Detection and time/frequency analysis of electric fields in the ground

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Abstract

Purpose – This paper sets out to detect and characterize electric fields in the ground (such as stray current fields) using a tandem time/frequency method of signal analysis.

Design/methodology/approach – Results were obtained from investigations performed in the presence of a generated electric field with controlled variable characteristics, and in the presence of an electric field generated by a tramline. The analysis of measurement registers was performed using Short-Time Fourier Transformation. The results were presented in the form of spectrograms, which illustrate changes in the spectral power density of the measured signal versus time.

Findings – Tandem time/frequency analysis reveals the random or deterministic character of the electric field, enabling its complete time/frequency characteristics to be obtained. Such information is inaccessible using exclusively the frequency analysis methods that utilize classical Fourier transformations. Moreover, an analysis of the spectral power density distribution of the signals in three directions on the ground surface makes it possible to define the localization of the field source.

Practical implications – Analysis methods for electric fields in the ground should be adapted to the evaluation of non-stationary signals because the stray currents are of this type. Such a possibility is given by combined analysis in the domains of time and frequency. This method can be used as complementary to applied measurement techniques of stray current interference.

Originality/value – The method of electric field detection and characterization, as related to stray currents, previously has not been presented in the literature. This method of signal analysis may be adopted for other investigations that are reliant on the registration of voltages or potentials characterized by arbitrary frequencies.

Keywords Electric fields, Electric currents

Paper type Research paper

Introduction

Field investigations of physical and geophysical properties of soil, take advantage of the methods based on measurement of voltage, potential and electric field intensity. Measured and calculated parameters of these signals (i.e. their absolute value, fluctuation range, fluctuation rate, frequency, and damping) allow description of the properties of an environment, such as the presence of stray currents, geocurrents (telluric currents), electrical parameters of soil (resistivity, permittivity), humidity, level of ground waters and geological structure.

This paper concerns the measurements and joint time-frequency analysis (JTFA) of the voltages close to the surface of the ground that are connected by the presence of electric fields generated by various sources. Short-Time Fourier Transformation (STFT) was used to analyze the data. The following chapter presents selected problems and investigation techniques used for various fields connected with a soil environment, which are based on the measurement and analysis of the voltages generated by artificial and natural sources. The investigation methodology presented in the paper can used as a supplementary one providing new information useful in the interpretation of physical phenomena occurring in soil.

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Investigation techniques in soil environment based on analysis of electric signals

In urban areas, interference of the electric fields with metal underground structures is connected mainly with the fields originating from stray currents. The presence of stray current fields in the soil is usually identified based on the changes potential of the construction compared to the potential of a reference electrode, which is usually a copper/copper sulphate electrode. The changes of this potential are analyzed as a function of time or on the basis of correlation analysis (Freiman, 2003). Previous investigations (Zakowski and Darowicki, 2001) revealed that the analysis of the potential of a construction versus time did not always allow detection of the field. Moreover, it does not provide field characteristics. Additionally, it is desired to identify not only the presence of the electric fields but also their characteristics, For instance, to assess corrosion risk to a construction. This suggested that there was a necessity to analyze the signals also in the frequency domain.

In geomagnetically active regions, a phenomenon of geocurrents (known as telluric currents) may be induced. Induced currents appear throughout the world, though their effects are enhanced specially at polar and equatorial latitudes. Long underground pipelines located in these regions may suffer from such currents of significant intensity, e.g. currents with

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instantaneous intensities equal to 30 A were recorded in Finland (Pulkkinen *et al.*, 2001). In addition to, registration of induced geocurrents, monitoring of their interference with a pipeline also can be performed. Such monitoring is usually based on registration of the pipe-to-soil potential. Significant changes of this potential are observed during the periods of enhanced geomagnetic activity; e.g. 5 V fluctuations were recorded on a pipeline in Australia (Martin, 1993), 3 V fluctuations on a pipeline in Finland (Pulkkinen *et al.*, 2001). It is usually the case that an analysis of changes of the pipe-to-soil potential relies only on an assessment of fluctuation magnitude in time domain. However, the intensity of the currents induced in a pipeline by changing geomagnetic field depends on soil resistivity as well as on the intensity and rate of change of the magnetic field (Osella and Favetto, 2000). While monitoring geocurrents it is important, therefore, to obtain characteristics of the field not only in time domain but also in frequency domain. There are reports in the literature that describe the application of wavelet analysis (i.e. the STFT-related method of signal analysis) to evaluate signals induced in the soil during geomagnetic storms (Odim *et al.*, 2005). Wavelet analysis yields good results for single, instantaneous, short changes of a signal. Moreover, wavelets are characterized by inferior frequency resolution as compared to the STFT. The best application for wavelet analysis is when the frequency components of the measured signal differ significantly. If this difference is small, then STFT is advantageous.

Any metallic object subjected to the alternating electromagnetic field of the transmission system will exhibit an induced voltage. The interference caused by AC railway systems or AC power transmission lines on buried pipelines has been the subject of many investigations. Even under normal operating conditions, voltages and currents are induced on the pipeline. They may pose danger to working personnel or may accelerate the corrosion of the pipeline. There are three types of electromagnetic couplings between AC transmission systems and pipelines (Metwally and Heidler, 2005; Bortels *et al.*, 2006), and these are electrostatic or capacitive, resistive or Ohmic, and magnetic or inductive. The electrostatic or capacitive coupling occurs in the immediate vicinity of the overhead power lines, mainly when the pipe is laid on a foundation that is well insulated from the ground. The pipeline acts as one side of a capacitor with respect to ground. This is only of concern when the structure is above grade. The resistive or Ohmic coupling can occur when lightning strikes a transmission tower, or when there is a phase/ground fault. Fault currents flow on and off the underground structure. Magnetic or inductive coupling on pipelines occurs when there is extended and close parallel routing with overhead transmission lines. Induction may occur when the structure is either above or below ground. This coupling increases with rising operating currents in the overhead lines, with increasing quality of the coating on the pipeline, and with increasing length of line parallel to and close to the AC transmission lines.

In consequence, there is a need for a user-friendly method that can provide the capability of determining the characteristics of the electric field near the construction. The technique proposed in this paper seems to be suitable for that purpose.

High voltage direct current (HVDC) systems of energy transmission are the sources of current interferences on underground pipelines (Fitzgerald and Kroon, 1995). In the vicinity of the ground electrode of the HVDC system, the gradient of the electric field in the soil is very large. Such a field distribution is influenced by any change in soil resistivity near the electrode due to heating effects caused by the current flow, which results in an alteration of soil humidity (Villas and Portela, 2003). The gradient of the electric field in the soil in different directions can be determined using the technique presented in this paper.

A review of the investigation techniques presented above indicated there was a possibility to extend them to provide a new method of analysis. A great deal of new information, inaccessible so far via traditional analysis, can be provided by the joint time-frequency analysis of measured signals.

The aim of this paper is the presentation of a method of detection and analysis of electric fields in soil that is based upon an analysis of measured signals in joint time-frequency domain using STFT. Some examples of practical applications of the method, results of field investigations, analysis and a discussion of the results are presented.

Method of analysis of measurement registers

The method of JTFA was used (this group of methods is described thoroughly in the book by Carmona *et al.*, 1998). The approach employs the STFT approach (Quian and Chen, 1996).

The STFT transform of U voltage changes is described by the dependence:

$$\mathrm{STFT}\{U(t)\} = \int U(\tau)\gamma(\tau - t)\exp(-j\varpi\tau)d\tau \qquad (1)$$

where γ – window function, t – time localization of the window.

The STFT transform differs from a classic Fourier transform (FT) by application of an analyzing window (for example, a rectangular window, Hamming window, Hanning window, Blackman window, or Gauss window). The analyzing window localized in a time instant t selects a fragment of the analyzed signal. Outside the window, the signal is equal to zero. The abstracted fragment is subjected to the classic Fourier transformation and then $|\mathrm{STFT}\{U(t)\}|^2$ is calculated; i.e. spectral power density corresponding to the time instant t is determined. In the next step, the window is shifted to the following time localization and a new fragment of the analyzed signal is abstracted. The spectral power density value then is also is calculated for that fragment, and so on. By repeating this process over the entire register, the evolution of the spectral power density versus time can be tracked. A result of the analysis is a spectrogram, which reflects the time-frequency analysis of the registered signal.

The frequency and time resolution of this analysis depend on the size of the abstracted signal fragment, i.e. on parameter σ. The time resolution of σ_t is equal to:

$$\sigma_t^2 = \frac{\int t^2|\gamma(t)|^2\mathrm{d}t}{\int|\gamma(t)|^2\mathrm{d}t} = \frac{\sigma^2}{2} \qquad (2)$$

The frequency resolution σ_ω is given by the dependency:

$$\sigma_\omega^2 = \frac{\int \omega^2|\gamma(\omega)|\mathrm{d}\omega}{\int|\gamma(\omega)|\mathrm{d}\omega} = \frac{1}{2\sigma^2} \qquad (3)$$

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

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

An increase in σ is identical with an increase in the analyzing window size. It causes an increase in σ_t – and hence there is a deterioration of the analyzed voltage resolution in the domain of time. Simultaneously, this causes an improvement of the frequency resolution. Contrary to the above: deterioration of the frequency resolution (decrease in the analyzing window size) leads to improvement of the time resolution.

This method of analysis of measured signals was applied to detect and characterize the field in soil in outdoor conditions.

Measurement methodology

The general arrangement of the measurement set-up is shown in Figure 1. A voltage between two identical measurement electrodes, placed on the ground surface 1 m apart was registered (e.g. between R_1 and $R_{1'}$). Copper/copper sulphate reference electrodes were used to obtain this measurement. The pairs of electrodes were positioned in different directions: electrodes R_1 and $R_{1'}$ – parallel to the electric field lines, electrodes R_2 and $R_{2'}$ – perpendicular to the electric field lines, and electrodes R_3 and $R_{3'}$ – skew to the electric field lines. The measurements were performed in the electric field generated by controlled sources (generators) as well as in the electric field generated by a tramway line. In the case of the controlled source, the field of defined frequency and energy was generated between two auxiliary electrodes made from stainless steel and placed in soil 20 m apart. The manufacturer of the field were generators were Agilent Ltd

The measurements were carried out with 16 bit measurement National Instruments PCI-6052E card. The sampling frequency was 500 Hz. An analysis of the obtained registers was obtained using the software LabView Joint Time-Frequency Analysis.

Measurement results

Figure 2 shows an example result of the measurement registered in the presence of controlled sinusoidal field of frequency 35 Hz. The generator (output parameters: 8 V/ 3,2 mA) was turned on and off in 10 s cycles. A voltage between pair of electrodes R_1 and $R_{1'}$ was registered. The soil resistivity was equal to 230 Ωm.

Figures 3-5 shows the results of analysis of register obtained for the field, the parameters that were changed at 2 min intervals. The sequence of execution of the experiment was as follows:

- 0 ÷ 2 min: generator turned off;
- 2 ÷ 4 min: constant voltage at the generator output equal to 10 V, DC current;
- 4 ÷ 24 min: gradual decrease in the output DC voltage from 10 V to 0 V (at one V intervals every 2 min);
- 24-26 min: sinusoidal current of frequency 1.3 Hz, voltage at the generator output 7.5 V (rms value); and
- 26-34 min: gradual decrease in the output AC voltage from 7.5 to 0 V (at 1.5 V intervals every 2 min).

The voltage was measured simultaneously for three arrangements of the electrodes, as shown in Figure 1. The soil resistivity was 90 Ωm.

Figure 6 shows a result of time-frequency analysis of the register recorded near the tramway line. The voltage was measured between electrodes placed on the ground surface 1 m apart and 30 m away from the tram rails, in the perpendicular direction. The soil resistivity was 75 Ωm.

Discussion

In Figure 2, the variation of the obtained signal amplitude is unnoticeable independently of the presence of generated field. It is worth mentioning that a course of the obtained register (characterized by certain amplitude of oscillations around a mean value) results from the nature of potential measurements in dry soil in outdoor conditions, which was discussed in earlier publications (Zakowski and Darowicki, 2001, 2003). Thus, the analysis of the register shown in

Figure 1 Schematic layout of a measurement set-up

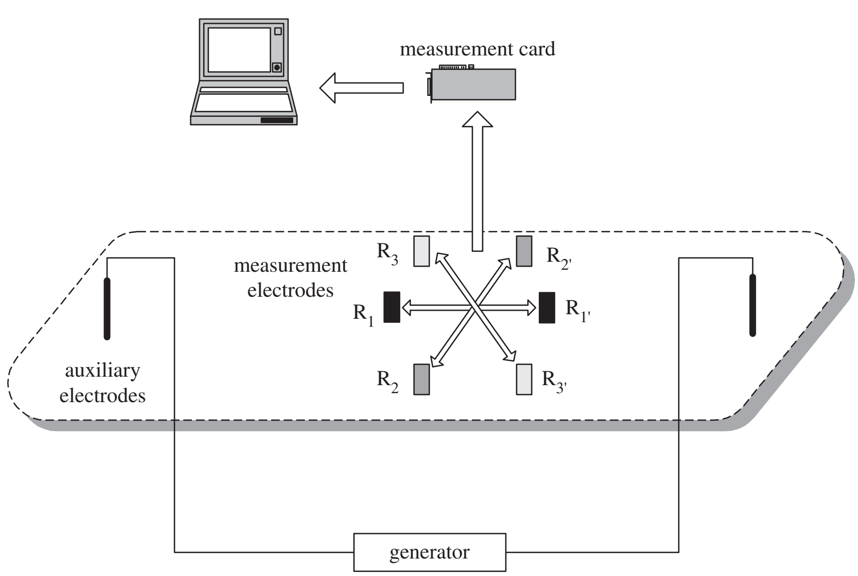


Figure 2 Time register of voltage U between measurement electrodes in the presence of a generated field at 35 Hz, its frequency spectrum (classic FT) and its spectrogram (STFT)

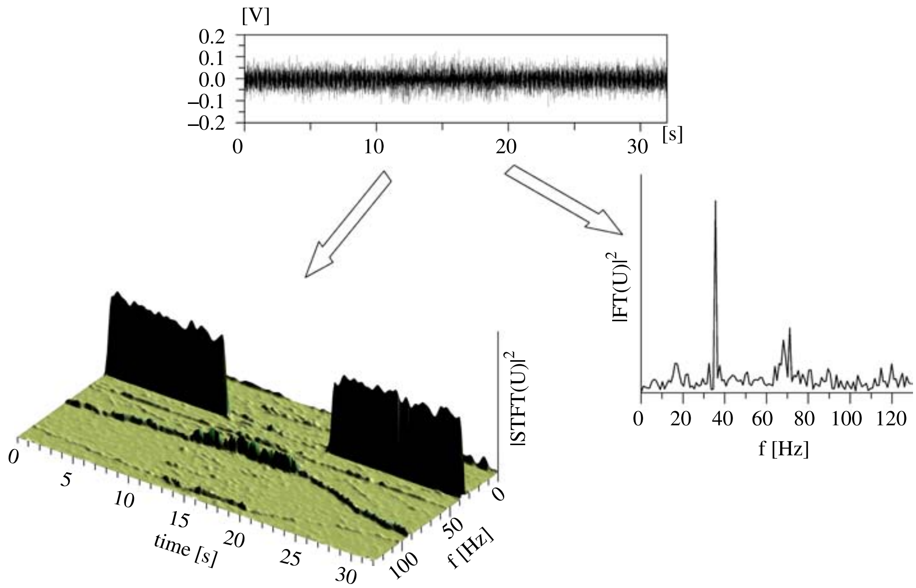


Figure 3 Time register and spectrogram of voltage between measurement electrodes placed in the parallel direction to the electric field lines

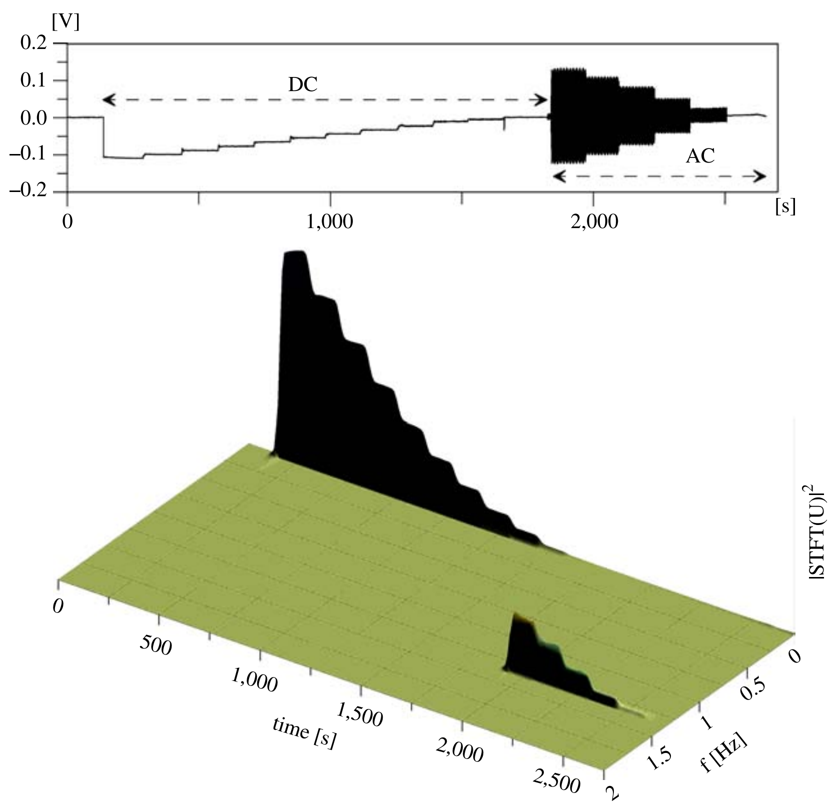


Figure 2 in the time domain does not allow detection of the presence of the field. The result of classical FT analysis indicates the presence of a frequency at 35 Hz in the register. This is the frequency of the generated field, but it is impossible to indicate at which moments and for how long were the periods when the field was generated. The reason is that FT provides a frequency spectrum averaged over the entire period of the registered duration. However, the result of

Figure 4 Time register and spectrogram of voltage between measurement electrodes placed in the skew direction to the electric field lines

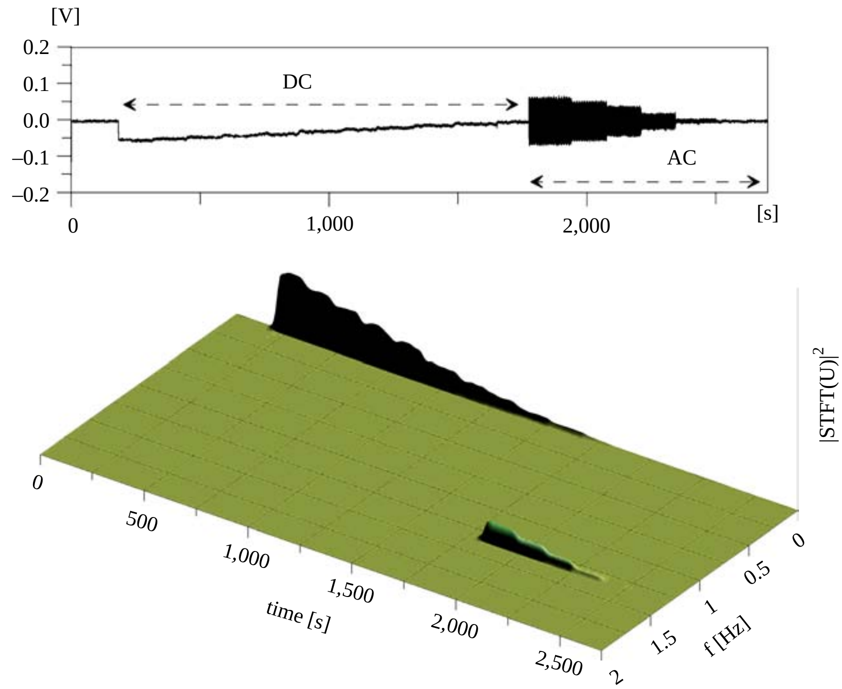
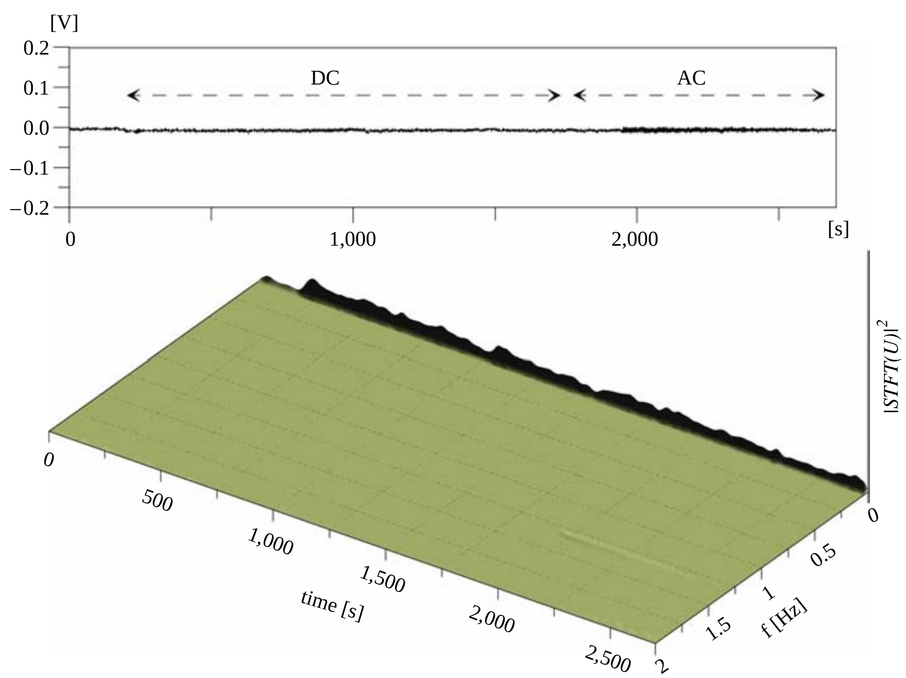


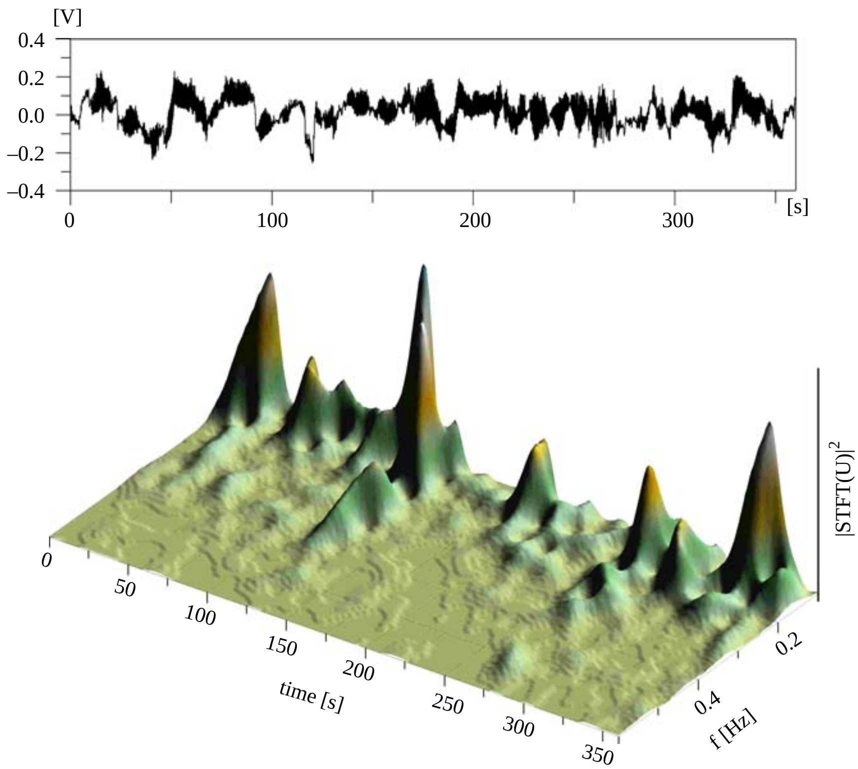
Figure 5 Time register and spectrogram of voltage between measurement electrodes placed in the perpendicular direction to the electric field lines



joint time-frequency analysis using STFT clearly indicates the presence of the 35 Hz frequency in the register. Moreover, the periods when the field was generated and the periods when there was no electric field (i.e. the periods when the field source was turned on and off, respectively) can be distinguished. Thus, the application of short-time FT analysis results in complete time and frequency characterization of the generated field.

A course of the measured signal shown in Figure 3, registered between two electrodes placed parallel to the electric field lines, changed in accordance with the changes of output voltage of the generator. The absolute value of the

Figure 6 Time register and spectrogram of voltage between measurement electrodes placed on ground surface in a vicinity of the tramway line



signal recorded in the presence of the DC field with the maximum generated voltage (generator output 10 V DC) was ca. 100 mV. For skew localization of the electrodes with respect to the field lines this value was about 50 mV (see the time register shown in Figure 4) and for the perpendicular arrangement ca. 0 mV (see the time register shown in Figure 5). Identical dependencies are observed for the remaining output parameters of the generator: the highest absolute value of the signal measured is always for the parallel orientation, the lower one for the skew orientation and an almost zero value for the perpendicular one. This rule holds true also in the presence of a generated sinusoidal field.

Comparison of the energies of the signals measured for all directions, presented on the spectrograms in Figures 3-5, reveals analogous dependencies. For parallel orientation, the energy of the DC signal and of the 1.3 Hz signal is the highest of all the arrangements investigated. A lower value is found for skew orientation and practically zero energy is recorded for the perpendicular orientation. The performed analysis yields the conclusion that comparison of the results obtained for all three directions in field conditions allows determination of the electric field lines and thus localization of the source of the field.

The time register shown in Figure 6 reveals the changes of voltage between the measurement electrodes placed perpendicular to the tram track. They suggest changes of electric field intensity caused by the passing trams. The increases in signal energy are visible on the spectrogram and their localization in the time domain correspond to the time instants of line loading. The spectrogram characterizes the stray currents field, which is connected with changes in load on the tramline. It is evident that the field does not possess deterministic characteristics: the energy of the signal increases during loading of the line, but there are no repeatable frequency characteristics. The obtained result of analysis indicates the random character of the field detected.

This time-frequency method of measurement register analysis can be used to evaluate stray current interference on underground pipelines (Darowicki and Zakowski and Darowicki, 2004, 2005). If spectrograms of rail potential and of pipe-to-soil potential are the same in character, this points to the presence of interference. If the spectrograms are different, it indicates a lack of interference.

Conclusions

The method of detection and analysis of electric fields in soil described in the present paper has many advantages. It reveals the random or deterministic character of the fields detected and enables the user to obtain the complete time-frequency characteristics of such fields. This information is inaccessible using the methods based on signal analysis exclusively in the time domain or from frequency analysis methods utilizing classic FT analysis.

The presented method of analysis is universal – it can be applied in all investigation situations where voltages of arbitrary frequency are registered. Depending upon requirements, a suitable sampling frequency must be selected in order to reflect all of the frequency components of the signal.

The results presented in the paper reveal that the applied method of field detection is very sensitive. It allows detection of fields, the intensity of which may be so small in the area of electrode localization that its presence is invisible in the

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amplitude of potential registers (Note: the registers from the fast digital data loggers and computer measurements cards are always characterized by some oscillations around a mean value when they are acquired in soil).

The analysis method allows localization of the field source via comparison of the spectrograms of measurement registers determined for three directions during field measurements. The energy of the measured signal increases with the tendency for the measurement electrodes to approach parallel orientation with respect to the electric field lines. In the direction perpendicular to a source, the energy of registered signal is close to zero.

The method can be used as a complementary one to existing measurement techniques in soil environments. Knowledge of the joint time-frequency characteristics is especially useful when fluctuations of the measured signal last for longer durations and when they change their characteristics over time. The technique also can be applied in the case of a single, instantaneous change of signal.

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