period, i.e., period in which the measurements were carried out.

On the frequency plots of pipe-to-soil potential for unprotected pipeline, it can be noticed that the measured potential values are in the range from −1.900 up to 0.606 V, which leads to the conclusion that the pipe-to-soil potential varies in vary wide range due to effects of dynamic stray current. The value of the pipe-to-soil potential with the longest time duration was −0.699 V, and corresponds to the corrosion potential of the cathodically unprotected pipeline. Although the period in which the pipe-to-soil potential has extreme values is short, any positive probe current value is characteristic of the anode polarization of the pipeline and therefore gives high likelihood of corrosion due to stray currents.
The probe current ranges from $-4.32$ to $4.79$ A, while pipeline current ranges from $-18.69$ to $14.61$ A. By calculating the anodic charge passed through the probe, and by taking into account the sampling interval of 120 s and the probe surface area of 18.47 cm$^2$, the corrosion rate of 1.51 mm/year may be calculated.

Frequency plots of the probe current and pipeline current for unprotected pipeline are almost symmetrical around the zero value of the probe current and pipeline current. The forms of frequency plots and the values of probe and pipelines current indicate the existence of a current source with a time-varying intensity, and this can be due to the presence of dynamic stray currents. Therefore, it can be concluded that the anodic polarization of the pipeline at this location is caused by the presence of dynamic stray currents.

Dynamic stray currents at cathodically protected pipeline also cause an anode polarization of the pipeline, i.e., changing the pipe-to-soil potential towards more positive values and cathodic probe current to the lower levels. The frequency plots at second location has a bimodal shape, thus indicating the presence of two current sources, one low-intensity current source and long time duration, or a permanent state that can be
attributed to the cathodic protection system. The presence of another source of high current intensity and much shorter time duration can be attributed to the passing of trams. On the frequency plots of pipe-to-soil potential for cathodically protected pipeline, it can be noticed that the measured potential values are in the range from $-1.649$ up to $0.904\, \text{V}$, with pipeline spending most of the time in the interval from $-1.429$ to $-1.302\, \text{V}$. The additional peak is observed at $-1.137\, \text{V}$. For this case, the probe current ranges from $-1.64\, \text{A}$ to $-0.004\, \text{A}$, while pipeline current ranges from $-39.30$ to $40.69\, \text{A}$. Since there is no anodic charge passed through the probe, corrosion rate cannot be calculated and it can be concluded that applied cathodic protection system eliminates the negative corrosion effects of stray currents.

By comparing the span as well as the values of the pipeline current from frequency plots for different pipelines, it can be noted that the intensity of the stray currents is considerably higher on the cathodically protected pipeline compared to the unprotected pipeline. On the other hand, by comparing the span and values of pipe-to-soil potential on the frequency plots, it is noticeable that the pipe-to-soil potential is more negative on cathodically protected pipeline. Also, it can be noted that the range of pipe-to-soil potential values i.e., change of the potential due to dynamic stray currents is significantly lower at cathodically protected pipeline. Although the presence of dynamic stray currents leads to the change of pipe-to-soil potential to the positive side, the presence of the cathodic protection system ensures sufficient negative protective potential of the pipeline. This further emphasizes the benefits of the application of the cathodic protection system of the pipeline that is placed in the field of dynamic stray currents.

6 CONCLUSION

Evaluation of the dynamic stray current corrosion likelihood is particularly challenging in urban areas due to the non-stationary (stochastic) nature of the dynamic stray currents, multiplicity of possible stray current sources, the complexity of buried infrastructure, nonlinear polarization of metallic infrastructure, etc. In this paper, new approach for measurement data analysis and visualization based on the simultaneous multiparametric field measurement is presented. Proposed methodology for analysis and visualization of measurement results is based on continuous wavelet cross-correlation and frequency plots. The purpose was the development of the reliable method for estimation of harmful effect of dynamic stray current on underground metallic infrastructure and benefits of application of cathodic protection system in such an environment.

From the analysis methodology proposed in this paper, following conclusion can be made:

1. Based on the period position of the 5% statistical significance levels on the spectrograms obtained by continues wavelet cross-correlation between the pipe-to-soil potential and the probe current, the severity of stray current influence may be estimated for the particular location of measurement.
2. From pipe-to-soil potential and probe current frequency plots, the impact of stray current may also be estimated. Additionally, corrosion rate may be calculated by calculating the anodic charge passed through the current probe, as a quantitative indicator of stray current effect severity.
3. Depending on the location measurement, observation of stray current influence may be linked to specific events, such as passing of trams, through analysis of pipeline current frequency plot and comparison of pipeline current log with the cross correlation graphs.

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REFERENCES


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