Post-print of: Darowicki K., Żakowski K.: A new time-frequency detection method of stray current field interferenceon metal structures. CORROSION SCIENCE. Vol. 46., (2004), p. 1061-1070. DOI: 10.1016/j.corsci.2003.09.007

A new time–frequency detection method of stray current field interference on metal structures

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Abstract

A new detection method has been presented of stray current field interference on underground metal structures. The method employs short time Fourier transformation (STFT). This method of analysis allows determination of signal spectral power density changes (e.g., structure potential) in the function of time. In the paper results have been presented of total time–frequency analysis of a pipeline potential in a stray current field generated by a tram traction. The presented results have unequivocally shown that the described method allows accurate identification of the stray current source and determination if it interacts with the underground metal structure.

Keywords: Stray currents; STFT

1. Introduction

A number of factors affect the corrosion rate of external metal structure surfaces. One of them is interaction of stray current fields [1]. DC electric tractions: tram, rail and metro are the largest, and simultaneously the best known, stray current sources [2]. Stray current leakage occurs from rails, an element of the traction current return circuit. The leakage magnitude depends on the voltage drop in the rail (being a function of the current flowing in rails and the rail resistance) and the rail resistance

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doi:10.1016/j.corsci.2003.09.007

in relation to the ground [3]. Also high voltage DC transmission lines used for long distance transmission of energy can be sources of stray currents [4].

Detection of stray current interactions is usually carried out on the basis of potential measurements [5]. The structure potential value and its variability are adopted as criteria of the electrolytic corrosion hazard [6]. Interpretation of results is made difficult by the IR component of recorded potential changes. Martin [7] provides the following method of IR elimination, helpful in cathodic protection systems: measurement of the switch-off pipeline potential, measurement of coupon switch-off potential, impulse techniques, potential measurements of special probes, potential measurement in relation to an electrode placed near the pipeline, measurement of the voltage gradient in the ground, AC techniques.

The electric field in the ground connected with flow of stray currents in an electrolytic environment is not identical in time or in space. Changes of this field are random in character. Ferenc [8] estimates the current and direction of the electric field in the ground (hence the flow direction of stray currents in the ground) on the basis of potential difference measurements between pairs of electrodes placed on the ground surface perpendicularly to each other. Park et al. [9] propose independent measurements of pipeline potential and electric traction rail potential. They determine activity of stray currents by giving mean values of these potentials and their standard deviations. The quoted authors emphasise that if stray currents interact with a structure, the structure potential and rail potential change symmetrically in relation to each other.

Bazzoni and Lazzari [10] extrapolate the functional dependency simultaneously measured for several minutes between values of: structure potential and gradient of electric field in the ground in a direction perpendicular to it. For this they use two portable electrodes, of which one is placed over the pipeline and the second at such a distance so that the measured voltage drop is equal to 20–30 mV. They recognise the potential value obtained by extrapolation as the structure potential with no IR component. Martin and Brinsmead [11] measured for 2 min the pipeline potential and current flowing through a coupon connected to the pipeline. By using the linear regression method they determine the potential corresponding to a zero current value. This potential is recognised as the pipeline polarisation potential. Zakowski and Sokolski [12] measure simultaneously for 20 min the pipeline potential and voltage between the pipeline and tram rails. They evaluate the electrolytic corrosion hazard on the basis of asymmetry of pipeline potential changes versus the stationary potential (calculated by the regression method for a zero voltage value). They assume the measure of the corrosion hazard to be the value of the asymmetry coefficient, calculated as the ratio of the sum of pipeline anodic polarisation periods to the measurement time [13,14].

Methods of stray current interaction listed above are based mainly on measurement and analysis of potential changes. However, measurement results in a stray current field should be interpreted with great caution, mainly due to presence of the IR component. Intensity of potential changes need not be an indicator of the intensity of ongoing electrode processes (polarisation) on the metal surface [15,16]. Stray current are non-stationary signals as their mean value and standard deviation change in the function of time [14]. Hence, measurement result analysis methods should be adapted to non-stationary signals. Such a possibility is given by total analysis in the domains of time and frequency [17].

In this paper a new method has been presented of detection of stray current interference based on application of short time Fourier transformation (STFT). The method allows obtaining of instantaneous spectral power density values. It allows accurate identification of each stray current source and allows unequivocal statement whether a given source interacts with the investigated metal structure. This is a novel detection method and has not been presented in the literature up till now.

2. Theoretical analysis of voltage changes in the total time and frequency domain

Let us assume that object A is a stray current generator (e.g., tram rails). Measurement of voltage $U_A(t)$ in the function of time between the object A from which stray currents leak and the auxiliary electrode (as in Fig. 1) allows detection of these currents. The recorded voltage changes are the generator characteristic. This characteristic can be presented also in the form of a frequency spectrum of recorded voltage changes. Fourier transformation of voltage $U_A(t)$ leads directly to the frequency spectrum. This transformation is effective in the case of signals denoted in mathematical statistics as stationary (of invariable random parameters in time). However, stray currents are non-stationary signals—their mean value and standard deviation depend on recording time. In the case of non-stationary signals Fourier

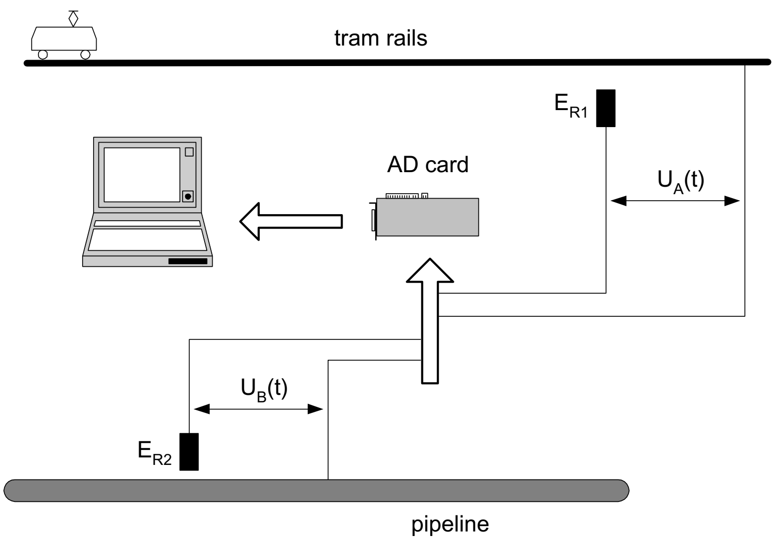


Fig. 1. Scheme of investigated system. E_{R1}, E_{R2}—$Cu/CuSO_4$ reference electrodes; $U_A(t)$—voltage tram rails-electrode, $U_B(t)$—voltage pipeline-electrode.

transformation gives averaged results. Hence, the result of such analysis strongly depends on recording time.

Time–frequency methods are effective methods of analysis of non-stationary signals. Short time Fourier transformation (STFT) is such a method. The STFT transform differs from the classical Fourier transform by the application of an analysing window. The STFT transform of voltage changes $U_A(t)$ is given by relation:

$$\mathrm{STFT}\{U_A(t)\} = \int U_A(\tau)\cdot\gamma(\tau - t)\cdot\exp(-\mathrm{j}\omega\tau)\,\mathrm{d}\tau \tag{1}$$

where γ is the window function, t the window localisation time, ω the frequency.

The analysing window placed in time t cuts out a fragment of analysed signal $U_A(t)$. Beyond the window frame the analysed signal is equal to zero. Next this fragment is subjected to classic Fourier transformation and $|\mathrm{STFT}\{U_A(t)\}|^2$ is determined, corresponding to time t. In the next step the window is shifted to the subsequent time, a new portion of the analysed signal is cut out and its spectral power density is determined, etc. The result of such an analysis is determination of the spectrogram, i.e. distribution of signal energy in the joint time–frequency domain.

In measurement practice different analysing windows are applied [18]: rectangular window, Hamming window, Hanning window, Blackman window. However, the Gauss window $g(t)$ is most frequently used:

$$g(t) = \frac{1}{(\pi\sigma^2)^{1/4}}\exp\left(-\frac{t^2}{2\sigma^2}\right) \tag{2}$$

where σ is a parameter characterising the window width.

The Fourier transform of a Gauss window is a Gauss window:

$$\begin{aligned} G(\omega) &= \int \frac{1}{(\pi\sigma^2)^{1/4}}\exp -\frac{(\tau - t)^2}{2\sigma^2}\exp(-\mathrm{j}\omega\tau)\,\mathrm{d}\tau \\ &= (4\pi\sigma^2)^{1/4}\exp\left(\frac{-\omega^2\sigma^2}{2} + \mathrm{j}\omega t\right) \end{aligned} \tag{3}$$

By using an STFT transformation for a Gauss peak determined in the time domain, analysis is transferred to a total time and frequency domain. The frequency and time resolution of this analysis depend on the size of the cut out signal portion, i.e., on parameter σ. The time resolution σ_t is equal to

$$\sigma_t^2 = \frac{\int t^2|g(t)|^2\,\mathrm{d}t}{\int |g(t)|^2\,\mathrm{d}t} = \frac{\sigma^2}{2} \tag{4}$$

The frequency resolution σ_ω is given by relation:

$$\sigma_\omega^2 = \frac{\int \omega^2|G(\omega)|\,\mathrm{d}\omega}{\int |G(\omega)|\,\mathrm{d}\omega} = \frac{1}{2\sigma^2} \tag{5}$$

The frequency resolution and time resolution are connected with each other by the uncertainty rule:

$$\sigma_t^2\sigma_\omega^2 = \frac{\sigma^2}{2}\frac{1}{2\sigma^2} = 1/4 \tag{6}$$

Increase of σ is identical with increase of the analysing window size. It causes increase of σ_t—hence deterioration of the analysed voltage resolution in the domain of time. Simultaneously, increase of σ causes improvement of the frequency resolution. Contrary to the above: deterioration of the frequency resolution leads to improvement of the time resolution.

From the presented short introduction it results that STFT transformation reflects changes of the recorded voltage $U_A(t)$ in the domain of time. Simultaneously, for each moment in time spectral power density is obtained for recorded voltage changes. Such an approach is innovative in analysis of stray currents.

3. Experimental

The schematic diagram of the investigated system is presented in Fig. 1. It is a typical measurement system used for determination of correlation curves between the pipeline potential and the electric traction rail potential. The tram traction powered by a DC current was the stray current generator. The investigated object was an over 10-year-old ϕ300 underground steel pipeline with bituminous insulation, running parallel to the traction at a distance of 20 m. Two $Cu/CuSO_4$ electrodes were used as reference electrodes. Before measurements electrodes were seasoned for 24 h in a saturated $CuSO_4$ solution. The voltage $U_A(t)$ between tram rails and the E_{R1} reference electrode was measured. (As measured signals include large and variable IR ohmic drop components in time in this paper we resigned from using the phrase "potential" and use "voltage" instead.) The E_{R1} electrode was placed at a distance of 5 m from the earthing point of tram rails. The voltage $U_B(t)$ was simultaneously measured between the pipeline and E_{R2} reference electrode. The electrode was placed over the pipeline at a distance of approximately 1.5 m.

The measurement system was made up of an ADDIDATA APCI 3120 measuring card connected to a PC computer. The sampling frequency was equal to 10 Hz. Analysis of voltage signals $U_A(t)$ and $U_B(t)$ was performed with a LabView, Joint Time Frequency Analysis software package.

4. Results and discussion

In Fig. 2 a 2-min fragment has been presented of a voltage $U_A(t)$ time register and a corresponding $U_B(t)$ voltage register. The calculated correlation coefficient value for these signals was equal to −0.684.

Mathematical STFT analysis is reduced to formation of a network in the domain of time and frequency. Information on the energy of analysed signal is ascribed to

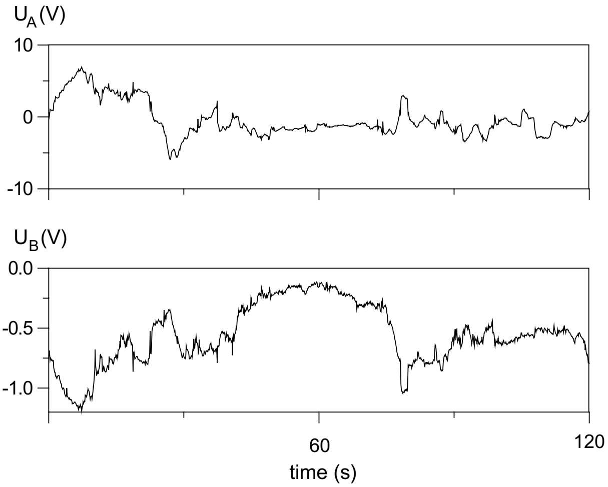
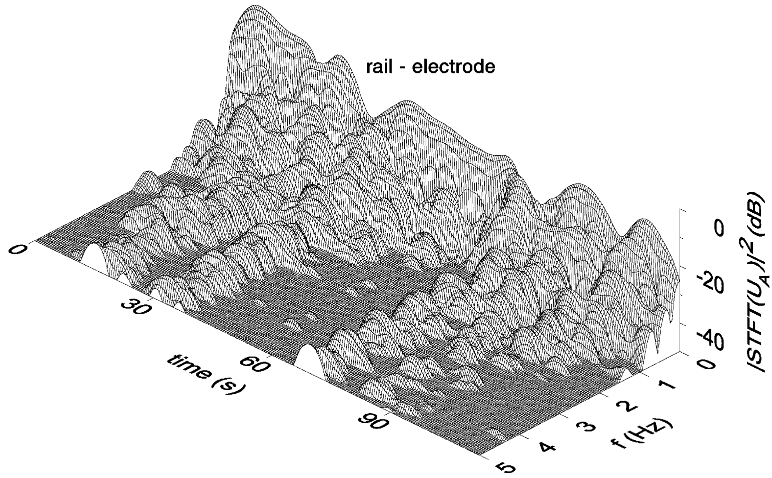


Fig. 2. Fragment of time registers. U_A—voltage of tram rails versus $Cu/CuSO_4$ reference electrode; U_B—voltage of pipeline versus $Cu/CuSO_4$ reference electrode.

knots of such a formed network. In accordance with the definition, the spectrogram is the square of the STFT transform module and is determined in the domain of time and frequency. Hence, it is the measure of the leakage of energy from the tram traction.

STFT spectrograms corresponding to the registers shown in Fig. 2 are illustrated in Fig. 3. They are spectral line compositions of a determined frequency structure. The length of analysing window was selected in a manner allowing to obtain both—appropriate time resolution σ_t and frequency resolution σ_ω according to the uncertainty rule described by the formula (6). In Fig. 3 line location correlation is visible in the domain of time for voltage U_A and U_B—for both voltages spectra are similar in form. The highest energy of signal is registered for the lowest frequencies, close to 0 Hz value. Changes of signal's energy for these very low frequencies are small in the entire time domain. Moreover, it can be spotted in Fig. 3 that for the frequencies above 1 Hz, energy of the signal is minimum at certain moments of time. At other moments the energy increases in the entire domain of analysed frequency (being the range up to 5 Hz). Described shape of both spectrograms from Fig. 3 is closely correlated with tram traffic. Energy of signal takes minimum value when there is no traffic. Increase in the energy occurs at passing of tram.

So localisation of spectral lines in the domain of time strictly corresponds to the times of passing of trams. Presence of frequency peaks on a spectrogram is a characteristic feature connected with passing of a tram. Comparison of time and frequency location of spectral lines on a spectrogram corresponding to voltage U_A and spectrogram corresponding to voltage U_B is unequivocal proof that the electromagnetic field generated by passing trams affects the state of investigated pipeline.



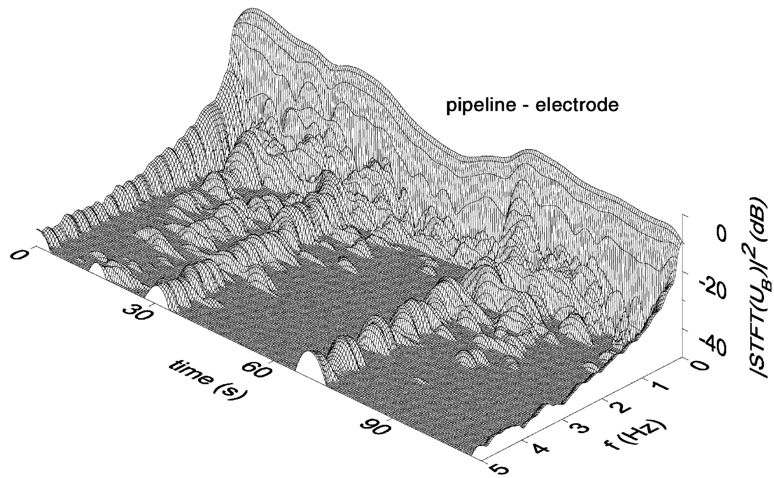


Fig. 3. STFT spectrograms of signals from Fig. 2.

STFT spectrograms corresponding to registers of voltage U_A and U_B obtained on another pipeline at a distance of approx. 50 m from the tram traction are given in Fig. 4. On a spectrogram corresponding to the rail-electrode voltage signal's energy takes non-zero values in the entire time and frequency domain. Spectral lines connected with passing of trams are visible. On a spectrogram corresponding to the pipeline-electrode voltage these spectral lines do not occur. Energy of signal is high only for very low frequencies, just as in Fig. 3. For the frequencies exceeding 1 Hz the energy is minimum and constant in the entire time range. It is so also when tram is passing. This means that the electromagnetic field generated by passing trams does not interact with the investigated pipeline.

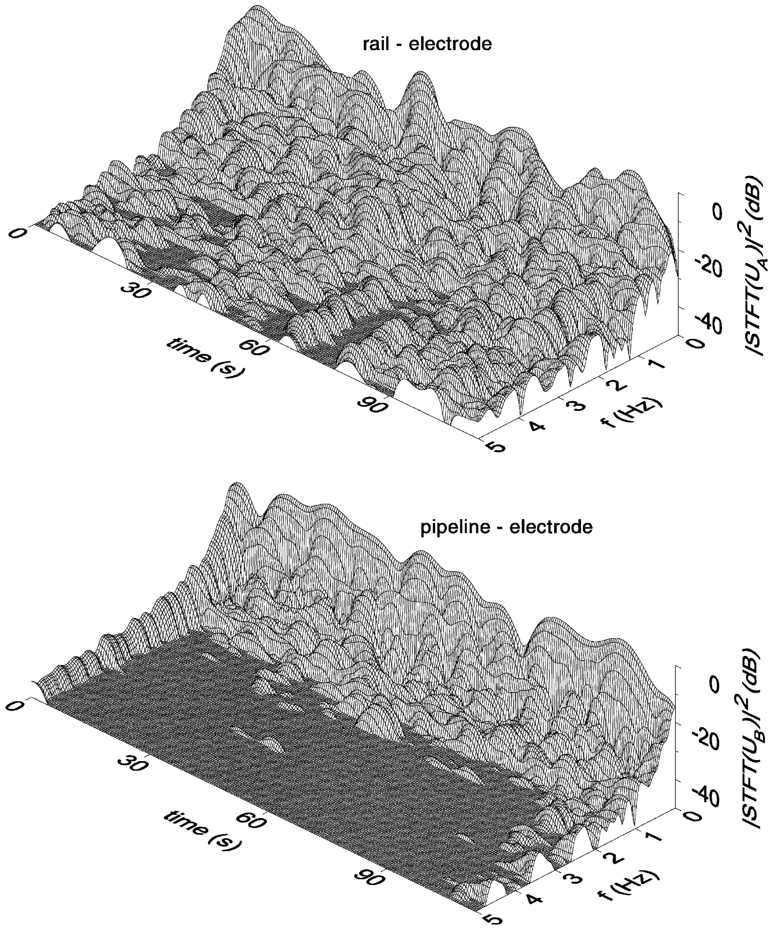


Fig. 4. STFT spectrograms presenting the lack of electromagnetic field interference on pipeline.

The method presented in this paper allows determination if and which stray current source interacts with the investigated metal structure. It does not allow determination of the intensity of electrolytic corrosion processes. However, the proposed method allows accurate, unequivocal identification of the source of interference on the underground structure.

5. Conclusions

The proposed detection method of stray current field interactions on a metal structure has several advantages. An identical time and frequency localisation of spectral lines on the spectrograms corresponding to recorded voltages (stray current source and investigated structure versus the reference electrode) points to interaction of an electric field generated by passing trams.

Differing STFT spectrograms corresponding to the voltage structure-electrode and voltage tram rails-electrode indicate lack of interaction of the investigated stray current source with the underground metal structure. In such a case, characteristic spectral lines corresponding to tram passing times are not visible on the structure spectrogram. When the shape of instantaneous spectral power density spectra on both spectrograms is different, such a result points to interaction of another electromagnetic field source.

The presented method enables identification of the electromagnetic field source and determination of interaction of this source with the investigated structure. Regrettably, it does not give information on the intensity of electrolytic corrosion processes of the external surfaces of the investigated structure.

Acknowledgements

This work has been supported by grant no. 7 T08C 00821 from the Polish Committee for Scientific Research.

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