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Review

Assessment Methods for DC Stray Current Corrosion Hazards in Underground Gas Pipelines: A Review Focused on Rail Traction Systems

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Abstract

Stray currents leaking from electrified DC rail systems cause the greatest corrosion risk to underground metal gas pipelines and can lead to pipeline wall perforation in a very short time. Leakage and gas explosion, and other direct and indirect effects, can even disrupt the stability of the energy system. Maintaining the reliability of gas pipelines, therefore, requires protecting them against corrosion caused by stray currents. It is therefore necessary to conduct field studies to identify sections of gas pipelines at risk and where protective installations should be installed. The paper discusses the most important field methods for assessing the risk of stray currents to gas pipelines: the potential of rail traction relative to ground, electric field gradients in the ground associated with stray current flow, correlation of gas pipeline potential and voltage of pipeline vs. the rail, and time-frequency analysis of the pipeline and rail potentials. A typical application case for each method is indicated, and the advantages and disadvantages of each research technique are identified. The criterion for selecting methods for this review was a short measurement duration (tens of minutes), after which it is possible to determine the level of the hazard to the gas pipeline caused by stray currents in the examined location. This is why these methods have an advantage over other research techniques that require long-term monitoring or exposure of probes or sensors. The review will be useful for cathodic protection personnel involved in the operation of gas pipelines and may be helpful in developing new methods for assessing the impact of stray currents.

Keywords: gas pipelines; stray current; stray current corrosion; stray current hazard; field measurement methods

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1. Introduction

This paper provides a comprehensive review of field methods used to evaluate the corrosion hazard posed by stray DC currents from rail systems to underground gas pipelines. Gas transmission pipelines are one of the key elements of critical infrastructure, ensuring stable supplies of natural gas to industrial, municipal, and individual customers. The importance of gas transmission pipelines is growing in the context of the energy transition, in which natural gas plays the role of a bridge fuel, supporting the process of moving away from high-emission energy sources.

Corrosion of gas pipelines is absolutely critical in terms of the reliability of the energy system. Failures in gas transmission infrastructure can lead to disruptions in the operation

of power, heating, and industrial systems. This requires the use of advanced methods for assessing and maintaining the reliability of gas pipelines, including anticorrosion protection.

The greatest corrosion hazard for underground pipelines is stray currents flowing from electrified DC rail systems: tram, railway, and subway. Therefore, national and international legal and technical requirements for gas networks include mandatory protection of gas pipelines against the harmful effects of stray currents. For example, in Poland, corrosion protection of steel gas pipelines is mandatory and regulated, among others, by the Regulation of the Minister of Economy of 26 April 2013—the use of insulating coatings, cathodic protection, and protection against stray currents is required. Internationally, procedures such as ECDA (External Corrosion Direct Assessment) are used [1]. Its purpose is to detect and assess areas of the pipeline exposed to external corrosion, identify sections with an increased risk of corrosion, e.g., in areas with high soil moisture and those suffering from stray currents, and then plan corrective and preventive measures. Therefore, it is necessary to evaluate the possible corrosion risk of gas pipelines in the analyzed area. The main causes of current leakage are connected with the fact that the rails are not electrically isolated from the ground. Consequently, some return currents (flowing along the rails to the negative pole of the supply substation) flow from the rails to the ground. The magnitude of leakage increases when the longitudinal resistance of the rails increases due to technical faults in the return circuits, for example, damage to the longitudinal connectors between successive rail sections or to the transverse connectors between the left and right rails. Stray currents flow from the ground into the metal walls of gas pipelines because, in practice, pipelines with flawless insulation do not exist, and the number of defects increases over time.

The actual impact of stray currents on a gas pipeline can be examined using coupon corrosion testing [2]. The coupons are buried next to the pipeline and connected to it with an electrical cable, which exposes them to stray currents in the same way as the gas pipeline at the tested location. The risk of electrolytic corrosion is determined on the basis of an analysis of the currents flowing through the coupons, changes in their potentials, and the mass loss of the coupons [3]. Although this method provides reliable test results, it is cumbersome to use as it requires the coupons to be buried and a long exposure time of at least several months.

Therefore, cathodic protection personnel use other methods that allow the risk to gas pipelines to be determined immediately. The results are not the corrosion rate of the structure, but a determination of whether stray currents in the measurement area can cause intense electrolytic corrosion of the gas pipeline at the site of the external insulation defect.

The purpose of this paper is to discuss field research methods employed to assess the corrosion risk of gas pipelines due to the impact of stray currents flowing from DC traction (the review does not apply to AC interference). Identifying areas of gas pipelines at risk of electrolytic corrosion allows appropriate anticorrosion measures to be taken. These measures result in the reliability of gas transmission pipelines and increase energy security and the high level of safety of gas network operation. The presented overview will be useful for cathodic protection personnel involved in the operation of gas pipelines. It may also help develop new field methods for assessing the effects of stray currents. The need to elaborate field techniques arises with the development of technologies for the gas pipelines with a tight coating (like 3LPE: three-layer polyethylene coating), as this affects the flow of stray currents in the gas network through a small number of coating defects (with an area of several mm^2) [4].

2. Corrosive Impact of Stray Currents Leaking from DC Electric Rail Traction Systems on Gas Pipelines

The leakage of stray currents from DC electric traction rails to the ground is widely described in scientific literature, e.g., [5–8]. Their intensity can be estimated based on mathematical models developed and presented in the articles such as [9–12]. From the operational experience of underground pipelines and measurements of the intensity of the current flowing in them, it is known that in the vicinity of tram and railway traction, the instantaneous intensity of stray currents flowing through pipelines with decades-old external insulation can reach up to several dozen amperes [13–16]. In DC traction systems, stray currents are estimated to be about 5% of the return currents [17]. For example, measurements made by Vranešić et al. [18] on the tramway traction in Ostrava (Czech Republic) showed instantaneous return currents of almost 700 A, so the maximum stray current intensity can be estimated at ca. 35 A.

The mechanism of corrosion caused by stray currents on underground metal pipelines and reinforced concrete structures is well described in scientific literature, e.g., [6,19,20]. The flow of current through the metal/electrolyte interface causes polarization of the metal, i.e., a change in its potential. In areas where current flows from the ground to the pipeline (at points where the insulation is defective), cathodic polarization of the pipeline occurs. This results in a lowering of the potential of the pipeline and no risk of corrosion—a reduction reaction takes place on the metal surface. In natural environments, this is the reduction of oxygen dissolved in water ($O_2 + 2H_2O + 4e \rightarrow 4OH^-$). In turn, the current flowing from the pipeline to the ground causes the anodic polarization of the metal, which increases the potential of the pipeline—oxidation and metal dissolution reactions occur ($Fe \rightarrow Fe^{2+} + 2e$).

Metal loss can be calculated using Faraday's Law [21]; e.g., a direct current with an intensity of 1 A dissolves approximately 9.6 kg of steel per year. So, electrolytic corrosion caused by stray currents can be very intense, even several mm/year. If the surface area where the current flows from the pipeline into the ground is small (a few cm^2), then the density of the current dissolving the metal is very high, and perforation of the pipeline wall may occur after only a few months, even at a distance of several hundred meters from the tram traction [22]. Examples of electrolytic corrosion of underground pipelines are shown in the photos in Figure 1. The corrosion defects presented occurred on a DN300 (diameter nominal 300 mm) medium-pressure gas pipeline with bituminous insulation, running near the tram traction.

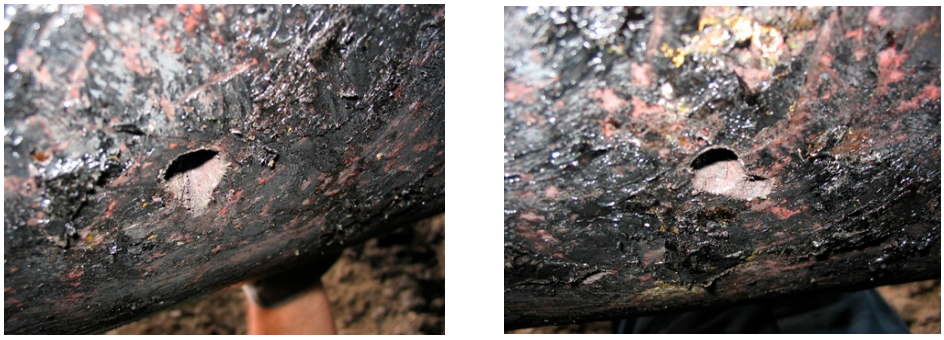


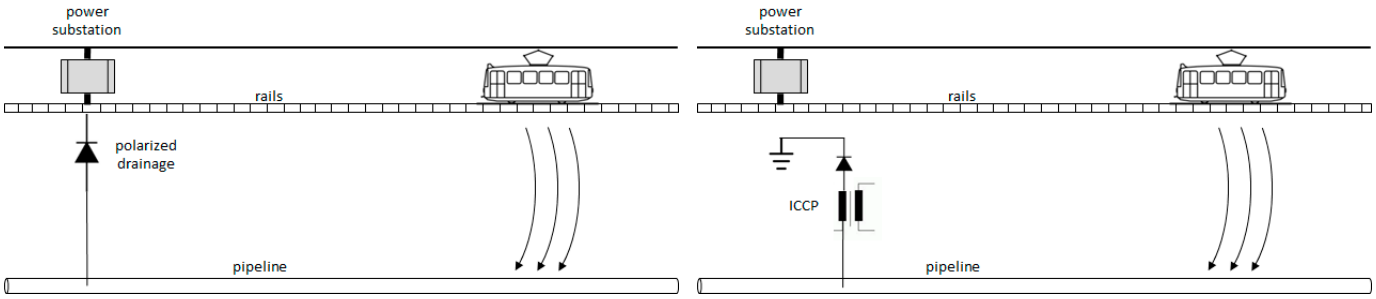
Figure 1. Examples of corrosion damage of pipelines caused by stray currents (from the authors' photographic archives).

The leakage of stray currents from the rails can be reduced by rail fastening systems and increasing rail-to-ground resistance [23–25]. This is regulated by guidelines and standards that are applied at the design stage of new traction lines [26,27]. It is also possible

to limit stray currents flowing through the ground to pipelines by using a stray current collection system [25,28]. This is a metal mesh installed under the track that traps stray currents and directs them to the return point of the power substation (negative pole of the DC substation) [29].

However, no measures can eliminate stray currents completely, as evidenced by numerous scientific papers presenting the corrosion hazard to underground metal and reinforced concrete structures located in the vicinity of electric traction systems (e.g., [30–34]). This is also demonstrated by the articles devoted to calculating stray currents depending on the through-type structure characteristics of the return current system, traction power supply system, multiple trains running, rail resistance to earth, ground resistivity, and other environmental factors [35,36].

It is therefore necessary to protect gas pipelines against stray currents [4] by eliminating the phenomenon of current leakage from the pipeline directly through the metal/electrolyte interface, which causes metal dissolution. Several electrochemical protection methods are used for this purpose. The main ones are shown schematically in Figure 2 [37]. The basic method is the use of polarized electrical drainage. This involves connecting the gas pipeline to the rail with an electrical cable via a diode, which allows stray current to flow through the cable from the pipeline to the rail (instead of from the pipeline to the ground), as shown in Figure 2a. The use of impressed current cathodic protection (ICCP) is shown schematically in Figure 2b. The current from the anode system polarizing the gas pipeline has the opposite direction to the stray current flowing from the gas pipeline to the ground and prevents the corrosive dissolution of the metal. The use of a grounding electrode for the gas pipeline prevents stray currents from flowing from the gas pipeline into the ground, but instead allows them to flow from the grounding electrode connected to the gas pipeline. In each of these methods, the phenomenon of stray currents flowing from the gas pipeline into the ground directly through the metal/electrolyte interface, causing metal dissolution, is eliminated [38,39].



(**a**) (**b**)

Figure 2. Reducing the impact of stray currents by implementing: (**a**) polarized electric drainage, (**b**) impressed current cathodic protection. (prepared based on the original figure from Ref. [37]).

3. Methods for Testing Gas Pipelines for Electrolytic Corrosion

In the practical operation of gas pipelines, there is often a need to immediately determine the risk of stray currents of traction origin to the pipeline. For this purpose, various testing methods based on the analysis of random signals are used. Since many electric locomotives move on the traction section powered by the traction substation, each with an individual instantaneous traction load, the current load of the traction substation changes randomly, resulting in random changes in the potential of the rails relative to ground [40–42]. Stray currents, as part of traction return currents, are therefore also random in nature [43,44]. Their instantaneous intensity and flow direction change randomly and dynamically [45,46]. Since the current polarizing gas pipelines (i.e., stray current) is random

in nature, the polarization (potential change) caused by this current is also random. The result is dynamic, random changes in the potential of the gas pipeline, both in the anodic and cathodic directions (depending on the instantaneous value and direction of stray currents), and the duration of the periodic anodic and cathodic polarization is different, and has different proportions of anodic polarization periods during the day. Therefore, studying the impact of dynamic stray currents on underground structures is not a simple matter, unlike the analysis of static stray currents originating from cathodic protection systems of other foreign underground structures. The analysis of the impact of dynamic stray currents should be carried out by qualified personnel with at least a level 4 competence (on a 5-level scale) according to [47].

The purpose of field studies of corrosion hazards caused by stray currents is to locate sections of the gas pipeline where stray currents flow from the pipeline into the ground and cause electrolytic corrosion of the pipeline, and to indicate the location on the pipeline where stray current protection should be applied. In practice, this means that anodic zones (sections) on the gas pipeline and locations where the proportion of anodic polarization periods of the gas pipeline is highest are located.

3.1. Rails Potential Testing Method

This is the simplest method for determining the zone of probable stray current impact on the gas pipeline in the area of the field measurement site. It does not require connecting measuring instruments (recorders) to the pipeline, but only to the electric traction rails. In this method, the potential of the rails relative to a portable reference electrode (e.g., $Cu/CuSO_4$) is recorded, as schematically shown in Figure 3 [48].

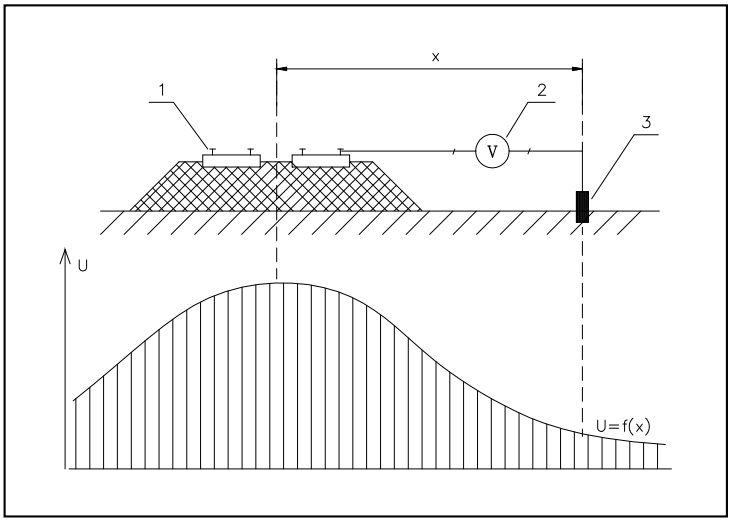


Figure 3. Scheme of potential measurement of electric traction rails: 1—rail, 2—voltage recorder, 3—reference electrode, and example of instantaneous electric field distribution around the track (by Zakowski and Darowicki [48]).

Based on the analysis of the rail potential record relative to the ground, conclusions can be drawn about the flow of stray currents in the area [49]. In turn, based on the flow of stray currents, it is possible to conclude whether there is an anodic zone on the gas pipeline in the measurement area and a risk of stray currents [50], as illustrated in Figure 4 [51]. The principle of analysis is as follows: positive rail potential values indicate that current is flowing from the rails to the ground (anodic polarization of the rails). Since stray current flows from the rails to the ground, it means that it flows into the underground pipeline in this area, polarizing it cathodically, which means that there is no risk of electrolytic

corrosion. The corrosion hazard will occur in another section of the gas pipeline, where stray currents will flow from it into the ground.

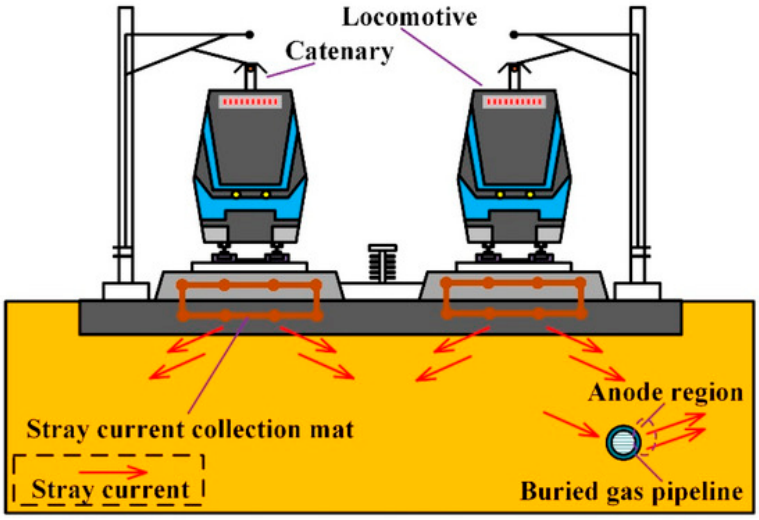


Figure 4. Stray current in the rail system (by Wang et al. [51]).

Similarly, negative rail potential values indicate that stray current flows from the ground into the rails (cathodic polarization of the rails), and therefore, this current previously flows from the underground pipelines in this area, causing their electrolytic corrosion. There is therefore a correlation: the anodic zone of the rails indicates the cathodic zone of the gas pipeline in this area (no risk of stray currents), while the cathodic zone of the rails indicates the anodic zone on the gas pipeline in this area (risk of electrolytic corrosion of the gas pipeline).

An example of a tram rail potential record is shown in Figure 5. At the measurement site, there is an anodic zone of the rails, as there is a predominance of periods of anodic polarization of the rails (predominance of positive instantaneous values of the rail potential). This means a cathodic zone for underground pipelines in this area, where stray currents flow into underground metal structures, and therefore, there is no risk of stray current corrosion in this area.

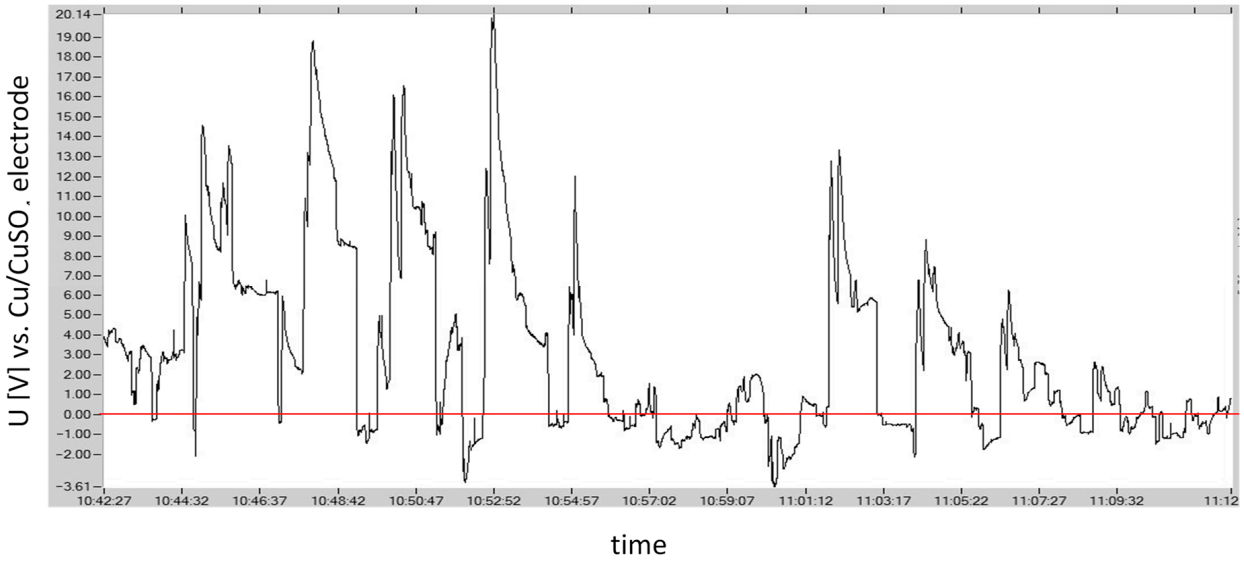


Figure 5. Example of tram track potential record.

Method summary	
measured quantity:	potential of railway or tram rails
measuring equipment:	voltage recorder, $Cu/CuSO_4$ reference electrode, cable connection to the rail
what conclusion can be drawn:	determining whether there is an anodic or cathodic zone on the gas pipeline near the rails based on the rails' potential

3.2. Method for Determining Electric Field Gradients on the Ground Surface

This method involves measuring the electric field gradient associated with the flow of stray currents through the ground. The gradient is measured at the gas pipeline between two measuring electrodes of the same type, e.g., copper/copper sulfate electrodes commonly used by cathodic protection personnel. The field gradient is measured perpendicularly to the gas pipeline by placing one electrode above the gas pipeline and the other at a distance of approximately 10 m from the pipeline, as shown in Figure 6.

In these tests, it is not the gradient values that are analyzed, but their sign, as it is related to the direction of current flow through the ground. The current flows towards the point with lower potential [52,53]. For example, at the location on the gas pipeline in Figure 6b, a negative average gradient value was recorded. In the shown configuration of the measuring system, this indicates that stray current flows from the gas pipeline into the ground, because at the location of the electrode away from the gas pipeline, the ground potential is lower than the ground potential above the gas pipeline. Therefore, there is a risk of electrolytic corrosion of the gas pipeline at this location. In contrast, in the example shown in Figure 6c, the average value of the electric field gradient is positive, which indicates the flow of stray current from the ground to the gas pipeline. At this point, it is therefore not at risk of harmful stray currents. By measuring the gradient at successive points along the gas pipeline route, it is possible to determine the points of entry and exit of stray currents from the gas pipeline, and thus to identify its cathodic and anodic zones.

Similarly, the electric field gradient in the ground near tram or railway traction can be analyzed. Measurement of the potential gradient of soil can determine the direction and magnitude of stray current [31,54,55], and thus also determine the type of impact of currents on adjacent pipelines, whether there is an anodic zone of interaction or a cathodic zone, similarly to the analysis of traction rail potential relative to the ground (Section 3.1).

3.3. Correlation Method 'E = f(U)' for Testing the Impact of Stray Currents on Gas Pipelines

This method examines the correlation between changes in two physical and electrochemical quantities related to the impact of stray currents from DC electric traction systems. One of them is a physical quantity related to the cause of the impact of stray currents on gas pipelines—it is the voltage U of the gas pipeline relative to tram or railway traction rails, which is directly proportional to the intensity of stray currents flowing through the gas pipeline. The second quantity is the electrochemical effect of stray currents, i.e., changes in the potential E of the gas pipeline due to induced cathodic and anodic polarization. Next, the relationship $E = f(U)$ is analyzed. The measurement system scheme is shown in Figure 7. Measurements are taken during periods of maximum impact, i.e., during the morning and afternoon rush hours. The measurement duration should be no less than 20 min for tram traction and 30 min for railway traction. The sampling frequency of the measured signals should be at least 4 readings per second [56]. In special cases, 24-h measurements are carried out [33].

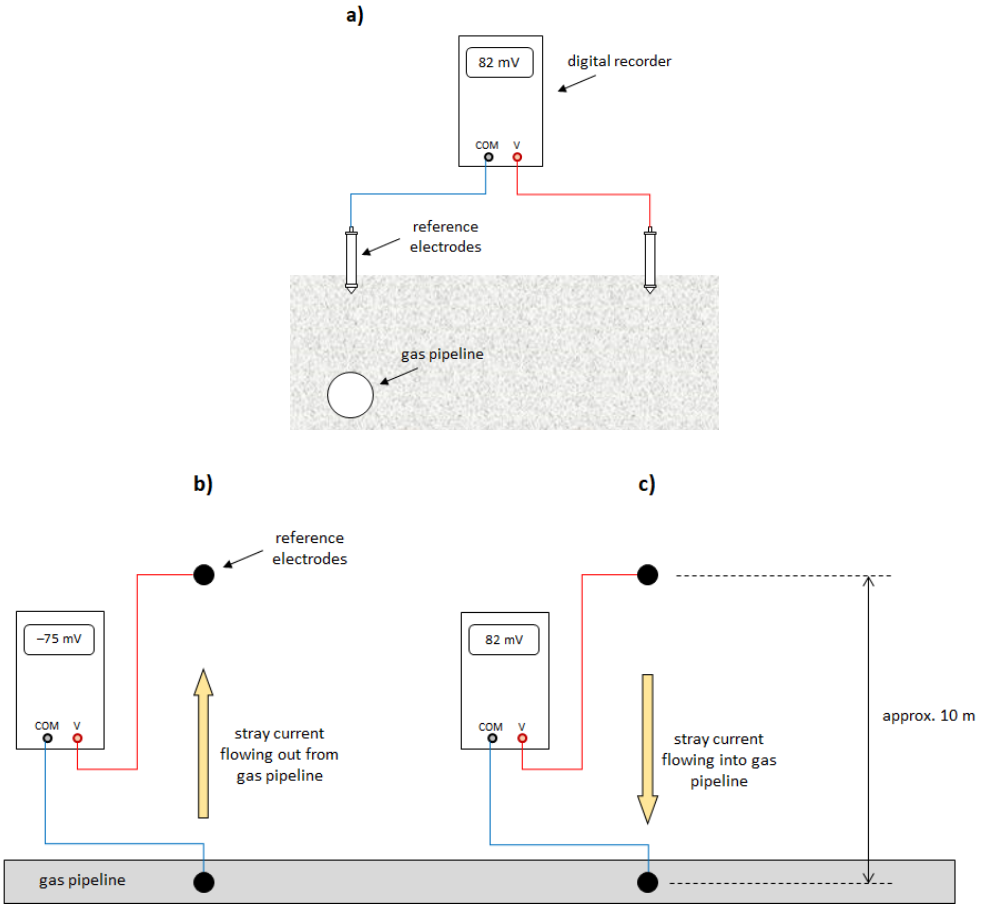


Figure 6. Scheme of electric field gradient measurement at a gas pipeline: (**a**) side view, (**b**,**c**) top view. Location of: (**b**) point where current flows out pipeline, (**c**) point where current flows into the pipeline.

Method summary	
measured quantity:	potential gradient on the ground surface
measuring equipment:	voltage recorder, two $Cu/CuSO_4$ reference electrodes
what conclusion can be drawn:	determining the locations where stray currents flow from the pipeline into the ground (anodic zones on the pipeline) based on the potential gradient direction

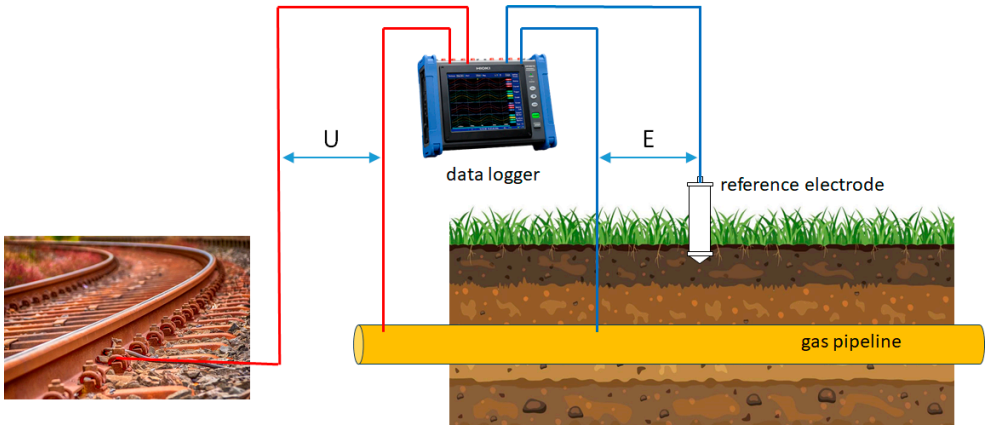


Figure 7. Scheme of the measurement system in the stray current correlation method.

The risk of corrosion of a gas pipeline due to dynamic stray currents occurs when periods of anodic polarization of the gas pipeline prevail [4,56,57]. If periods of cathodic polarization of the gas pipeline prevail, there is no risk [58,59]. The dynamically changing potential values recorded must therefore be analyzed and compared with the 'base' potential value of the gas pipeline, i.e., the potential of the gas pipeline in the absence of stray currents. This value is referred to as the stationary potential E_S. One way to determine the E_S potential is to measure its value at night when there is no electric locomotive traffic on the tram (or railway) traction. However, this is not necessary in the correlation method, as the E_S value is determined by linear regression from the relationship $E = f(U)$ and corresponds to the potential value calculated for zero voltage. At zero voltage, the stray current intensity is also zero, so this is the moment when there is no stray current influence. An example of a 24-h record of the gas pipeline potential in the zone of influence of dynamic stray currents and a correlation graph $E = f(U)$ are shown in Figure 8. The E_S value calculated by the linear regression method coincides with the average value of the gas pipeline potential during the night, when there is no electric locomotive traffic on the traction.

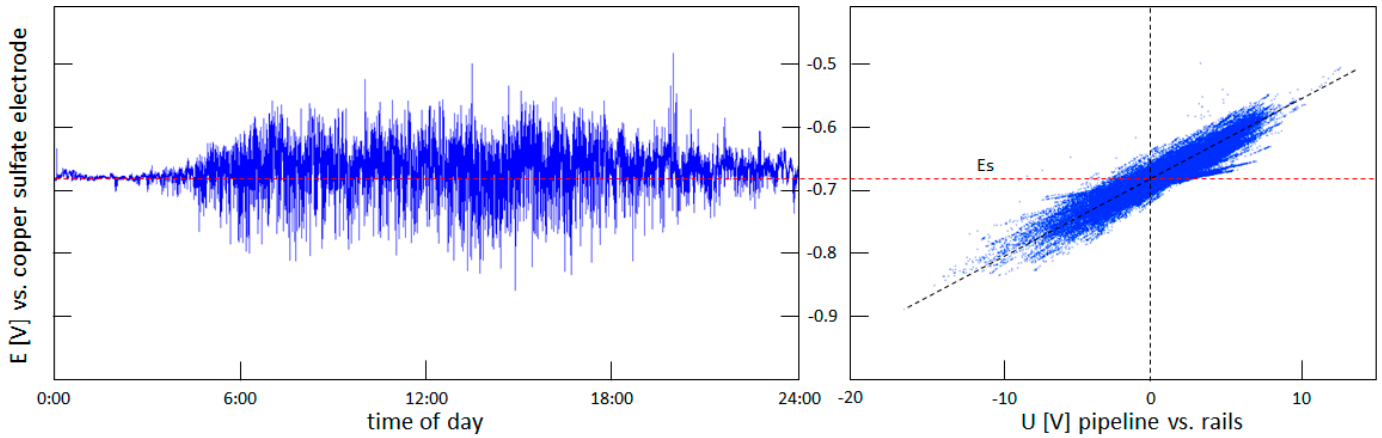


Figure 8. Example of a 24-h record of gas pipeline potential E and correlation graph $E = f(U)$.

The test methodology is as follows: the instantaneous values of voltage U_i and potential E_i are recorded synchronously, then the stationary potential of the gas pipeline E_S is determined according to Formula (1), and then the asymmetry coefficient γ of the gas pipeline potential changes relative to the E_S value is calculated according to Formula (2). The asymmetry coefficient determines the total contribution of anodic polarization periods of the gas pipeline during the measurements. If its value is greater than 50%, the gas pipeline is at risk of electrolytic corrosion caused by stray currents [51] and requires electrochemical protection.

$$E_S = \frac{\sum U_i^2 \cdot \sum E_i - \sum U_i \cdot \sum (U_i \cdot E_i)}{N \cdot \sum U_i^2 - (\sum U_i)^2} \quad (1)$$

where E_S [V]—stationary potential, U_i [V]—instantaneous value of voltage of pipeline relative to rails of the electric traction, E_i [V]—instantaneous value of potential of gas pipeline, N—number of measured signal samples.

$$\gamma = \frac{T_A}{T} = P[E > E_S] = \frac{N_{E_i > E_S}}{N} \quad (2)$$

where T_A [min]—total anodic polarization time of the pipeline, T [min]—duration of the measurement, P—probability of an event that the potential E assumes a more positive

value than the stationary potential E_S, $N_{Ei>Es}$—the number of signal samples, for which the instantaneous value of potential E_i is more positive than E_S, N—the number of all readings.

The measurement should be performed during peak traffic on the railway or tramway, i.e., during the morning or afternoon rush hour. The length of the rail potential measurement should be equal to the time it takes for an electric locomotive to travel through a section of traction powered by a single substation. In the case of a tram network, the length of a section powered by a single substation is usually 3–4 km. Reducing the distance between electrical substations, i.e., the use of several return cables between the rail and electrical substation, is also recommended as a measure for reducing the quantity of stray currents [60]. It takes a tram about 20 min to travel through such a section (travel, stops, intersections, etc.). The distance between railway substations is usually about 20 km, and it takes a train about 30 min to travel this section. Therefore, it was assumed that the measurement should last 20 or 30 min, respectively.

In practice, stray current impact studies are performed at several measurement points along the gas pipeline route. The area most at risk of electrolytic corrosion is where the asymmetry coefficient γ is the highest. This is where the electrochemical protection system for the gas pipeline is designed and installed.

Examples of $E = f(U)$ correlation graphs are shown in Figure 9. The graph in Figure 9a illustrates the high risk of stray currents to the gas pipeline, as there is a very large predominance of periods of anodic polarization of the gas pipeline (potential values higher than the stationary potential E_S marked with a red dotted line). In turn, the graph in Figure 9b illustrates the absence of a threat to the gas pipeline at the measurement point—there is a predominance of cathodic polarization periods of the gas pipeline (potential values lower than E_S prevail).

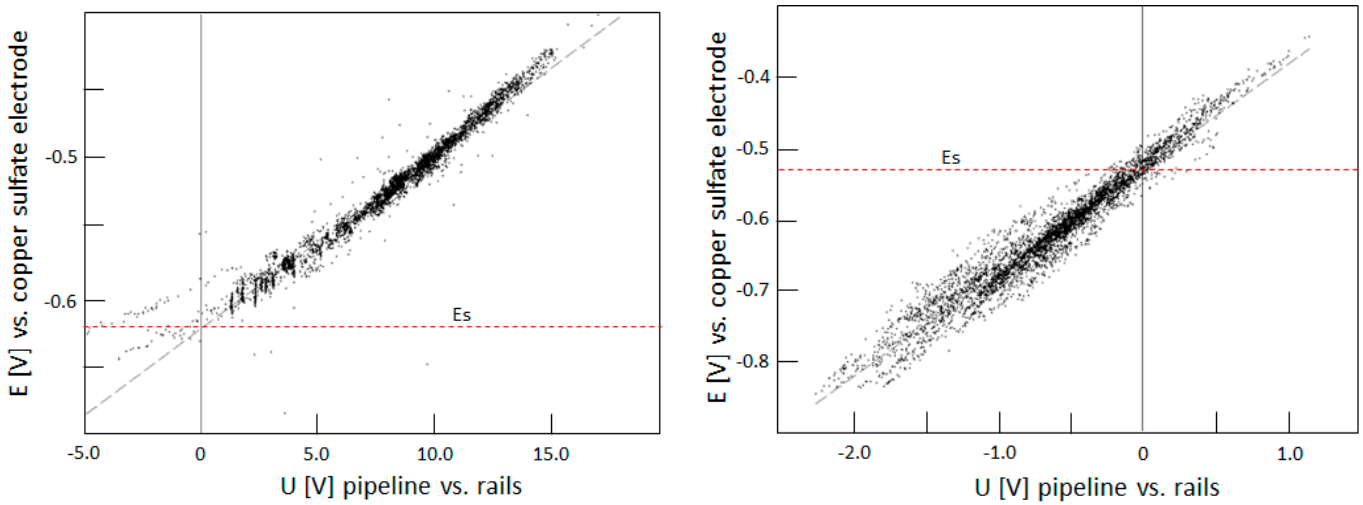
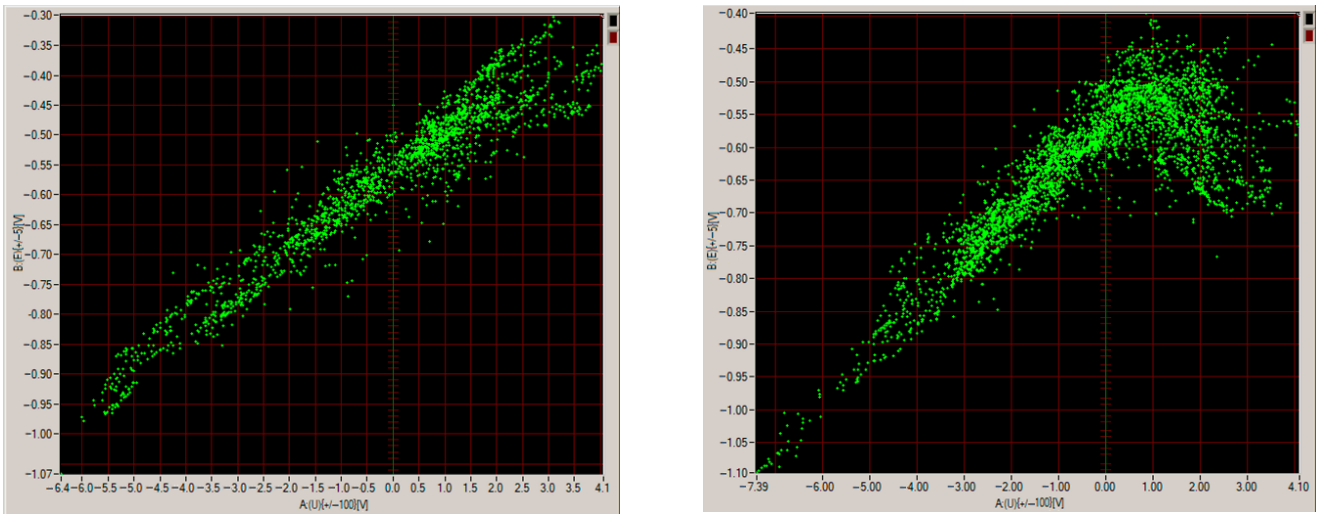


Figure 9. Examples of correlation charts $E = f(U)$: (**a**) very high risk of stray currents to the gas pipeline, (**b**) no risk of stray currents.

The correlation method allows the assessment of the effectiveness of stray current protection systems, the most basic of which is polarized electrical drainage. The graph in Figure 10a was obtained under conditions without the protection of a gas pipeline, while the graph in Figure 10b was obtained after switching on polarized electrical drainage. In the positive voltage range, after exceeding the forward voltage of the silicon diode (approx. 0.7 V), a typical bend in the correlation graph towards lower potential values is visible. This indicates the correct operation of the diode and the correct operation of the

polarized electric drainage, which reduces the risk of corrosion of the gas pipeline caused by stray currents.



(**a**) (**b**)

Figure 10. Typical correlation graphs $E = f(U)$ obtained under the following conditions: (**a**) without protection, (**b**) with polarized electrical drainage in operation.

Figure 11 illustrates the effect of switching on the cathodic protection system of a gas pipeline affected by stray currents. Graph (a) was obtained under conditions without electrochemical protection, while graph (b) was obtained after switching on the cathodic protection installation, resulting in a shift in the graph towards lower potential values due to cathodic polarization.

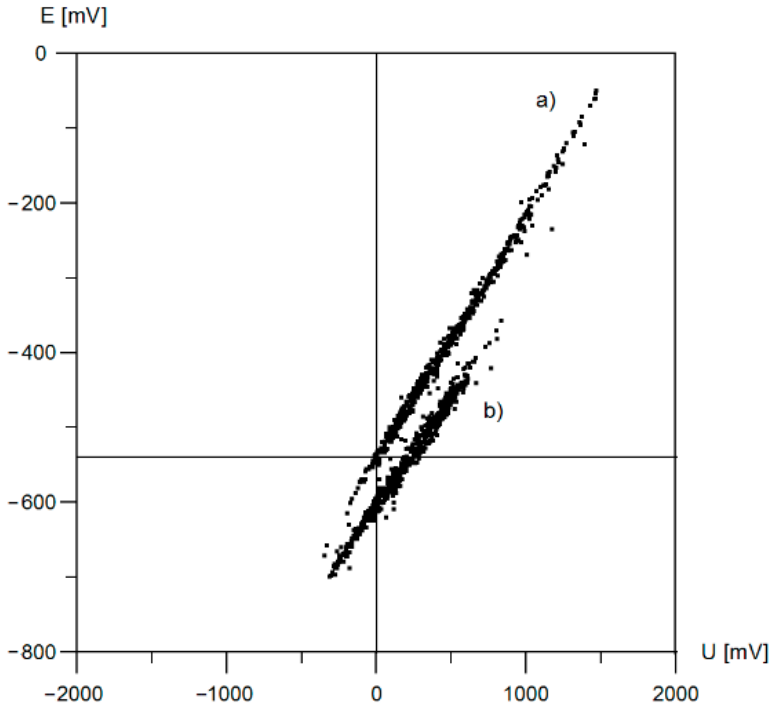


Figure 11. Correlation graph $E = f(U)$ obtained under the following conditions: (**a**) without protection against stray current, (**b**) after switching on the cathodic protection station polarizing the gas pipeline (ICCP).

Method summary	
measured quantity:	simultaneous measurement: potential of the gas pipeline and voltage of the gas pipeline relative to the rails
measuring equipment:	two-channel voltage recorder, $Cu/CuSO_4$ reference electrode, cable connection to the gas pipeline, cable connection to the rail
what conclusion can be drawn:	- assessment of the magnitude of the stray current hazard based on the value of the gas pipeline potential asymmetry coefficient at the measurement site, - assessment of the effectiveness of the gas pipeline's electrochemical protection system based on the shape of the correlation graph E = f(U) and the value of the asymmetry coefficient

3.4. Correlation Method 'U = f(E)' for Testing the Impact of Stray Currents on Gas Pipelines

A variation of the correlation method discussed in the previous section is the method presented by Peabody [19]. The same signals are recorded, i.e., the potential of the gas pipeline E and its voltage relative to the traction rails U, but the inverse correlation relationship is analyzed: $U = f(E)$. Conclusions about the intensity of the impact of stray currents on the gas pipeline are drawn based on the slope of the correlation spectrum, i.e., the angle of slope of the linear regression line—the so-called beta coefficient. The slope of the regression line is a measure of exposure: the greater the slope, the greater the exposure. Measurements are taken along the route of the gas pipeline running near the electric rail traction. The result of the research is the so-called 'beta profile' along the gas pipeline [20]. The point at which the beta coefficient is the highest is considered to be the place of greatest harmful impact of stray currents. The idea of taking measurements together with the beta profile is illustrated in Figure 12.

In the case of gas pipelines with damaged coatings with poor barrier properties and multiple defects (e.g., pipelines over 20 years old with bituminous insulation), measurements taken according to the scheme in Figure 12 will accurately indicate the location of maximum exposure. In the case of pipelines with a coating with high barrier properties (e.g., new gas pipelines with triple LPE insulation), the point of maximum exposure may be located at some distance from the designated location. This may happen when the coating is defect-free here, but there are defects in other distant locations through which stray currents flow from the pipeline into the ground.

The $U = f(E)$ method is also sensitive to changes in soil resistivity along the tested section of the gas pipeline. This affects the measured potential of the pipeline, as it includes an IR component (voltage drop across the resistance between the reference electrode and the pipeline). The value of the IR component increases with increasing soil resistivity. Local soil properties, therefore, affect the slope of the correlation, which can lead to an incorrect determination of the location of the expected greatest impact of stray currents.

In this respect, the correlation method $E = f(U)$ has an advantage, in which the risk criterion refers to the time domain (total length of anodic polarization periods of the gas pipeline) rather than to the potential value. Therefore, in the previous method, changes in soil resistance do not affect the final conclusions regarding the magnitude of the risk of electrolytic corrosion.

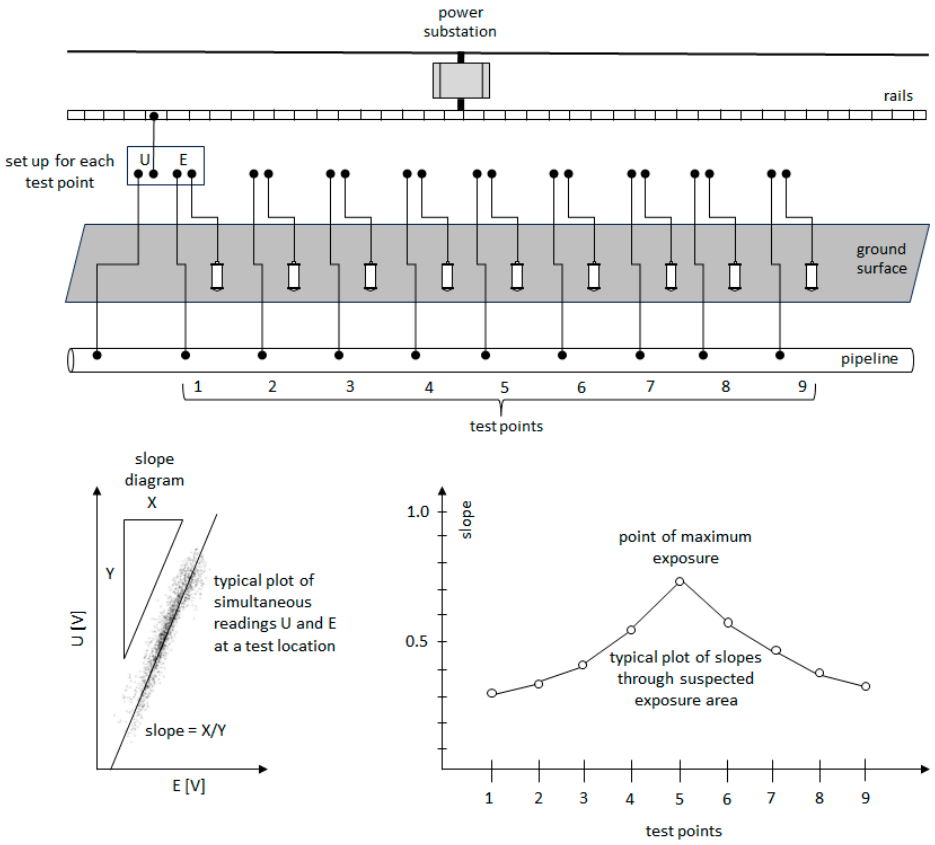


Figure 12. Determination of the point of maximum stray current exposure (prepared based on the original figure from Ref. [19]).

Method summary	
measured quantity:	simultaneous measurement: voltage of the gas pipeline relative to the rails and potential of the gas pipeline
measuring equipment:	two-channel voltage recorder, $Cu/CuSO_4$ reference electrode, cable connection to the gas pipeline, cable connection to the rail
what conclusion can be drawn:	intensity of the impact of stray currents on the gas pipeline based on the slope of the correlation graph U = f(E)

3.5. Time-Frequency Detection Method of Stray Current Interference on Gas Pipeline

This method is based on comparing changes in power density over time between two recorded signals: the gas pipeline potential and the tram (or railway) rail potential, i.e., the structure subject to interference and the source of interference, respectively. Synchronous records of both potentials are subjected to time-frequency analysis using the short-time Fourier transform (STFT). The obtained spectrograms are compared with each other. If the spectrograms match, this indicates the influence of stray currents on the gas pipeline [61–63].

The STFT of the signal $u(\tau)$ is described by the relationship given in Formula (3) [64].

$$STFT\{u(\tau)\} = \int u(\tau) \cdot g(\tau - t) \cdot e^{-j2\pi f \tau} d\tau \quad (3)$$

where τ—time, g—window function, t—window localization time, f—signal frequency.

The STFT differs from the classical Fourier transform FT described by Formula (4):

$$FT\{u(t)\} = \int u(t) \cdot e^{-j2\pi ft} dt \tag{4}$$

The difference lies in the use of the analyzing window function [65] that cuts out a fragment of the signal for analysis. Therefore, not the entire register is analyzed (Fourier transform), but only the part 'cut out' by the analyzing window (short-time Fourier transform).

In practical measurements, various analyzing windows are employed [65], including rectangular, Hamming, Hanning, and Blackman ones. However, the Gauss window g(t) is most often utilized, given by Formula (5).

$$g(t) = \frac{1}{(\pi\sigma^2)^{1/4}} exp\left(-\frac{t^2}{2\sigma^2}\right) \tag{5}$$

where σ is a parameter characterizing the window width.

The window located at time t cuts out a fragment of the signal (beyond the window frame, the analyzed signal is equal to zero). Next, this fragment is subjected to a classic Fourier transform, and the value $|\mathrm{STFT}\{u(t)\}|^2$ is determined, which is a measure of the energy of the signal components at specific frequencies at a specific moment in time (spectral power density of the analyzed signal). In the next step, the window is moved to the next moment in time. A new portion of the analyzed signal is cut out, for which the spectral power density is determined. By repeating the process of moving the window on the time scale and cutting out subsequent portions of the signal, information about changes in spectral power density as a function of time is obtained. The result of the analysis of the entire measurement record is a spectrogram, which is defined by Formula (6) [66].

$$SPEC_x(t, f; g) = |STFT_x(t, f; g)|^2 = \left| \int x(\tau) \cdot g(\tau - t) \cdot e^{-j2\pi f\tau} d\tau \right|^2 \tag{6}$$

A spectrogram is a measure of the energy of signal components at specific frequencies at a specific point in time. The result of the analysis of the entire measurement record is the distribution of the spectral power density of the signal components in the time domain and in the frequency domain, represented as normalized values in the x-y (time-frequency) coordinate grid.

By using the STFT transformation determined in the time domain, the analysis is transferred to the total time and frequency domain. The time resolution and frequency resolution of this analysis depend on the size of the window being cut, i.e., on the parameter σ [67].

The time resolution σ_t is described by Formula (7):

$$\sigma_t^2 = \frac{\int t^2 \cdot |g(t)|^2 \, dt}{\int |g(t)|^2 dt} = \frac{\sigma^2}{2} \tag{7}$$

The frequency resolution σ_ω is described by Equation (8):

$$\sigma_\omega^2 = \frac{\int \omega^2 \cdot |g(\omega)| \, d\omega}{\int |g(\omega)| d\omega} = \frac{1}{2\sigma^2} \tag{8}$$

where $\omega = 2\pi f$.

Frequency and time resolution are related to each other by the uncertainty principle (9):

$$\sigma_t^2 \cdot \sigma_\omega^2 \geq \frac{\sigma^2}{2} \cdot \frac{1}{2\sigma^2} \geq \frac{1}{4} \tag{9}$$

So, increasing the value of σ is equivalent to increasing the size of the analyzing window. This results in a deterioration of time resolution, while frequency resolution increases. Conversely, a deterioration in frequency resolution (reducing the size of the analyzing window) leads to an improvement in time resolution.

In this method, the simultaneously recorded potentials of the gas pipeline and rails should be sampled at an appropriate frequency to obtain data on the power of individual frequency components that make up the analyzed signal. In the case of rail electric traction, the frequency of individual components of the rail potential is usually below 1 Hz and does not exceed 2 Hz [61,68–70], so the minimum sampling frequency should be 4 Hz. In accepted practice, the potential value is read 10 times per second.

An example of time-frequency analysis is shown in Figures 13 and 14 [71], for the potential of tram rails and the potential of a gas pipeline vs. $Cu/CuSO_4$ reference electrode, respectively. Analysis was performed with LabVIEW 7.1, Joint Time Frequency Analysis software package. A 30-min fragment has been presented of a potential time register and a corresponding STFT spectrogram—they are spectral line compositions of a determined frequency structure. The square of the STFT module yields the spectrogram, which is obtained in the time and frequency domains. Accordingly, it provides a measure of energy leakage from the tram traction. Appropriate time σ_t and frequency σ_ω resolutions were acquired via selection of the analyzing window's length according to the uncertainty rule provided by the Formula (9).

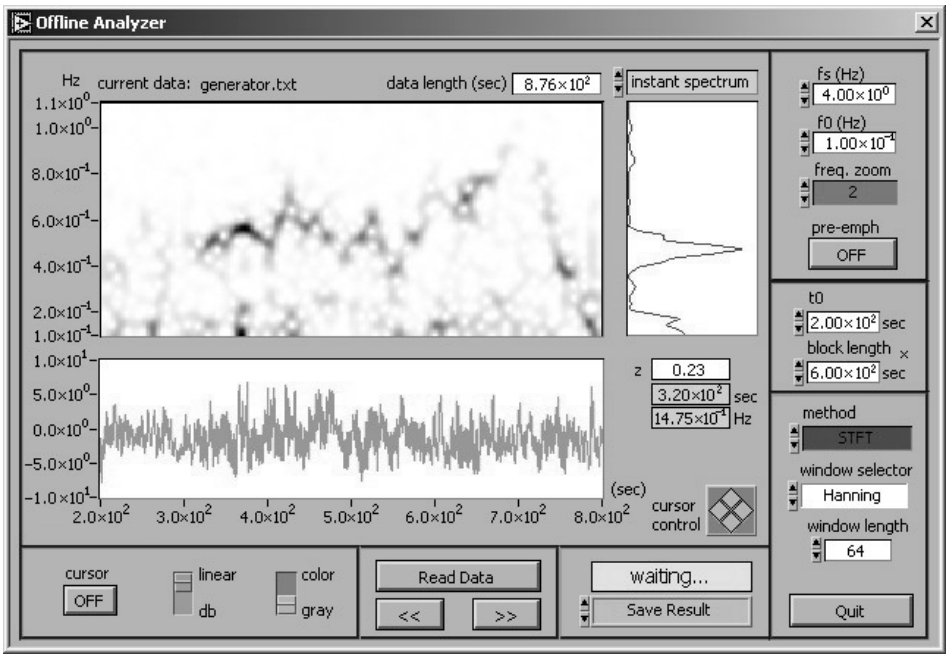


Figure 13. Potential of tram rails versus $Cu/CuSO_4$ reference electrode: fragment of time register (below) and STFT spectrogram (above) (by Zakowski and Darowicki [71]).

In Figures 13 and 14, both potential spectra have a similar form. The signal with the highest energy is recorded for the lowest frequencies, near 0.1 Hz. In the entire time domain, there are small changes in the signal's energy for these very low frequencies. It is also evident that the signal's energy takes a minimum at certain time instants beyond 0.2 Hz. At other moments signal's energy rises in the entire frequency domain (up to 1 Hz range). The shape of the spectrograms (Figures 13 and 14) correlates closely with tram traffic. Signal's energy is minimum for a no-traffic situation. The energy increases at the passing of the tram.

Accordingly, the presence of spectral lines in the time domain strictly agrees with the times of tram passing. The occurrence of frequency peaks on the spectrogram is a characteristic feature associated with the passing of a tram. The time and frequency location of spectral lines on both spectrograms is unequivocal proof that the stray current generated by passing trams affects the state of the investigated pipeline.

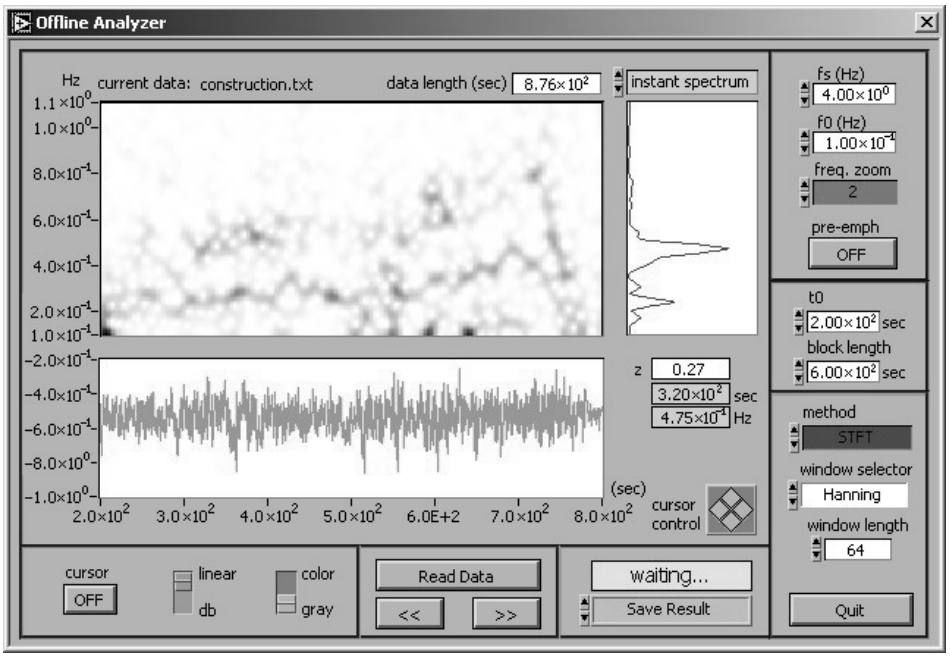


Figure 14. Potential of gas pipeline versus $Cu/CuSO_4$ reference electrode: fragment of time register (below) and STFT spectrogram (above) (by Zakowski and Darowicki [71]).

Dong et al. [69] show an example of the analysis of recorded signals using continuous wavelet transform (CWT). CWT transforms signals from the time domain to the frequency domain and allows simultaneous analysis of the signal in both domains. The pipeline potential and the leakage current from the metro station were analyzed. The synchronous changes and similarities between the spectrum of leakage current of the metro station and the spectrum of pipeline potential indicate that the pipeline is subject to stray current interference.

Method summary	
measured quantity:	simultaneous measurement: potential of gas pipeline and potential of rails
measuring equipment:	two-channel voltage recorder, two $Cu/CuSO_4$ reference electrodes, cable connection to the gas pipeline, cable connection to the rail
what conclusion can be drawn:	whether rail traction affects the gas pipeline, or there is no impact, based on a comparison of the energy spectra of both measured signals in the joint time and frequency domain

4. Discussion

The methods of assessing the corrosion risk of gas pipelines caused by stray currents discussed in this review and used in practice make it possible to identify which sections of gas pipelines are at risk of electrolytic corrosion and require the application of corrosion protection. However, each method has certain limitations:

Methods based on measurements of rail potential, or electric field gradient near the rail traction, or electric field gradient near the gas pipeline allow determination of the direction of stray current flow in the ground. On this basis, it is possible to identify what kind of impact is expected on the pipeline in this area (anodic or cathodic zone of impact). These methods are therefore useful at the stage of designing the route of the gas pipeline in order to avoid future risks, or in the preliminary phase of identifying the corrosion risk to the gas pipeline. However, they cannot be employed to predict the magnitude of the effects and, consequently, to indicate the most appropriate form of corrosion protection for the gas pipeline (polarized drainage or ICCP).

Methods for testing the correlation between the potential of a gas pipeline and its voltage relative to electric traction rails provide the most information about the hazard caused by stray currents. The criteria for assessing the impact refer to the asymmetry of changes in the potential of the gas pipeline relative to the steady-state potential, i.e., the potential of the gas pipeline in the absence of stray currents. The hazard occurs only when the periods of anodic polarization of the gas pipeline prevail. This is due to the nature of stray currents, which are randomly variable rather than constant. If the current flowing from the pipeline to the ground had a constant intensity, there would be continuous metal dissolution. This phenomenon occurs in the case of stray currents originating, for example, from the cathodic protection system of a foreign object—the intensity and direction of such stray currents are constant [72]. Meanwhile, in the case of electric rail traction, dynamic changes in the intensity and direction of stray currents flowing across the metal/electrolyte interface cause processes related to charge separation reflected by the electrical capacitance of the double layer [73]. Electrochemical processes connected with capacitance are non-Faradaic (non-corrosive) in nature, whereas corrosive processes are related to direct current, known as Faradaic current, which flows across the metal/electrolyte interface with the participation of metal reduction and oxidation processes (metal dissolution, corrosion). Therefore, in practice, corrosive metal loss in pipelines occurs only when anodic polarization periods caused by dynamic stray currents prevail.

Correlation methods give unambiguous results in the case of pipelines with damaged external insulation, with a large number of insulation defects through which stray currents flow between the pipeline and the ground. In the case of gas pipelines with tight insulation (without defects), the results of pipeline potential recording may in fact be changes in the electric field in the ground, rather than changes in the electrochemical potential of the metal in the coating defect. The identified threat of stray currents may therefore only be probable and not actual, i.e., it will appear with the formation of an insulation defect. In locations where measurement results indicate a high probability of harmful stray current effects and the gas pipeline has highly tight insulation, protection against stray currents is not necessary until stray currents enter the pipeline. Further action by cathodic protection personnel should therefore involve periodic monitoring of the current flowing through the gas pipeline wall. Such measurements are routinely performed by personnel [4,19,74]. They are conducted at special measuring points (posts) routinely installed along the gas pipeline route during its construction, typically spaced every 1 or 2 km. Conductors connected to the gas pipeline are fixed to the posts, allowing for indirect current measurement using Ohm's law. Stray current flowing through the pipeline causes a voltage drop across the resistance of the pipeline section between the connected conductors. Knowing this resistance and the voltage drop, the stray current can be calculated. Stray currents flowing through a gas pipeline will occur when an insulation defect develops. Electrochemical corrosion protection (polarized electrical drainage or cathodic protection, depending on the intensity of stray currents flowing through the gas pipeline wall) will then be necessary.

Methods of time-frequency analysis of signals recorded in the field and related to the impact of stray currents are based on a comparison of power density spectrograms obtained for the stray current source and the pipeline. If both spectrograms reveal identical changes in the power of frequency components in the time domain, it is considered that interaction is present. The lack of clear evaluation criteria raises doubts. They are not parameterized, so the evaluation of interactions cannot be automated and must be based on a visual comparison of spectrograms. The difficulty in applying these methods also lies in the need to skillfully select the width of the analyzing window so that the resulting resolution of the spectrograms shows the frequency components of the analyzed signals as a function of time. Another disadvantage is that the analysis of spectrograms can only determine the presence of stray currents on the pipeline. However, it is not possible to determine the type of this interaction, whether it is cathodic or anodic, which is key information in terms of corrosion protection of the gas pipeline.

All of the methods discussed can be used separately or in combination, in which case the conclusions from the measurements can be confirmed by several methods. The choice of methods depends on the problem and the task to be solved by the cathodic protection personnel, as shown in Table 1, which compares all methods and indicates typical applications, advantages, and disadvantages. Technical aspects are also important, e.g., whether it is possible to connect a cable to the gas pipeline at the measurement site. If not, then the method of testing the potential of the rails or measuring the electric field gradient can be used. However, these are diagnostic methods, so if there is a high probability of harmful effects of stray currents, confirmatory tests should be performed using correlation methods.

Table 1. Summary of the discussed methods for assessing the risk of stray currents in gas pipelines.

Method and Time for Obtaining Conclusions	Typical Application Case	Advantages	Disadvantages
Rails' Potential Testing immediate conclusions	preliminary identification of the risk of stray currents when: - designing the gas pipeline route, - it is impossible to connect the measuring cables to the pipeline.	- no complicated measuring equipment is required, - the measurements are simple to perform, - the method can be used by basic cathodic protection personnel, - low cost of testing.	- information obtained is for exploratory purposes only, - it only determines the probability of harmful impacts, which may differ depending on actual pipelines (unknown distribution of stray currents in the field after the construction of the gas pipeline network).
Electric Field Gradients on the Ground Surface immediate conclusions	determining the anodic zones of the gas pipeline along its route	- no complicated measuring equipment is required, - the measurements are simple to perform, - the method can be used by basic cathodic protection personnel, - low cost of testing.	- sensitivity of measurement results to foreign electric fields, - non-homogeneous soil resistivity has the potential to affect electric field gradients.

Table 1. *Cont.*

Method and Time for Obtaining Conclusions	Typical Application Case	Advantages	Disadvantages
Correlation E = f(U) conclusions after analyzing the data in the laboratory	- determining the magnitude of electrolytic corrosion risk of the gas pipeline at the measurement site, - determining whether electrochemical protection of the gas pipeline at the measurement site is necessary, - evaluating the effectiveness of the gas pipeline's stray current protection system: polarized drainage, ICCP, or sacrificial anodes.	- it provides clear results regarding the magnitude of the stray current hazard (potential change asymmetry coefficient), - the hazard criterion is related to the time domain, not to potential values; therefore, changes in ground resistivity do not affect the obtained results.	- application of this method requires specialized training, - proper analysis of correlation graphs requires extensive experience, - the costs are higher than in previous methods due to the need to use two-channel recorders and software for analyzing the results.
Correlation U = f(E) conclusions after analyzing the data in the laboratory	determining the place of greatest impact on the section of the gas pipeline running along the traction line	- measurements easy to perform by trained personnel, - no need for specialized software.	- sensitivity of measurement results to changes in soil resistivity along the tested section of the gas pipeline, - in the case of gas pipelines with high insulation tightness, the measurement results are closely related to the location of insulation defects—there is a possibility of misinterpretation of the beta profile.
Time-Frequency Analysis conclusions only after analyzing the data in the laboratory	- determining which stray current source is affecting the gas pipeline (e.g., tram or railway traction), - determining the range of the stray current source's impact on the gas pipeline (testing remote pipeline sections).	- ease of performing field measurements.	- high costs associated with the equipment recording the measured signals and the software for time-frequency analysis, - advanced post-processing, complicated time-frequency analysis procedures, - obtained results do not provide information about the type of stray current interaction (anodic or cathodic).

The implementation of the presented methods for measuring rails' potential, electric field gradient, and correlation methods is easy, unlike time-frequency analysis, mainly due to the complex analysis of signals using the STFT or CWT transforms.

The $E = f(U)$ correlation method has the greatest potential for application to various test cases. It allows for the assessment of stray current hazards at the tested location on the gas pipeline, the determination of the anodic or cathodic zone on the gas pipeline, and the

identification of the location of the greatest hazard on the tested section of the gas pipeline. In addition, it can be used to easily determine the effectiveness of corrosion protection systems, mainly polarized electric drainage and impressed current cathodic protection. None of the other methods presented offers such combined possibilities. Another advantage is that it is not sensitive to local changes in soil resistivity. However, the measurement results may be affected by extraneous electric fields in the ground, which may originate, for example, from the cathodic protection system of a neighboring pipeline.

5. Conclusions

Stray currents flowing from DC rail traction systems on underground gas pipelines often fluctuate in a dynamic and random manner, which necessitates effective methods for evaluating their corrosive impact. The paper provided a summary of such tests, including:

- measurements of the potential of electric traction rails or the electric field gradient on the ground surface, which allow identification of the possibility of electrolytic corrosion based on the direction of current flow,
- studies of the correlation between the potential of the gas pipeline and its voltage relative to the electric traction rails, which provide information on the corrosion hazard from anodic areas on the pipeline,
- frequency domain analysis of the pipeline potential, which unequivocally identifies the stray current source that impacts the pipeline.

Routine execution of those tests evaluating the risk for structural integrity due to corrosion contributes to an increase in operational safety of pipelines.

The challenge, which should be faced in the near future, is the induction of alternating voltage in tightly insulated gas pipelines running near high-voltage power lines. In case of coating defect occurrence, intense alternating current corrosion processes may occur [75,76]. There is an increasing number of cases of such corrosion, as reported in scientific papers [77]. Methods and criteria for assessing the risk of alternating current corrosion in gas pipelines have been developed [78]. However, gas pipelines may be subject to the combined effects of DC stray currents and AC current. That is why there is a need to develop methods for testing such synergistic effects in the field.

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