Evaluation of the Interference Effects of HVDC fault on a buried pipeline

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***Abstract*—HVDC transmission systems have potential effects on buried pipelines in their vicinity. Thereby, significant interferences can arise when a fault occurs on an HVDC overhead line, depending on factors such as the distance between the line and the pipeline, the exposure length, the soil resistivity, and the line configuration. This paper investigates the effects of these parameters on the pipeline's induced transient overvoltage. Under normal operating conditions, only small current variations occur in the poles, and their electromagnetic field effects are negligible. However, when a pole-to-ground fault occurs, a transient stage lasting a few milliseconds leads to a significant increase in the electromagnetic field. This paper presents a variety of simulation studies obtained using an electromagnetic transients software (EMTP). Simulations were conducted for different HVDC configurations, specifically symmetric monopolar and bipolar setups. The results show that the induced voltage is significantly higher in bipolar configuration, but in both cases, the effects are not negligible. Precautions must be taken to mitigate adverse effects on the pipeline, particularly regarding its cathodic protection, and to prevent electrocution through contact with the pipeline. The effects on the human body during transient events were analyzed based on various models, considering both the magnitude of the current passing through the body and the duration of the exposure. The findings indicate that with appropriate protection measures in place, there is no risk to human safety and no risk of damage to the pipeline system.**

***Keywords*: HVDC, pipeline, inductive coupling, overhead line, human safety, electromagnetic transient calculation**

I. Introduction

TO reduce costs and minimize environmental impact, long stretches of pipelines are often buried next to overhead lines, sharing a common path. While the coupling effects between AC lines and pipelines have been extensively studied [1-3], the interactions with HVDC lines—being more recent—are less well understood. HVDC lines offer unique advantages for long-distance power transmission, such as avoiding capacitive effects, and ensuring high operational stability. As a result, the use of HVDC lines is expanding, with some of these lines running alongside buried pipelines. It is crucial for both transmission system operators and gas transportation stakeholders to be aware of the interactions between these two infrastructures.

One of the main differences between an HVDC line and an AC line regarding electromagnetic coupling with pipelines is the duration of interaction. For AC lines, coupling occurs permanently in steady-state conditions, leading to long-term corrosion issues. In contrast, for HVDC lines, the coupling duration is typically less than a second, occurring only during fault conditions. While this short duration may not significantly increase the corrosion rate of the pipeline, it raises concerns about the potential impact on cathodic protection systems, which are not designed to handle high voltage levels. Another concern is human safety during fault conditions.

Both AC and DC power lines have capacitive, conductive, and inductive coupling with pipelines [3,4]. An overhead line can have strong capacitive coupling if the pipeline is above ground [5]. However, this is not the case for buried pipelines, where the electric field is shielded by the surrounding soil. Since soil acts as a good electrical conductor, free charges within the soil compensate for the electric field produced by the line. Conductive coupling is related to the ground potential rise in the vicinity of a faulted tower due to the discharge of current through the grounding electrodes. An insulated pipeline in the vicinity of the tower's potential gradient will experience a voltage across its insulating coating due to the voltage difference between the pipeline and the adjacent soil [4]. However, this effect is disregarded in this paper because the distance between the faulty tower and the pipeline is sufficiently long to neglect it. Therefore, inductive coupling is the most significant in the context studied

HVDC systems can operate in various configurations, each of them having a specific influence on the coupling. In bipolar mode, a fault creates a closed loop through the poles and the metallic return, minimizing conductive coupling. However, in symmetric monopolar configurations, current is drained through the ground, and the effects of this must be considered, particularly in relation to the separation distance between the overhead line and the pipeline.

Given the complexity of HVDC interference mechanisms and in order to simulate realistic scenarios, we based the study on numerical simulation. This approach allows us to account for the numerous factors involved and to explore different line configurations. The EMTP [6] software program was used for

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this purpose, as it provides comprehensive models of converters and overhead lines, making it well-suited for our research.

A. Basics regarding pipelines and cathodic protection

Pipelines are typically constructed from steel pipes, which are coated to protect against corrosion. Today, plastic coatings like polyethylene are the most commonly used. Insulating devices known as insulating flanges are installed along the pipeline to electrically isolate different sections, preventing the flow of electric current between them. Thus, the distance between two flanges defines a segment of the pipeline which could be considered separately regarding potential interference effects.

Since the primary material of the pipeline is steel, the main issue affecting its durability is corrosion, which is inevitable in an underground environment. In the oxidation reaction responsible for pipeline degradation, the steel structure of the pipeline serves as the anode. The soil acts as an electrolyte due to its water content, and the composition of the soil is an important parameter to consider in our study.

Cathodic protection is a technique used to prevent corrosion by applying a voltage to the metallic pipeline, converting it into a cathode, and thereby reducing oxidation. Several methods of cathodic protection exist, but we will focus on *Impressed Current Cathodic Protection* (ICCP) as shown in Fig.1. In ICCP systems, a rectifier is used to convert AC power into direct current, allowing for precise control of the injected current. This DC current is directed to inert anodes, which are buried near the pipeline section to be protected. The current then flows from these anodes to the pipeline through the soil, which acts as the electrolyte.

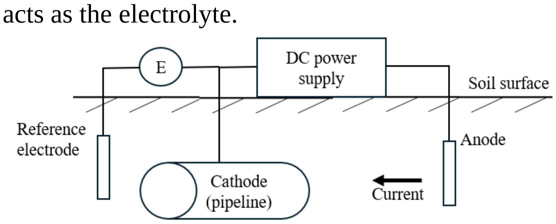

Fig. 1. Layout of an impressed current cathodic protection system

Additionally, a reference electrode is placed, as shown in Fig.1, to monitor and regulate the current flow. This electrode, along with the DC power supply, is vulnerable to damage if exposed to excessively high voltages. Proper protection measures are, therefore, crucial to ensure system integrity.

B. The principle of the numerical coupling model

The transmission line behavior is dictated by the well-known Telegrapher's equations

$$\frac{\partial \underline{V}}{\partial z} = -(R' + \mathrm{j}\omega L')\underline{I} = -\underline{Z}'\,\underline{I} \quad (2)$$

$$\frac{\partial \underline{I}}{\partial z} = -(G' + \mathrm{j}\omega C')\underline{V} = -\underline{Y}'\,\underline{V} \quad (3)$$

where R', L', G' and C' are the per-unit-length (pul) resistance, inductance, conductance, and capacitance matrices, respectively; z denotes the axis along the line and ω the angular frequency. These pul parameters are frequency-dependent. In the context of the paper, it is crucial that those pul parameters capture the electromagnetic coupling between aerial HVDC lines and underground pipelines.

As mentioned above, when the pipeline is located at some distance from the grounding electrodes of the towers, the conductive and capacitive effects are negligible between an aerial line and an underground pipeline due to the soil medium between them. Then, the main coupling appears in the series (longitudinal) impedance matrix $\boldsymbol{Z'}$ due to the ground circulating currents. Traditionally, the ground impedance was calculated via the Carson equation for overhead lines [8] or via the Pollaczek equation for underground cables [9]. More recently, the MoM-SO technique has been proposed as an alternative to overcome some limitations on the above equations [13][24]. The MoM-SO technique consists of a discretization of the surface of the conductors with a Fourier series formulation. Earth return currents are modeled through a discretization of the surrounding medium via the Green function [10]. A unique advantage of this method is the accurate representation of skin and proximity effects while accounting for both aerial and underground conductors.

The solution of equations (2) and (3) in numerical simulations is typically achieved by discretization of the following equation [25]

$$\underline{I_k} = \underline{Y_c}\,\underline{V_k} - \underline{H}\left(\underline{Y_c}\,\underline{V_m} + \underline{I_m}\right) \quad (4)$$

where $\underline{Y_c}$ denotes the characteristic admittance and $\underline{H}$ denotes the propagation function, the subscripts *k* and *m* refer to the line terminals.

II. Induction of an Overhead Transmission Line on a Pipeline

A. Description of the configurations

The pipeline considered in this study is covered by a polyethylene layer, whose characteristics are outlined in Table I below. The metallic part of the pipeline is detailed in Table II. The pipeline is buried 1 meter underground, with the surrounding soil having a resistivity of 100 Ω·m. The pipeline is grounded on one side with an earth electrode whose resistance is 1 Ω in series with a capacitor is 100 mF. This capacitor is used to prevent the current impressed by the cathodic protection to circulate in the ground.

TABLE I
CHARACTERISTICS OF THE PIPELINE'S COATING

Transverse resistivity	10^{17} Ω·m
Transverse resistance	10^{13} Ω/m^2
Relative permittivity	2.3
Thickness	4 mm

TABLE II
CHARACTERISTICS OF THE PIPELINE'S METALLIC PART

Inner radius of the metallic part	19.69 cm
Outer radius of the metallic part	20.32 cm
Resistivity	17E-7 Ω·m
permeability	300

The pipeline configuration remains consistent across all simulations, while the characteristics of the transmission lines differ as we examine the impacts of various line configurations. As discussed in the introduction, symmetric monopolar and bipolar configurations have different effects on the pipeline. In a bipolar configuration, the overhead line consists of five conductors: two shield wires, one Direct Metallic Return (DMR) conductor, and two poles (+320 kV and -320 kV). The DMR is grounded at one end and the other one is equipped with an arrester to limit overvoltages. The line is considered homogeneous, maintaining the same characteristics along its entire length. The bipolar line configuration, as described in Table III, is primarily based on [11].

We also analyzed the impact of 320 kV and 500 kV systems in a monopolar configuration, using four conductors (without DMR), as taken from [12]. However, increasing the voltage requires greater spacing between conductors to ensure proper insulation, as detailed in Table III. For voltages around 500 kV, it is typical to use three-bundle conductor configurations, as outlined in [7].

TABLE III
PARAMETERS OF THE OVERHEAD LINES [11,12]

	Voltage	parameters	Horizontal distance from the axis of the tower (m)	Height of the conductors at towers (m)	Conductor radius (mm)	Lineic resistance (Ohm/km)
Bipolar configuration	320kV	Sky wire 1	6.45	38.29	25.2	0.162
		Sky wire 2	-6.45	38.29	25.2	0.162
		Pole +	6.55	31.5	44	0.0292
		Pole -	-6.55	31.5	44	0.0292
		DMR	0	33.5	44	0.0292
Monopolar configuration	320kV	Sky wire 1	3.66	41.71	25.2	0.162
		Sky wire 2	-3.66	41.71	25.2	0.162
		Pole +	4.46	37.18	44	0.0292
		Pole -	-4.46	37.18	44	0.0292
	500kV	Sky wire 1	5.55	58.56	25.2	0.162
		Sky wire 2	-5.55	58.56	25.2	0.162
		Pole +	8.14	39.70	44	0.0292
		Pole -	-8.14	39.70	44	0.0292

The spans are 400 meters long, and the grounding resistance of each tower is 10 Ω. In our study, we assessed the influence of various parameters such as the exposure length (length of the zone where the influence is significant [7]) for potential interference effects, separation distance between the pipeline and the HVDC line, and soil resistivity. In each scenario, we maintained a 150 km section of overhead line and a 30 km section of pipeline, both uncoupled, near the converters. These sections aim to eliminate reflection issues [12]. A simplified diagram of the configuration is provided in Fig.2. According to this figure, the impact of the exposure length will be assessed by adjusting the number of 400-meter spans to achieve the target length.

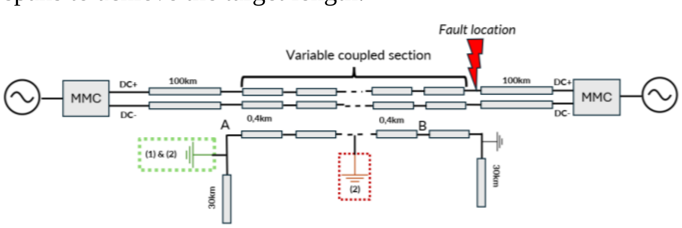

Fig. 2. Layout of the configuration studied for the coupling

B. Modeling in EMTP

In this paper, the Line/Cable Data module [13] from EMTP [6][13] is used for the HVDC transmission line modelling based on the configurations described above and accounting for the electromagnetic coupling with the pipeline. Under this approach, the line model obtained consists of six conductors (five in the monopolar case), including the pipeline. This module applies a two-step process to obtain a suitable model for transient simulations.

In the first step, per-unit-length (pul) electrical parameters (resistance, inductance, conductance, and capacitance) are computed for a frequency range. These pul parameters are obtained applying the MoM-SO technique combined with state-of-the-art formulas [15]. The inner part of the pipeline is considered as air but it does no have any real influence because the pipe's wall has a high permeability and experience a strong skin effect.

In the second step, the pul parameters are processed to obtain a suitable model for time-domain simulations using the Wideband modelling approach. The Wideband technique relies on rational approximation of the propagation function and characteristic admittance functions by means of curve fitting [25].

For the towers, the tower/phase insulator strings are modeled as flashover switches, with a withstand voltage of 900 kV, except for the shield wires, which are directly connected to the tower body. The tower itself is modeled with an inductance of 16 µH and is grounded through a 10 Ω resistance.

The pipeline is modeled as a cable covered with an insulating layer, resembling a single-core cable. The pipeline model used in the simulations is illustrated in Fig. 3, where the insulated parts are represented in grey.

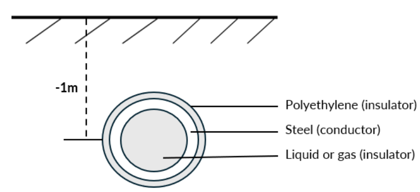

Fig. 3. Model of the pipeline on the EMT program

The converter, which is half-bridge, plays a critical role in evaluating the coupling effect, especially in terms of converter protection systems. These protections help prevent equipment damage by limiting current spikes along the line. Circuit breakers on the AC side can be opened to stop overvoltage and overcurrent conditions. The detection threshold is set at 4 p.u. of the DC current at the output of MMC, meaning the protection will be triggered when the current reaches 6 kA, given that the nominal current in the poles is 1500 A. By reducing the fault current spike, the duration of the induction phenomenon in the pipeline is limited. It is important to note that the current remains the same across different configurations and voltage levels by adjusting the rated power.

C. Results and analysis

Faraday's law of electromagnetic induction states that the induced voltage is proportional to the magnetic flux passing through the circuit. The larger the exposure length between the pipeline and the overhead line, the greater the magnetic flux impacting the pipeline. This means a larger section of the pipeline is exposed to the magnetic field generated by the HVDC line, thereby increasing the induced voltage. This behavior was confirmed through simulations in EMTP, where increasing the exposure parallel length can be compared to increasing the length between two insulating flanges. Fig. 4(a) illustrates the effect of exposure length, demonstrating a significantly higher impact in the bipolar configuration.

In a symmetric monopolar configuration, the influence of the fault current is much lower because no current loop is created between the converter and the line due to the absence of a ground connection at the converter. The voltage between poles remains, but with a different distribution. The consequence of the fault is not a high steady-state fault overcurrent like in the bipolar configuration but a large and sustained overvoltage on the healthy pole [16]. In contrast, in the bipolar configuration, the line impedance, which is directly related to its length, plays a crucial role. The results presented in this study assume a separation distance of 50 meters between the overhead line and the pipeline. In the bipolar case, the relationship between exposure length and peak voltage is approximately linear, whereas in the monopolar case, the peak voltage on the pipeline will reach a maximum value resulting in an induced voltage independent of the exposure length after attaining this limit.

The influence of the separation distance between the overhead line and the pipeline was thoroughly investigated, with distances ranging from a few meters to several dozens of meters. This parameter plays a crucial role in the electromagnetic coupling between the two systems. As illustrated in Fig. 4(b), the impact is particularly pronounced in the case of a bipolar configuration, where induced voltages reach critical levels. For example, to maintain induced voltages below the 2 kV threshold, a separation margin of approximately 1.6 km between the overhead line and the pipeline is required for an exposure length of 25 km.

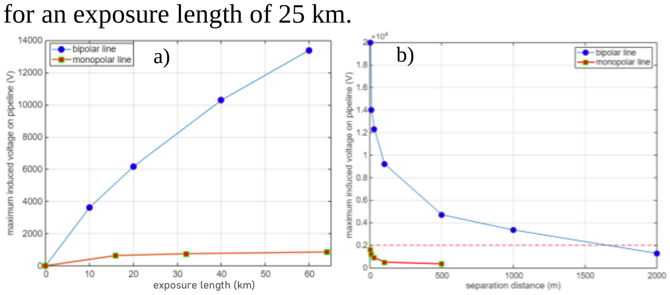

Fig. 4. Influence of : a) the exposure length on pipe disturbance for a 50m separation.
b) the separation distance for a 25km exposure length.

These simulations were performed to assess the highest voltage levels induced on the pipeline. The fault was simulated 30 km downstream from the converter station, as shown on Fig. 2. For the bipolar configuration, the voltage was calculated at the "floating" end of the pipeline corresponding to point A in Fig. 2., which is furthest from the ground connection. In the monopolar configuration, the highest voltage was measured at point B, at the pipeline section closest to the fault. The results are presented in Fig. 5.

Fig. 5. depicts the induced voltage waveform for a 20km coupled pipeline in both configurations. The frequency of the induced voltage in the monopolar fault case is much higher than in the bipolar configuration, corresponding to the behavior of the pole currents. In the bipolar configuration, a sudden surge in the current in the faulty pole causes a rapid change in current (di/dt is high), as shown in Fig. 5(a). However, in the monopolar fault case, only a small disturbance occurs, characterized by oscillations, as seen in Fig. 5(b). The oscillations are directly associated with the disturbance in the faulty pole, exhibiting the same 2,5kHz-frequency as observed in Fig. 5(b).

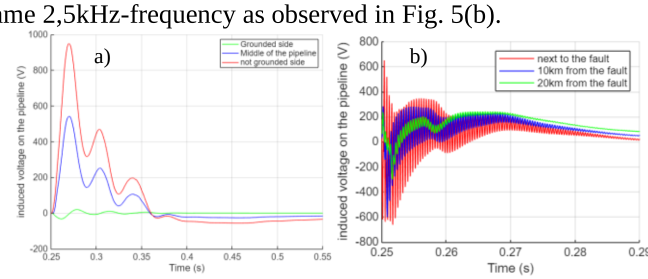

Fig. 5. Overvoltage at several positions along the pipeline: a)Bipolar configuration; b) Monopolar configuration

D. Damage to the pipeline system

The primary risk of damage is not to the pipeline itself, but rather to the cathodic protection equipment and the insulating joints. As stipulated in [17], the interference voltage between the metallic pipeline system and the earth, as well as the voltage between any electric or electronic equipment connected to the pipeline and the earth, must not exceed 2,000V (RMS value). Similarly, the voltage difference across an insulating joint must remain below this 2,000 V limit. The faults analyzed in this study, with durations ranging from 0.1s to 0.04s, are significantly longer than transient phenomena like lightning-induced surges, which last only a few hundred microseconds. Due to this substantial difference in timescale, it is not possible to directly use the data or thresholds established for another type of event (such as lightning-induced surges) to fix the damage threshold in this case.

Contrary to the approach outlined in [17], which considers the root mean square (RMS) value of the voltage, our analysis focuses on the maximum voltage, as it better reflects the transient nature of the phenomenon under study. Focusing on the maximum voltage is also particularly relevant in the safe side because it considers the worst-case scenarios, ensuring that protective measures and system designs can handle even the most extreme voltage spikes. As a result, a 2.8 kV peak voltage threshold was established.

To ensure compliance with this rule throughout the entire pipeline system, we analyzed the voltage distribution along the pipeline in the presence of a bipolar HVDC line, as it is the only configuration that poses a significant risk of damage with overvoltage above 2.8kV. In the studied configuration (Fig. 2), the induced voltage exhibits a linear increase along the pipeline. To mitigate this voltage rise, we explored the effect of adding extra grounding connections at one end or at both ends for two cases of separation distances between the pipeline and the HVDC line 3 meters and 25 meters (see Fig. 6)..

Two grounding scenarios were considered with the same fault location as before at the end, next to the rectifier: (1) placing ground connections at both ends of the pipeline, and (2) supplementing this setup with an additional ground connection at the pipeline's midpoint. The locations of these ground connections are represented in Fig. 2 depending on the scenario considered. The necessity of each scenario depends on the separation distance. For the two cases presented Fig. 5., adding a midpoint ground connection is unnecessary, as grounding at both ends effectively limits the voltage rise, keeping it within the 2,800 V threshold.

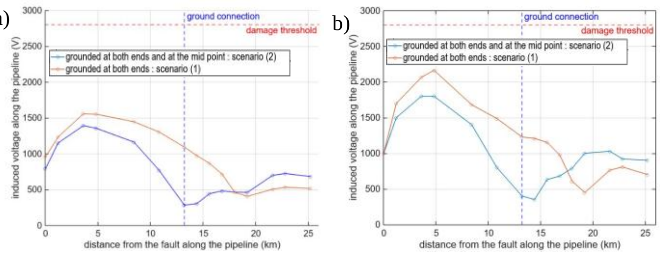

Fig. 6. Crest voltage distribution along the pipeline during the fault for different distance of separation between the line and the pipeline: a) 50m; b) 3m

These calculations show that overvoltage along the pipeline can be reduced appropriately with a limited number of grounding electrodes.

E. The effects of overvoltages on humans in contact with the pipeline

An operator could come into contact with the pipeline during a fault, which might occur during maintenance when the operator touches a valve or during the installation of the pipeline when it is not yet buried. The calculations in this section were conducted in accordance with the IEC 60479 standard [18], which addresses the effects of electric current on humans and animals.

A key challenge in this analysis is modeling the human body as accurately as possible by considering variations in impedance. The impedance of the human body changes with frequency and voltage, especially the impedance of the skin, which can be modeled as a parallel combination of a capacitor and a resistance. Our study focuses primarily on voltage values exceeding 800V. At these levels, skin impedance becomes negligible, allowing the body to be modeled as a simple resistance.

In this case, we examine a scenario where current flows between a hand and a foot on the same side of the body, as illustrated in Fig. 7. The contact area is assumed to be large, and the conditions are considered dry. The final body impedance calculated for this scenario is 620 Ω, factoring in that the total resistance of the body is about 20% lower for a hand-to-foot current path compared to a hand-to-hand path [18]. This value represents the median: 50% of the population has a higher impedance, and the other 50% has a lower one.

The impedance of shoes and contact with the ground cannot be ignored. The contact impedance, R_c , depends on soil resistivity according to the relation

$$R_c = 1.5\rho$$

, where ρ is the soil resistivity. In our case, $R_c = 150\Omega$. The resistance of shoes varies with their type and condition: dry shoes can have a resistance as high as 10 MΩ, while wet shoes can occasionally have resistances below 5 kΩ [19, 20]. For this study, we used an intermediate shoe resistance value of 500 kΩ.

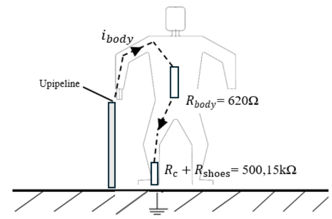

Fig. 7. Simplified schematic diagram for a current path hand to foot

Since the induced current in the pipeline is impulsive, calculating its RMS value is not straightforward. A method described in [21, 22] calculates the energy transferred to the body over time using the equation:

$$E = \int U_{\text{pipeline}} . i_{\text{body}} \, \mathrm{d}t \qquad (2)$$

Once the energy is computed, the time required to reach 95% of the final energy, denoted t_i , is recorded to calculate the RMS value of the current using the formula:

$$I_{\text{body,RMS}} = \sqrt{\frac{1}{t_i} \int_0^{t_i} i_{\text{body}}{}^2(t) \, \mathrm{d}t} \qquad (3)$$

The fault current magnitude should always be considered in conjunction with the fault duration. Naturally, the longer the fault lasts, the more severe its impact. To rapidly assess the potential danger of a situation, the IEC 60479-1 standard provides a graph that accounts for both current and duration of the fault. Table IV presents the results for the model depicted in Fig. 7 for two voltage levels in a monopolar configuration.

TABLE IV
CHARACTERISTICS OF THE IMPULSE CURRENT THROUGH HUMAN BODY, MONOPOLAR CONFIGURATION

Poles voltage	RMS Body current (mA)	Energy (J)	Fault duration(ms)
320kV	0.4	0.0018	26
500kV	0.7	4E-4	3

According to table IV, the impact of a 500kV line is lower than the impact of a 320kV line. The variation in line inductance is defined by a relationship in which the conductor radius appears in the denominator. In a bundled configuration, an equivalent radius can be defined, which increases the overall radius and consequently reduces the line inductance [23]. This reduction in inductance results in lower surrounding magnetic fields, thereby minimizing the induced voltages and currents in the pipeline.

We also evaluated the impact of a bipolar configuration depending on the separation distance which is a key parameter to evaluate the induction. The exposure length used to obtain the results presented in Table V is 30km.

TABLE V
CHARACTERISTICS OF THE IMPULSE CURRENT THROUGH HUMAN BODY, BIPOLAR CONFIGURATION

Separation distance (m)	RMS Body current (mA)	Energy (J)	Fault duration (ms)
10	10.2	5. 2	126

50	7.7	4.5	150
100	6.4	3.4	153

Although elevated current levels are observed, the short fault duration ensures that there is no significant risk to individuals in contact with the pipeline, as demonstrated in Fig. 8. For the points that represent the bipolar configuration, the separation distance is specified above them.

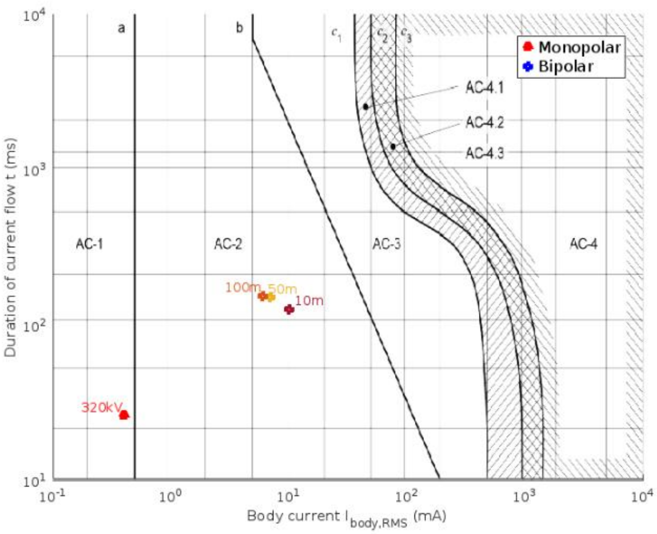

Fig. 8. Conventional time/current zones of effects of AC currents on persons for a hand to feet current path.

Points from the bipolar configurations exhibit a greater impact than those from the monopolar configurations. Due to the short fault duration of 500kV, the corresponding point was not included in the graph, but it involves a neglectable effect on humans. The data points are distributed within two zones: AC-1 and AC-2, both of which are associated with negligible physiological effects. Specifically, below curve b, perception and involuntary muscle contractions may occur; however, no organic damage is anticipated. More details can be found about the different zones in the IEC 60479-1 standards, table 11.

Different prevention methods can be established by gas transportation stakeholders to prevent any risk. The first one is the implementation of Collective Protective Equipment (CPE), such as a welded mesh connected to the pipeline, to ground it during the intervention and prevent potential differences. Then, a shoe resistance value of 500 kΩ is taken in our study but the use of Personal Protective Equipment (PPE) will significantly increase this value.

III. Conclusions

In this paper, different induction scenarios of HVDC overhead lines on a buried pipeline are explored. An electromagnetic transient program is employed to develop a comprehensive model of the configuration, taking into account both converter and cable behavior. Through time-domain simulations, we assess the impact of two key parameters: the exposure length and the separation distance between the overhead line and the pipeline. While overvoltage remains below 1 kV in a symmetric monopolar configuration, regardless of these parameters, significant overvoltages are observed in the bipolar configuration. Results indicate that the risk increases with longer exposure lengths and shorter separation distances. Depending on the measurement point along the pipeline, voltages of up to 10 kV can occur during transients lasting between 0.04 s and 0.1 s. It should be pointed out that they are impulse shape voltages.

As these parameters are often dictated by environmental constraints, it is challenging to mitigate the impact by simply altering the separation distance. However, it has been demonstrated that the induction effect can be significantly reduced by employing straightforward technical solutions such as grounding electrodes. The placement of ground connections must be optimized for each specific configuration to ensure that the peak overvoltage remains below 2.8 kV, thus protecting the cathodic protection equipment. This approach also helps prevent the risk of electrocution, even though calculations indicate a very low risk to personnel in contact with the pipeline without personal protective equipment (PPE).

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