Wall Fusion of Buried Pipelines due to Direct Lightning Strikes: Field, Laboratory and Simulation Investigation of the Damaging Mechanism

C.A. Charalambous, Member, IEEE, A. Dimitriou, N. Kioupis, T. Manolis and N. Kokkinos

Abstract— Wall fusion of buried pipelines can occur if the driving voltage and available current is sufficiently high. For example, it can occur from direct lightning strikes to earth, close to the pipelines’ routing. However, not all factors for defining the energy discharge needed to fuse the pipe wall are thoroughly investigated or understood. This article enriches the ongoing research activities in an attempt to understand such detrimental damages. In particular, the paper formulates its research contents around a documented wall fusion incident on an underground Gas Transmission System, due to a nearby direct lightning strike. The investigation embraces field, laboratory and modelling activities to provide insights on the damaging mechanism. Of particular importance, in understanding this mechanism is the influence of soil ionization. To this end, a model is developed to investigate the soil-ionized flow of the lightning discharge current - into the pipeline’s metal wall, through existing coating defects - thus revealing its detrimental effect.

Index Terms—Gas Pipeline, Lightning, Soil Ionization, Coating Defect, Metal Fusion

I. INTRODUCTION

The belief that gas pipelines are effectively protected against direct lightning strikes - by virtue of their buried nature and modern coating layers - has been progressively revoked by some serious incidents [1]-[2]. Preliminary investigations to this extent, suggest that the impact of the lightning current discharge on buried pipeline primarily depends on the buried depth of the pipeline and on the distance of the pipeline to the lightning discharge location. However, foreseeing the exact impact is a complex problem, with multiple interacting variables. In the related scientific literature, the mechanisms through which lightning activity causes a failure (i.e. wall fusion) to buried pipelines are still, not fully investigated.

Although there is no simple criterion for defining a limit to the energy discharge needed to fuse the pipe wall, the AUS standard [3] documents, some parameters that are associated with such risk. The risk sources are reported to be the peak value of the lightning current, the charge of the lightning current (Q_{\text{flash}}) consisting of the charge of the short stroke (Q_{\text{short}}) and the charge of the long stroke (Q_{\text{long}}), the soil resistivity, the proximity of the pipelines’ grounding systems to the lightning strike location, as well as the wall thickness of the pipeline.

However, there are other non-thoroughly investigated factors that may facilitate the flow of lightning discharge current into the pipeline metal. Such an example pertains to the influence of soil ionization (at the location of the lightning strike) on the pipeline’s withstand capabilities - especially in the presence of existing coating defects in the section of the pipeline that falls within the formed soil ionization region. The latter has been given little or no attention, since the current knowledge [4]-[10] suggests that soil ionization will typically reduce the effective local resistivity around buried conductors and hence improve their grounding performance. Nonetheless, as it will be evidently discussed in this paper, soil ionization may, under certain conditions, act to facilitate the flow of lightning discharge current into the pipeline’s metal through existing coating defects.

This paper manifests the quintessence of the above introductory remarks through the following structure: Section II describes a very recent metal wall fusion incident, on a high-pressure underground Gas Transmission System. This incident was caused by a direct lightning strike in the nearby vicinity of the pipeline. Section III, describes a series of laboratory experiments on specimens of the pipeline, which had suffered the metal wall fusion and gas leakage as a consequence. Finally, Section IV describes some state-of-the-art modelling techniques and analysis to understand the mechanism that has caused this damage. It is highlighted that the discussion remarks in Section IV are not limited to the reported incident, but they are also generically extrapolated.

II. BRIEF DESCRIPTION OF REPORTED PIPELINE DAMAGE

In mid-March 2017, there was a reported gas leakage and metal wall fusion on a secondary branch (100 km in length) of the high-pressure natural gas pipeline, of the Hellenic Gas Transmission System. The incident took place at the 52nd km (approximately) of this 100 km branch. An emergency field investigation, from the Gas Transmission System Operator has revealed that the cause of the wall fusion, was a direct lightning strike on a nearby small bush. The location of the lightning strike has been identified to be, at approximately 5 m away from
the wall fusion location (see Fig.1). Moreover, the location of the lightning strike had also been reported/confirmed through the long-range lightning detection system of the National Observatory of Athens (NOA). The detection system is based on a network of six receivers located in Europe (ZEUS lightning detection system) [11]. The information registered on the incident’s day, suggests that there was a lightning strike very near to the location (~ 60 m) of the pipeline’s damage. Interestingly, two more lightning strikes had been also registered near (~ 200 m) to the location of the damage, however earlier in the month.

To facilitate a comprehensive overview of the underlying physical conditions, infrastructure’s characteristics as well as to highlight the findings - of the thorough field investigation carried out by the transmission operator – the following information (A, B) is documented.

A. Pipeline Design and Material Characteristics

The inquired pipeline is a branch that diverts from the main Gas Transmission Line. This branch has a total length of 100 km. The characteristics of the pipeline are given in Table I.

<table>
<thead>
<tr>
<th>PIPELINE CHARACTERISTICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipeline wall resistivity (relative to annealed copper)</td>
</tr>
<tr>
<td>Pipeline wall permeability (relative to free space)</td>
</tr>
<tr>
<td>Pipeline coating resistivity</td>
</tr>
<tr>
<td>Coating thickness</td>
</tr>
<tr>
<td>Pipeline radius</td>
</tr>
<tr>
<td>Wall thickness</td>
</tr>
<tr>
<td>Buried Depth (upper edge at the location of the damage)</td>
</tr>
</tbody>
</table>

Moreover, the whole of the 100 km branch embraces 103 earthing mitigation wires. These had been installed to eliminate the effects of long and short term Electromagnetic Interference from adjacent power lines in the pipeline’s right of way. These electrodes are continuous hot dip galvanized steel stay wires. The minimum external diameter of the wires is 12 mm that includes a 70 $\mu$m layer of zinc (500 g/m²). They are installed at the same level and in parallel to the pipeline routing, through dc decoupling devices equipped with Transient Voltage Suppressors (TVS). The nearest earthing wires, to the damage location (i.e. 52$^{rd}$ km), are installed at 48,074 km (electrode length 135 m) and at 61.61 km (electrode length 110 m).

Additionally, the pipeline is grounded at its 54.56 km through a 20 × 20 m grid. This grid is associated with a valve station.

Finally, at the area near the location of the damage, some soil resistivity measurements (see Table III) were performed soon after the reported gas leakage incident. These measurements were obtained using the standard Wenner Method, at various depths across four different axis.

B. Field Investigation and Findings

Soon after the reported incident, the system operator has carried out a thorough field investigation that included the excavation of a pipeline’s sector (see Fig.1) near the location of the damage. The main findings of this investigation are reported in Fig. 2. In particular, Fig. 2 shows a single line diagram of the excavated section. This section is 12m in length (i.e. between two welded joints). Within, this section, five locations with evident marks of coating and pipe wall damage had been identified. The exact locations of the damages are shown in Fig. 2 with reference to the circumference of the pipeline.
The metal wall fusion and gas leakage had been identified, at location 1, as a hole with a conical shape. This damage is clearly shown in Fig. 3. The diameter of the hole at the surface of the coating was circular in shape with a diameter of 6.7 mm along the length of the pipeline and 6.2 mm along its circumference. On the inner surface of the coating, there was a bigger footprint (28 mm along the length and 27 mm along the circumference). The diameter of the hole associated with the metal wall fusion (location 1) has been measured to be approximately 2.3 mm.

In the remaining four locations (2-5), there were evident marks of coating damage, as well as small damage on the external surface of the metal wall. The dimensions of this damage, for location 2 in particular, were 15 mm along the length, 18 mm along the circumference and the depth of the defect was 0.65 mm. A characteristic photo of the damage at location 2 is also shown in Fig. 3.

III. LABORATORY BASED TESTS

A. Experimental Procedure and Objectives

The laboratory experiments carried out for this case study, reflect on some details and definitions described in the IEC 62305-1 [13]. It is thus important to quote that a downward lightning flash may consist of a first impulse (i.e. short stroke) and it may be followed by a long stroke (i.e. "part of the lightning flash that corresponds to a continuing current"). To this extent, the IEC 62305-1 [13] explicitly defines: a) the Impulse Charge (\(Q_{\text{short}}\)) as the value resulting from the time integral of the lightning current in an impulse and b) the long stroke charge (\(Q_{\text{long}}\)) as the value resulting from the time integral lightning current in a long stroke. As per the clauses of IEC 62305-1, the tests for the short or the long strokes can be applied on the test specimens separately, or as a combined test, where the long stroke follows the first impulse instantaneously.

Thus, the main objectives of the laboratory based testing were to simulate the specific energy of the first impulse (\(Q_{\text{short}}\)) and the charge of the long stroke (\(Q_{\text{long}}\)), on some specimens of the exact pipeline that had suffered the reported metal wall fusion (See Table I). More explicitly, the test results were used to elaborate on the hypothesis that it is mainly the \(Q_{\text{long}}\) that is capable of fusing the pipe metal wall. To this end, previous laboratory testing [14]-[15] has revealed that the long stroke charge is the dominant factor for metal fusion. Moreover, the work reported in [16] has noted the poor simulations of damage on airplane wings from the impulse current. It has nevertheless confirmed that severe damage can be attributed to large charge transfers that occur during the long-duration of lightning discharges (i.e. the continuing current phase). Finally, in [17], [18] a lightning arc test for Optical Ground Wires (OPGW) is described. The purpose of this test is to subject OPGW to lightning conditions that represent field conditions, in order to verify their mechanical performance. Of particular note to this end, is the fact that the lightning test parameters in [17] conform to charge transfers that result from the continuing current phase of a lightning flash.

1) Description of Test Specimens

To facilitate the investigation, a number of test specimens were extracted/cut from the circumference of a full ring pipeline unit. Each extracted specimen had dimensions of 150×150 mm. The metal wall of thickness of each specimen was 10 mm and the coating thickness was 5 mm (see Fig. 4). In the interest of space, this paper hosts the test procedures and results for three specimens only (D₁, D₂ and D₃).

2) Description of Test Procedure and Equipment

Two of the specimens (D₁, D₂) underwent a thorough process of preparation that involved accelerated environmental aging and some discrete artificial damaging on the coating material. The third specimen (D₃) was not subjected to any preparation/aging process. The preparation processes are briefly documented in Table V while the test specimens are shown in Fig. 4.

![Fig.4 Photos of Test Specimens before and after the Environmental Ageing Process](Image)

The artificial damaging on the coating material (for specimens D₁, D₂) had been enforced before the accelerated environmental aging process. The latter has been achieved using an environmental chamber for salt mist ageing and an environmental chamber for humid sulphurous atmosphere ageing.

Following the completion of the preparation process, each specimen has been singly and consecutively subjected to the two stress tests described in Table VI. The experimental arrangement is shown in Fig. 5. In particular, Fig. 5 illustrates...
the connection of the test-specimen to the output of the impulse current generator, via a pin brazed copper wire of 25 mm².

<table>
<thead>
<tr>
<th>TABLE V</th>
<th>BRIEF DESCRIPTION OF SPECIMENS’ PREPARATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Specimen</td>
<td>Accelerated Environmental Aging</td>
</tr>
<tr>
<td>D₁ &amp; D₂</td>
<td>1. Salt mist treatment (3 days) according to IEC EN 60068-2-52:2017 [19]</td>
</tr>
<tr>
<td></td>
<td>2. Humid sulphurous atmosphere treatment (7 days) according to EN ISO 6988:1985 [20]</td>
</tr>
<tr>
<td>D₃</td>
<td>No Accelerated Aging Process has been applied</td>
</tr>
</tbody>
</table>

It is worth noting that due to practical constraints, the DC follow test (#2) has been performed approximately 15 minutes after the impulse current test. However, it should be appreciated that this time delay, erred on the side of requiring high $Q_{long}$ values for fusing the metal wall of the specimen. This is because any heat gained from the lightning impulse test was allowed to convect through the air.

<table>
<thead>
<tr>
<th>TABLE VI</th>
<th>DESCRIPTION OF ELECTRICAL TESTS AND EQUIPMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Description</td>
<td>Remarks</td>
</tr>
<tr>
<td>#1</td>
<td>Lightning Impulse Current Test</td>
</tr>
<tr>
<td>#2</td>
<td>DC follow Current Test</td>
</tr>
</tbody>
</table>

Test #1 has been performed through the use of a Lightning Impulse Current Generator 100kA, 65C, 187kJ. This test has been performed to simulate the Impulse Charge ($Q_{imp}$) on the pipeline specimen.

Test #2 has been performed through the use of a DC Voltage Generator 20kW, 625A. This test has been performed to simulate the long stroke charge ($Q_{long}$) on the pipeline specimen.

Note: The following two elements were used in the testing:
- Resistive Impulse Shunt 1mΩ, 100 kA, 2500kΩ/Ω
- Digital Oscilloscope 400MHz, 20 Gs/sec

3) Summary of test results

The results pertaining to the performed tests are summarized in Table VII. Moreover, the recorded damage on the specimens (D₁-D₃) upon the completion of each test is illustrated in Figures 6 – 8 respectively.

<table>
<thead>
<tr>
<th>TABLE VII</th>
<th>SUMMARY OF TEST RESULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1. Impulse Current Test ($Q_{imp}$)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D₃</td>
</tr>
<tr>
<td>Peak Current</td>
<td>99.9 kA</td>
</tr>
<tr>
<td>Specific Energy</td>
<td>2112 kJ/Ω</td>
</tr>
<tr>
<td>Charge</td>
<td>44.76 C</td>
</tr>
<tr>
<td>Performed at the point of artificial coating damage</td>
<td>Performed at the point of artificial coating damage</td>
</tr>
</tbody>
</table>

| #2. DC Follow Current Test ($Q_{long}$)¹ | | |
| | D₃ | D₁ | D₂ |
| Current | 520 A | 520 A | 460 A |
| Duration | 1.2 s | 1.2 s | 2.34 s |
| Charge | 624 C | 624 C | 1078 C |
| Bore on the specimen (Full Penetration) | Cavity with Dimensions: 5.2×4.5 mm, 3.4 mm depth (See Fig. 7) | Bore on the specimen (Full Penetration) (See Fig. 8) |

¹ To deduce the charge ($Q_{long}$) required to achieving a bore on the specimen (i.e. D₁ and D₃) the DC follow test has been performed on multiple samples of each specimen. For a selected number of tests, the current was kept constant but the time duration of each test was varied in steps of 0.02 s until the bore on the specimen was visually evident.
The modelling endeavor consists of the following:

1. Development and integration of a coating defect model; 
2. Development and integration of a soil ionization model; 
3. Development and integration of a energization principle model; 
4. Development and integration of a network model; 
5. Development and integration of a lightning model.

However, it was also observed that existing lightning models are not adequate to cause fusion of the metallic wall of the pipeline. Therefore, the latter test has not been subjected to any accelerated aging process and no artificial damage has been enforced on its coating material. Thus, the primary objective of this section is to further understand this process, through modelling activities. In particular, the modelling pertains in investigating whether the soil ionization can act to facilitate the flow of the long stroke (i.e., “part of the lightning flash that corresponds to a continuing current”) directly into the pipeline’s metallic wall through existing coating defects. It is noted that the modelling investigation in this paper is limited to simulating the long stroke, since it was experimentally verified that it is the dc component associated with the long stroke that is able to cause metal wall fusion. To this extent, the modelling endeavor consists of the following stages: a) design of a full-scale topologically accurate pipeline model, b) development and integration of a coating defect model, c) soil ionization model and dc energization principles, d) simulation and post-processing of results.

A. Development of Full Scale Simulation Model

Figure 9 illustrates the top plan view of the developed geometrically accurate simulation model. This was achieved through the use of CDEGS software [12].

The characteristics of the pipeline (i.e., material specifications, size, earthing electrodes, insulation joints) that are used in the simulation model, are those provided in the CIGRE report [21] for the case of aerospace vehicles. The lightning impulse can, however, create a severe damage on the coating material as well some deflection on the outer surface of the metallic wall of the pipeline.

Moreover, the same 624 C charge was then applied to D2 and the conclusion was that the metallic wall was partly melted (i.e., cavity with dimensions: 5.2 x 4.5 mm, 3.4 mm depth). The difference in the two tests lies in the fact that the artificial coating damage on specimen D1 was more severe (i.e., the metal wall was exposed and lightly damaged) than the artificial coating damage on D2. Therefore, D2 would require more charge to achieve a complete metal wall fusion. To verify the fact that the condition of the coating can influence the charge required to cause metal wall fusion, the test has been applied to specimen D3. It is reiterated at this point that D3 has not been subjected to any accelerated aging process and no artificial damage has been enforced on its coating material. Therefore, the latter test has concluded that metal wall fusion can occur at a charge value of 1078 C.

To this end, the generic conclusion that can be drawn from the DC follow tests (irrespective of the absolute $Q_{long}$ charge) is that when pre-existing defects are present on the pipeline (on the coating and metallic wall) the $Q_{long}$ charge required to cause metal wall fusion is much less than the charge required for a pipeline free of defects (i.e., just after its installation).

IV. FURTHER INVESTIGATION - MODELLING

By virtue of the reported damage (i.e., the pipe metal wall fusion) and by reviewing the field investigation findings (Section II), it is rational to assume that the direct flash episode has forced a high current-discharge to pass on the pipeline’s metal wall. Moreover, the laboratory tests carried out (Section III), have confirmed that it is the long stroke (i.e., “part of the lightning flash that corresponds to a continuing current”) that is capable to cause the metal wall fusion. However, it was also concluded that the level of $Q_{long}$ required to cause fusion depends on the presence of existing defects on the pipeline’s coating and metal layers.

Thus, this concludes that the level of $Q_{long}$ that is capable to cause fusion depends on the presence of existing defects on the pipeline’s coating and metal layers.
Section II-A. Further to the data described in Section II-A, for the subsequent simulations, the spark gap across the insulation joint, located at 61.336 km, is bridged (i.e. it was assumed that the voltage across the insulation joint exceeds its rated impulse spark over voltage - 2.2 kV (Table II), under the reported lightning strike location).

B. Development and Integration of an Equivalent Coating-defect Model

1) Relevant Literature Survey

The AUS standard [3] dictates that it is sensible to assume that a coating defect can occur anywhere on a pipeline and not use the existence of a pipeline coating as defense. As noted in [22], coating defects on buried pipeline systems can be caused from an earth fault at a transmission line tower, close to the pipeline. As a result, the pipeline’s coating may be left weakened/damaged and thus susceptible to further detrimental deterioration. Moreover, severe damage on the pipelines’ coating can occur due to direct lightning strikes in the immediate vicinity. To support this argument, the field investigation findings presented in section II-B (Fig. 2) have confirmed that a direct lightning strike, near the pipeline, can adversely damage its coating material and to some extent, its metal wall layer (see Figure 3b).

2) Coating Defect Model

To study the impact of coating defects on the pipeline’s susceptibility to lightning strikes, an equivalent coating defect model has been developed. This model has been integrated in the simulation model, as shown in Fig. 10.

![Integration of a Coating Defect in the Simulation Model](image)

To achieve this, it was assumed that the pipeline has a small cylindrical coating defect of an equivalent area of 1 cm². The resistance to earth \( R_D \) of this coating defect can be calculated as \( R_D = \frac{\rho}{4r} \) [23] where \( \rho \) is the local soil resistivity and \( r \) is the radius of the cylindrical defect. Depending on the value of the local soil resistivity and on the size of the assumed coating defect, the value of \( R_D \) can be determined. In the simulation model, the coating defect \( R_D \) is integrated by means of equivalent conductors, which are appropriately sized and calibrated to match the calculated \( R_d \). It is noted that the coating defect model has been integrated in the simulation model, at the location where the pipeline, has suffered the metal wall fusion (i.e. 52nd km).

C. Soil Ionization Model and Energization Principles

1) Relevant Literature Survey

Many theoretical and practical studies suggest that when an impulse current is injected into the soil, the high current density in the vicinity of the injection point, can locally increase the soil’s electric field [4]-[10], [24]-[30]. This increase has the effect of producing a local ionization zone in the soil. To this end, some experimental studies [5], [8], [10], [24]-[30] have shown that if this electric field exceeds some critical value \( E_c \), then soil breakdown can occur. We note however, that the soil is an inhomogeneous medium with subcomponents that include: a) solid soil particles, b) ionic liquid and c) humid-air. The mixture of solid, air and liquid elements results in a non-linear electrical conductivity [27]. Therefore, depending on the soil composition, the critical value of electric filed gradient \( E_c \) for soil breakdown can range between 300-1850 kV/m [4]-[5], [24]-[26]. In practice, due to the inhomogeneous soil’s nature, the ionization zone that is formed into the soil can have an arbitrary shape [24], [27], [30]. However, the ionization zone can be conveniently considered to be hemispherical [5], [8], [10], under the assumption that the lightning current can be radially dissipated in a homogeneous soil \( \rho \). In such case, the radius \( R_{ion} \) of the ionized hemisphere for a homogeneous soil can be calculated as given in (1). Within (1), \( I_m \) is the maximum lightning current [1] and \( E_c \) is the critical value of electric field for which soil breakdown can occur [1], [10]. This implicitly entails that all metallic objects within the ionized zone will be attracted by arcs formed in the soil.

\[
R_{ion} = \frac{I_m \rho^{\frac{3}{2}}}{2\pi E_c} \tag{1}
\]

It is nevertheless highlighted that in the ionized region, the soil resistivity can follow some dynamic hysteresis loop profile [7]-[9]. As described in [8] the soil resistivity value will remain constant before the critical value of electric filed \( E_c \) is reached. When \( E_c \) is exceeded, the ionization process commences and the value of the soil resistivity decreases, as the current density continues to grow. The residual resistivity in the soil ionization region, is considered to be 7% [29] or in the order of 0.001 – 0.003% of the original soil resistivity [30]. As indicated in [7]-[9], the residual soil resistivity can be sustained for some time before starting to gradually restore back to its initial value. The restore time is reported in [27] to be proportional to the impulse current amplitude that produces the ionization of the soil.

2) Equivalent Soil Ionization Model

For a uniform soil resistivity structure, the ionization radius \( R=R_{ion} \) of a hemispherical zone can be computed using (1). To this end, Fig. 11 shows a sensitivity analysis for \( R_{ion} \) with respect to different \( E_c \) values under three discrete \( I_m \) scenarios (31 kA, 100 kA and 200 kA). In all scenarios, the soil resistivity was assumed uniform (i.e. 1535.51 Qm). As evident in Fig. 11, \( R_{ion} \) depends on the maximum lightning current \( I_m \) and on the critical value of electric field \( E_c \) to allow for soil breakdown.

However, in this study a more rigorous approach has been followed to estimate an appropriate \( R_{ion} \) value. The approach followed, reflects: a) on the three-layer soil structure reported in Table IV (resulted from field...
measurements), b) on a maximum lightning current $I_m$ and c) on a critical value of electric field $E_c$ to allow for soil breakdown.

In particular, the $R_{ion}$ calculation relies on a series of parametric simulations using CDEGS software. The process initially involves injecting a lightning impulse current ($I_m$) at the ground surface of the three-layer soil model (Table IV). Following this injection, the voltage gradient (kV/m) that develops within the three-layer soil structure, is calculated through a build-in method (HIFREQ/FFTSES) that obtains the electromagnetic fields in the time domain, from a corresponding frequency domain response based on the shape of the lightning impulse current ($I_m$) [12].

The calculation of the voltage gradients conforms to 50 discrete circular surfaces, which are vertically distributed (i.e. every 0.10 m) across the depth of the 3-layer soil structure (Table IV). Thus, for each surface an equivalent $R_{ion}$ is determined, according to a specified critical value of electric field $E_c$ that is set as a boundary condition. The simulation results are shown in Fig. 12, for an $E_c$ value of 700 kV/m and $I_m$ 100 kA 10/350 µs.

We highlight that in this particular study, the 700 kV/m threshold was assumed to apply across the entire three-layer soil structure. This is a rational assumption since the combined depth of the two upper soil layers is only 1.14 m. Effectively, the dominant soil layer is the third one (1535.51 Ω.m for infinite depth). [Note: The pipeline is laid on the third soil layer].

For completeness, a comparison with regard to the ionization zone formed in the three-layer soil structure and in the uniform 1535.51 Ω.m soil structure is shown in Fig. 13. The conclusion from this comparison is that for the three-layer soil structure, $R_{ion}$ at the ground surface, is reduced to 5.8 m (Fig.12) when compared to the 5.9 m $R_{ion}$ value corresponding to the uniform soil structure (Fig. 11). A further conclusion is that the ionisation zone in the three-layer soil structure is not entirely hemispherical and thus, its calculated ionized volume is 4.47 % less than the ionized volume - calculated for the uniform soil structure (i.e. 1535.51 Ω.m).

Following the above remarks, the soil ionisation effects are integrated in the simulation model, through a build-in soil model (see Fig. 14) of the software.

This approach accounts for the fact that the ionization can be modelled by two-part soil models [8], [31]–[32]. The first part accounts for the non-ionization zone (i.e. the soil has its original value of resistivity $-\rho_{out}$) and the second accounts for a hemispherical ionization zone (i.e. the soil has a residual value of resistivity $-\rho_{in}$). For this case study, an $E_c$ value of 700 kV/m has been used, as a conservative

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1 In this simulation, $\rho_{out}$ was assumed to be equal to 1535.51 Ω.m. This soil resistivity corresponds to the bottom of the three-layer soil structure (Table IV) i.e. the layer at which the pipeline is laid.
value. Moreover, the dimensions (i.e. volume) of the ionized zone were set as per the results provided in Fig.12, for the three-layer soil structure. These input parameters ensure that the pipeline (and its coating defect) will fall into the ionisation zone. This is illustratively shown in Fig. 15. [Note: It was assumed that the center of the ionized hemisphere coincides with the lightning injection point into the soil].

Fig.15 Illustrative plot: Pipeline routing falling within ionization zone

3) **Energization of the Simulation Model**

With reference to Fig. 10, the simulation model is energized by means of a conductor that is modeled as a current source. The conductor can be energized by a lightning transient or a dc pulse to discretely emulate the effects of $Q_{\text{short}}$ or $Q_{\text{long}}$ on the pipeline. (Note: In the simulation model, (see Fig. 10) a direct current is injected into the soil at a 5 m distance from the modelled coating defect. This is to reflect on the field investigation findings described in Section II-B).

4) **Summary of Input Parameters**

Following all the remarks documented in Section IV, the input parameters employed in the simulation process are summarized in Table VIII.

### Table VIII

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionized Soil Resistivity Model</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil resistivity of non-ionization zone</td>
<td>$\rho_{\text{ns}}=1535.51 , \Omega \cdot \text{m}$</td>
<td>It reflects on the soil resistivity layer the pipeline is laid on</td>
</tr>
<tr>
<td>Soil resistivity of ionization zone</td>
<td>$\rho_{\text{i}}=1.53 , \Omega \cdot \text{m}$</td>
<td>Assumed value: 0.1% of original soil resistivity</td>
</tr>
<tr>
<td>Critical value of electric filed gradient ($E_{\text{c}}$)</td>
<td>700 kV/m</td>
<td>It may range between 500-1500 kV/m [4]-[5]</td>
</tr>
<tr>
<td>Dimensions of hemispheredial ionization zone</td>
<td>Figure 12</td>
<td>Resulting from the three-layer-soil structure (Table IV)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coating Defect Model</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent area of coating defect</td>
<td>$A=\pi r^2=1 , \text{cm}^2$</td>
<td>The coating defect is assumed to have a cylindrical shape.</td>
</tr>
<tr>
<td>Equivalent resistance to earth of coating cylindrical defect</td>
<td>$R_d=\frac{\rho}{4r}$</td>
<td>Depends on the local soil resistivity and on the size of the coating defect.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energization - Long Stroke</th>
<th></th>
<th></th>
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</table>

### Table IX

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long Stroke: part of the lightning flash that corresponds to a continuing current</td>
<td>$I_{L}=400 , \text{A}$</td>
<td></td>
</tr>
<tr>
<td>$Q_{\text{long}}$ as per IEC 62305-1 is 200 C [13]</td>
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<tr>
<td>$Q_{\text{long}}$ as per IEEE Standard 1138-2009 can be 400 A for 0.5 s [17]</td>
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D. **Simulation and Post-Processing of results**

1) **Solution Method**

The following simulation results pertain to a numerical solution that relies on the use of the MALZ computation module of CDGES [12]. This module relies on a hybrid method for calculating responses from grounding systems, namely, a quasi-static approximation of Maxwell equations [33]-[35].

2) **Simulation Results**

Figure 16 illustrates the simulation results for the current that is entering the pipeline through the coating defect. It is shown that when soil ionization is considered, 178 A out of the 400 A dc that is injected into the soil, enters the pipeline through the coating defect. That is 659 times higher than the current entering the pipeline when no soil ionization is considered (i.e. 0.27 A out of 400 A dc).

![Figure 16](image_url)

To this end, Fig. 17 shows a sensitivity analysis that captures the dependency of the current entering through the coating defect under varying values of the ionized residual resistivity (i.e. $\rho_{\text{n}}$). The conclusions from this analysis is that the amount of current entering the pipeline depends: a) on the magnitude of the dc component of the long stroke and b) on the local soil resistivity value of the ionized zone.

To further investigate the thermal effects on the pipe metal wall, at the location where the current enters the pipeline through the coating defect, the anode-or-cathode voltage drop model described in Annex D of the IEC 62305-1 [13] is used. This model provides conservative results for the volume ($V$) of melted metallic material under a lightning discharge event. This is mathematically described in (2) [13]. The conservatism arises from the assumption that all the energy injected through the defect is used to melt the conductive material by neglecting the heat diffusion within the metal.

$$V = \frac{U_{\text{i},c} \times Q}{\gamma \times (C_{\text{ns}} \times (\theta_s-\theta_0) + C_{\text{i}})} \ (2)$$

A description of the parameters shown in (2) as well as the values used in the calculation are documented in Table IX. To this extent, Fig. 18 shows the calculated volume of melted metal for different cathode voltage drops ($U_{\text{i},c}$). The analysis has been
performed for $Q=89$ C. The 89 C has been deduced since the current through the coating defect was calculated equal to 178 A (see Fig.15). Thus, assuming a time duration of 0.5 s as prescribed in [13], [16], the value of $Q$ is approximately equal to 89 C. With reference to Fig. 18, we take (as an example) the volume of melted metal (167 mm$^3$) calculated for a cathode voltage drop equal to 14 V. If we were to transfer this volume to an equivalent circular truncated cone with height 10 mm (i.e. equal to the thickness of the pipe metal wall) the diameters of the truncated cone would be 2.3 mm (upper surface) and 6.6 mm (lower surface). Thus, these values are comparable to the diameter of the conical shape hole that deduced from the field investigation of the real incident (see Section II-B). Therefore, this confirms that it is possible to have metal wall fusion when the conditions described and simulated in Section IV are met.

V. DISCUSSION OF RESULTS AND CONCLUSIONS

The paper has presented a documented wall fusion incident on an underground Gas Transmission System, due to a nearby direct lightning strike. The work embraces a field investigation report as well as in-house laboratory experiments and modelling activities. The main conclusions that are drawn from these endeavors are as follows: Depending on the type of lightning current, the corresponding charge ($Q_{\text{flash}}$) may involve the charge of the short stroke $Q_{\text{short}}$ and the charge of the long stroke $Q_{\text{long}}$. The laboratory tests have confirmed that it is the long stroke (i.e. “part of the lightning flash that corresponds to a continuing current”) that is capable to cause the metal wall fusion. However, it was also concluded that the level of $Q_{\text{long}}$ required to cause fusion depends on the presence of existing defects on the pipeline’s coating and metal layers.

Moreover, in the event of a direct lightning strike near a buried pipeline, a high value of electric field can be generated in the immediate vicinity of the lightning current discharge location. If this value of electric field exceeds the value of the “ground ionization gradient”, it may cause the influenced area of soil, to behave very conductively (i.e. soil breakdown). If the pipeline’s routing falls within the formed ionization zone, then the lightning discharge current can enter the pipeline through the pre-existing coating defects that they also fall within the ionization zone. Thus, the presence of a preexisting coating defect can drain the long stroke charge $Q_{\text{long}}$ to flow through the pipeline’s coating to reach its metal wall. These defects make the pipeline conductance to earth greater than that of a well-insulated section. Because the current enters the pipe through an imperfection in the coating, the current density at the defect’s location is high, even for humble current values, since the size of a defect is usually microscopic. This flow can cause intense localized heating and subsequent pipe wall fusion if all the necessary conditions are met.

REFERENCES

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRD.2019.2925622, IEEE Transactions on Power Delivery

ACKNOWLEDGMENT

The work was financially supported by the Hellenic Gas Transmission System Operator (DESFA), under a project-based agreement. The practical work performed by the staff of ELEMKO’s H.V. Laboratory (acknowledged according to EN/ISO-IEC 17025 and ISO 9001/2000) is sincerely acknowledged.

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