Analysis of Electromagnetic Interference of Multiple Power Transmission Lines in the Gobustan Region of Baku-Tbilisi-Ceyhan (BTC) Pipeline

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Abstract*—Energy transmission lines, metal pipelines, and rail systems share the same routes due to environmental and economic factors. The electromagnetic interactions occurring along these routes can lead to significant technical problems and some safety concerns. Since these effects can cause partial discharge and corrosion in metal pipelines, solutions are being developed to analyze and mitigate such impacts. In this study, the effects of electromagnetic interference on the Baku-Tbilisi-Ceyhan Oil Pipeline (the standard nominal pipe size 42") are analyzed under both steady-state and fault conditions. In steady-state analyses, when the cathodic protection system is in operation, the current density is reduced by 73.75% and the touch voltage by 74.2%. In fault conditions, it is observed that the step and touch voltages did not exceed the limits specified by international standards. The results highlight the significant impact of cathodic protection systems on safety and system reliability.

Keywords*—cathodic protection, transmission line, metal pipelines, EMI.

I. INTRODUCTION

In the developing world, population density is steadily increasing. Along with the growing population, the increasing investments in energy, industry, and transportation make it necessary to expand infrastructure in these areas. As the infrastructure for natural gas, electricity, oil, and railway lines increases, the issue of the routing of these lines comes into focus. Due to environmental (terrain conditions, usage characteristics) and economic reasons (high expropriation costs), parallel or intersecting routes are preferred. In this situation, electrical lines, oil and gas pipelines, and railway tracks share the same route. On these routes, electromagnetic interactions occur between energy transmission lines and nearby metal pipelines, leading to electromagnetic interference (EMI) [1, 2].

The EMI that occurs creates various risks in terms of equipment and personnel safety in the operation of the pipeline. From a personnel safety perspective, it presents electrical hazards for individuals in contact with the exposed parts of the pipeline, while corrosion that may occur in the pipelines can lead to serious malfunctions in the pipeline [3, 4]. In rail systems, it also causes disruptive noise in electronic circuits and security issues in system safety. EMI with these effects typically consists of three components: capacitive, inductive, and conductive components. The capacitive coupling is applied to above-ground pipelines and is often overlooked in underground pipelines. Conductive coupling occurs between the overhead lines and the pipeline, and it is important in cases where transmission lines are faulty or grounding errors occur. Inductive coupling, on the other hand, is a component caused by the magnetic field generated by the transmission lines, which affects both overhead and underground transmission lines [3-6].

There are many standards addressing AC interference in metallic pipelines, which include limitations for keeping electromagnetic interference within safe boundaries. These limits include the acceptable interference voltage caused by AC interference sources in pipelines under normal operating conditions. These standards provide information aimed at reducing the risks encountered [3,7].

There are alternative solutions in the literature for analyzing and reducing the effects of EMI occurring between energy transmission lines and nearby metal pipelines. Wang et al. [8] investigated the levels of electromagnetic interference (EMI) in both normal and single-phase fault conditions in an AC transmission line and an embedded metal pipeline in Shanghai. To reduce the AC EMI levels, they implemented zinc strip mitigation measures and conducted analyses using the Distribution Electromagnetic Field, Ground, and Soil Structure Analysis (CDEGS) software. Their results demonstrated that the proposed method effectively reduced the interference. Wang et al. [9], in their study, proposed combining field-measured ballast and soil resistivity data with simulation modeling in the CDEGS program for EMI occurring between electrical transmission lines and railways. The proposed method eliminates the need for the costly field measurement of ballast resistance, providing a new approach for determining ballast resistance. Noureddine et al. [10] used a method based on Faraday's and Biot-Savart's laws to model the inductive coupling between a metallic pipeline and an overhead

transmission line. Potential safety risks are mitigated by placing resistors at both ends of the pipeline. The obtained results are compared with those derived from the Carson equations, demonstrating the validity of the proposed method. Cetin et al. [11] investigated the EMI occurring between an overhead transmission line and a natural gas pipeline. They calculated and compared the resulting touch and step voltages under different tower grounding resistances, shielding, and soil resistance conditions. Nowak et al. [12] investigated the electromagnetic effects of having

400 kV and 110 kV power transmission lines on a common transmission path and studied the risk of electric shock.

In this study, the effects of electromagnetic interference (EMI) on the Baku-Tbilisi-Ceyhan Oil Pipeline (42") are analyzed in detail under both steady-state and fault conditions. Elective interactions between overhead transmission lines and embedded metal pipelines are examined using the Right of Way (ROW) program of the CDEGS simulation software. The effects of these interactions on human safety and the structure of the pipeline are evaluated.

II. ELECTROMAGNETIC INTERFERENCE

Electromagnetic waves and currents that cause unwanted conditions in electrical systems are referred to as electromagnetic interference (EMI) [13]. In electrical circuits, the current flowing through a conductor generates a magnetic field, while static charges and voltage sources in the circuit create an electric field. The electric field vectors consist of components from both the magnetic and electric fields. Alternating current in power lines generates an electromagnetic field around surrounding metallic objects. When power lines are adjacent to pipelines, this can lead to faults in the operation of the pipeline, safety issues, and accelerated corrosion [5].

There are three main coupling mechanisms of EMI: capacitive, inductive, and conductive coupling [5].

Capacitive Coupling

It occurs between conductors with different potentials. As a result of the potential difference between different conductors, an electric field is generated, and a capacitive effect is created between the conductors [14]. The occurrence of this capacitive coupling is shown in Fig. 1 [15]. When a voltage is applied to a conductor, an electric field is generated around it. A different conductor nearby is exposed to this electric field. This creates a capacitance between the two conductors that allows the transfer of electric charge from one to the other. The movement of charges can cause unwanted signals to pass from one conductor to the other when these signals are present [2, 14].

Pipelines above the ground are subject to capacitive coupling. If the pipeline is located near a high-voltage power line, a capacitance is formed between the power line and the transmission line. This capacitance varies depending on the distance between them, the voltage in the transmission line, and the operating conditions of the transmission line [15]. In cases where there is a deficiency in the pipeline's insulation and grounding, the effects of capacitive coupling, such as signal distortion, communication interference, and data loss, tend to increase [7].

Inductive Coupling:

In high-voltage overhead lines, time-varying magnetic fields are generated around the conductors due to the alternating current passing through them. The resulting magnetic field induces an electromotive force (EMF) that creates currents and voltages on a metallic pipeline located near the overhead line and installed parallel to the conductor. This phenomenon is referred to as inductive coupling [10, 16]. A simple illustration of inductive coupling is shown in Fig. 2.

The inductive effect caused by a high-voltage line on a pipeline located nearby varies depending on the distance between them, soil resistivity, the magnitude of the current flowing through the conductor, and the duration of exposure [15]. Inductive coupling, which also changes depending on the characteristics of the power transmission line, causes corrosion in pipelines, leading to a reduction in their service life and posing safety risks to maintenance personnel. Additionally, it can also lead to unwanted fires on the line. To eliminate or minimize these effects, measures such as installing grounding rods or grounding mats along the pipeline are among the solutions [3,16,17].

Conductive Coupling

In high-voltage transmission lines, in the case of a ground fault, electrical arc, lightning, or switching fault, the fault current flowing to the ground causes a potential rise. If metal

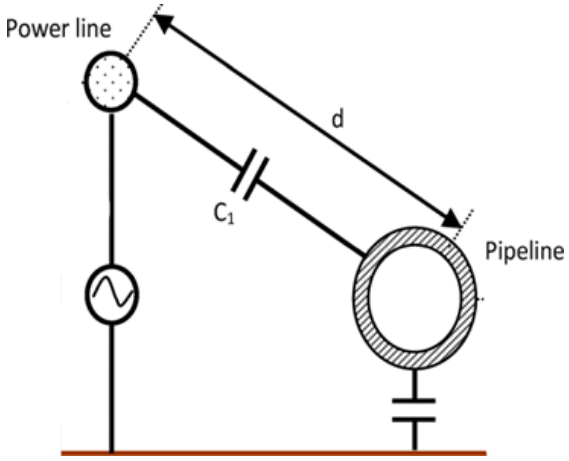


Fig. 1. Capacitive Coupling [15].

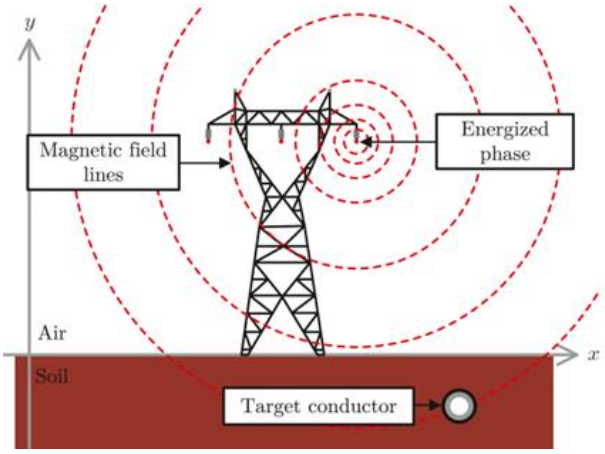


Fig. 2. Inductive Coupling [16].

pipelines located underground are near this ground fault point or within the affected area, a difference in potential occurs between the surface of the pipeline and the surrounding soil potential. This potential difference can lead to noise and unwanted signal transmission between circuits, as well as affecting the pipeline's coating [14, 18].

In the event of a fault, if the potential rise in the ground exceeds the voltage that the pipeline coating can withstand, perforations occur in the coating, and if the voltage continues to increase, melting on the surface of the pipeline may occur. Conductive coupling with these effects depends on parameters such as the total fault current, the characteristics of the grounding systems, and the distance between them. To reduce the negative effects, adequate insulation, surge protection devices, and isolated grounding systems are used [19].

III. SIMULATION STUDY

This study investigates the electromagnetic interference (EMI) effects of two 330 kV single-circuit, one 330 kV double-circuit, and one 220 kV double-circuit electric transmission lines on the Baku-Tbilisi-Ceyhan Oil Pipeline (42"). Modeling and measurement data are obtained using Google Earth software, while simulation studies and analyses are conducted using the CDEGS software.

The coordinates of the pipeline and overhead transmission lines are integrated into Google Earth software, and the intersecting areas along the defined routes are measured and transferred to the ROWCAD module of the CDEGS software. Through this module, the mechanical and electrical parameters of the transmission lines and the pipeline are modeled, and electromagnetic interferences are calculated using the ROW program.

As a result of the analyses, the length of the 330 kV (A) single-circuit line is determined to be 29.6 km, the length of the 330 kV (B) single-circuit line is 31 km, the length of the 330 kV double-circuit line is 30.9 km, and the length of the 220 kV double-circuit line is 31.6 km. The simulation results reveal that the overhead transmission lines analyzed generally extend in a parallel manner along the examined region. The intersection points between the overhead power transmission lines and the 42" crude oil pipeline have been thoroughly examined, and these intersection points are clearly shown in Fig. 3.

As a result of the examinations, four intersection points (A, B, C, and D) have been identified. The first intersection point (A) is where the 220 kV double-circuit overhead transmission line intersects with the oil pipeline. The second intersection point (B) is where only the 330 kV double-circuit transmission line intersects with the pipeline. The third intersection point (C) shows where the 330 kV double-circuit transmission line intersects with the pipeline. The fourth intersection point (D) is where the 330 kV single-circuit transmission line intersects with the pipeline. These intersection points allow for a more detailed analysis of the electromagnetic effects of the power transmission lines on the crude oil pipeline.

During the modeling process, the intersection areas of the power transmission lines and the pipeline, where the effects of electromagnetic interference are more pronounced, are also taken into account. In Fig. 4, the analysis model developed to more clearly demonstrate the interaction between the power transmission line and the pipeline has been simplified and made visually more understandable.

At the first intersection point along the route, at point A, the 220 kV energy transmission line intersects with the 42" crude oil pipeline. The intersection angle between the lines is 35.52° and the intersection point is located at the 16th kilometer of the pipeline. The points indicated by the letters B, C and D in Fig. 5 indicate the intersection points along the route. It was determined that the intersection point of the crude oil pipeline with the 330 kV single-circuit energy transmission line (Point B) is located at the 18.12 km mark of

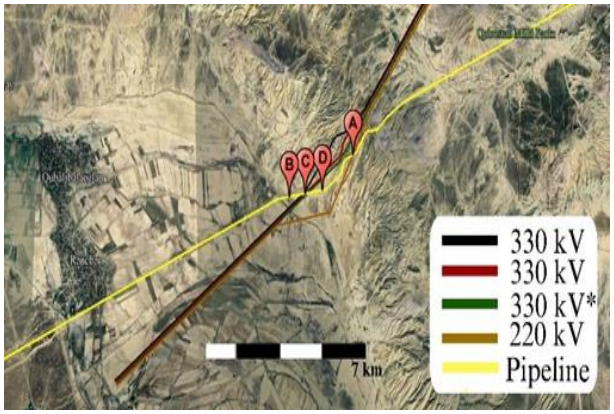


Fig. 3. Intersection Points of Transmission Lines and the Baku-Tbilisi-Ceyhan Oil Pipeline.

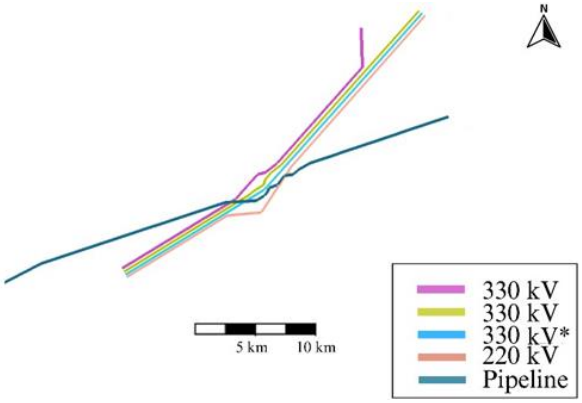


Fig. 4. Simplified CDEGS Analysis Model.

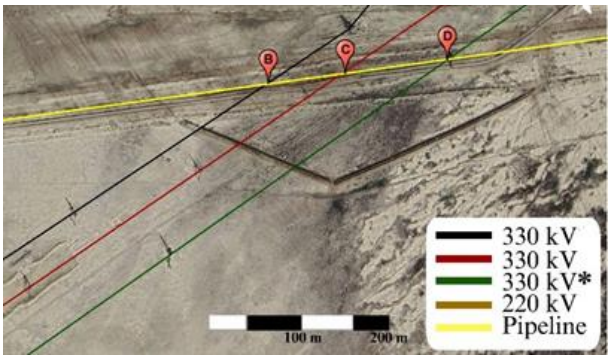


Fig. 5. B, C and D Intersection Points

the line with an intersection angle of 28.92°. It was determined that the intersection point of the crude oil pipeline with another 330 kV single-circuit energy transmission line (Point C) is located at the 18.02 km mark with an intersection angle of 27.16°. Finally, the intersection point of the crude oil pipeline with the 330 kV double-circuit energy transmission line (Point D) is located at the 29.44° It was determined that the pipeline is located at the 17.8 km mark with the intersection angle. Fig. 6 and 7 provide detailed views of the intersection points B, C and D in the developed analysis model. In the light of these findings, a total of four different intersection points were determined between the overhead energy transmission lines and the crude oil pipeline along the examined route.

The types of conductors and conductor carriers used during the modeling of power transmission lines are of great importance in terms of examining the effects of electromagnetic interference. In this context, the types of conductors and carriers used in the analysis of the route where the interference effects are evaluated are shown in Table I. An important parameter for making more precise measurements during the modeling and analysis studies is soil resistance. In the analysis of the stations of the examined line, the soil resistance used is approximately considered to be 2 Ω.

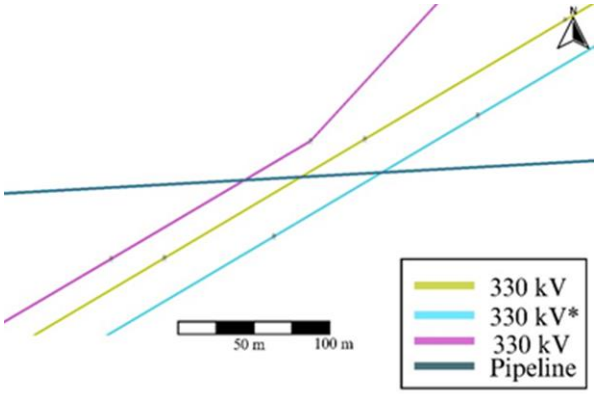


Fig. 6. The B, C and D intersection points of the developed analysis model

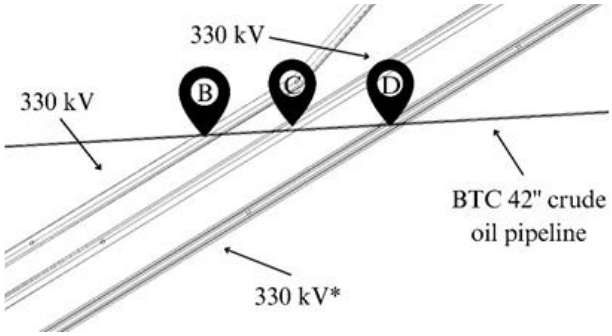


Fig. 7. Fig. 7. B, C and D intersection points detail of the developed analysis model

TABLE I. THE TYPES OF CONDUCTORS AND TOWER USED.

Electric Transmission Line	Tower types	Types of conductors
330kV single circuit	3A1	ACSR Cardinal
330kV single circuit	3A1	ACSR Cardinal
330kV double circuit	PA1	ACSR Cardinal
220kV single circuit	ZA1	ACSR Drake

IV. RESULTS AND DISCUSSIONS

Simulations are carried out by considering physical parameters such as intersection points along the line route, types of carriers and conductors, and soil resistance. In this context, maximum touch voltage and current density values are analyzed, and their effects on the pipeline are examined. This study focuses on investigating the inductive interactions of power transmission lines with the crude oil pipeline. For this purpose, steady-state analyses under balanced loading conditions and three-phase short-circuit fault condition analyses are performed. Additionally, separate scenarios are evaluated for both open and closed conditions of the pipeline's cathodic protection system.

Steady-State Analyses

Under steady-state operating conditions, the most significant electromagnetic interference mechanism observed is inductive interference. In this context, the most adverse interference scenarios related to the induced voltage on the pipeline have been identified, and improvement efforts for these scenarios have been carried out, considering the interaction mechanism.

Electromagnetic interference effects have been examined

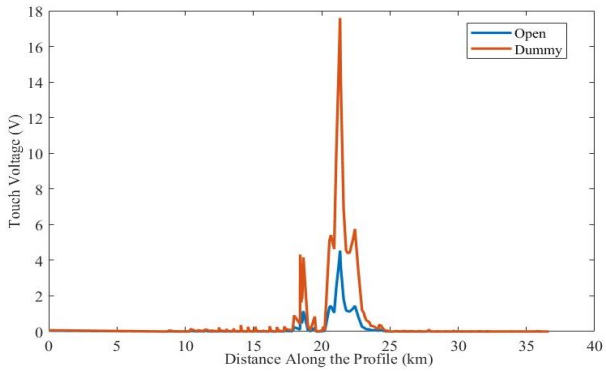


Fig. 8. Changes in touch voltage under normal operating conditions with no cathodic protection (dummy) and with cathodic protection (open)

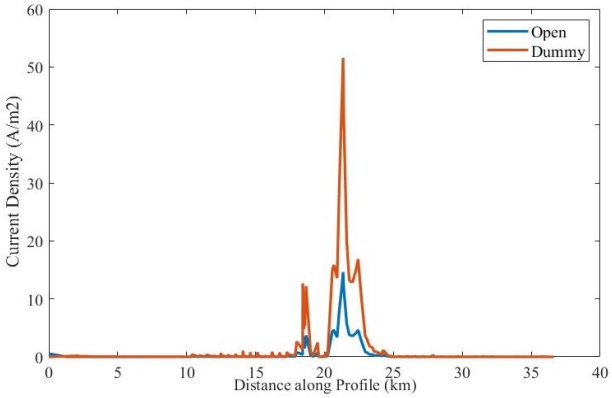


Fig. 9. Changes in current density under normal operating conditions with and without cathodic protection.

at four points identified along the Baku-Tbilisi-Ceyhan (42") oil pipeline. Additionally, analyses have been conducted under operating conditions where the cathodic protection system is either open (inactive) or closed (active). In Fig. 8, touch voltage values are presented for the cases where the cathodic protection is off (dummy) and where the pipeline is protected by the cathodic protection system (open).

The analysis results show that the lack of cathodic protection has significant effects on current density and touch voltage. In the absence of cathodic protection, the touch voltage reaches its maximum value of 17.59 V at the 22 km point, whereas with the cathodic protection system in place, this value drops to 4.53 V. Similarly, the leakage current density on the pipeline reaches its maximum value of 51.56 A/m² at the 17 km point without cathodic protection, while with the cathodic protection system active, this value decreases to 13.53 A/m².

Fig. 9 shows the changes in current density for the two different operating conditions of the cathodic protection system. In the absence of cathodic protection, it is observed that operating pipelines located in close proximity to high-voltage transmission lines may be exposed to severe electromagnetic effects. Current densities and touch voltages show significant differences in certain sections of the pipelines, indicating the need for additional protection and monitoring in these areas.

Fault Condition Analysis

Fault condition analyses are conducted under the assumption of a fault occurring in phase A of the 330 kV single-circuit transmission line. In these analyses, the fault current is determined to be 12.35 kA, and the fault angle is -83.87°. The step voltage and touch voltage changes obtained from the simulations are presented in Fig. 10 and Fig. 11, respectively.

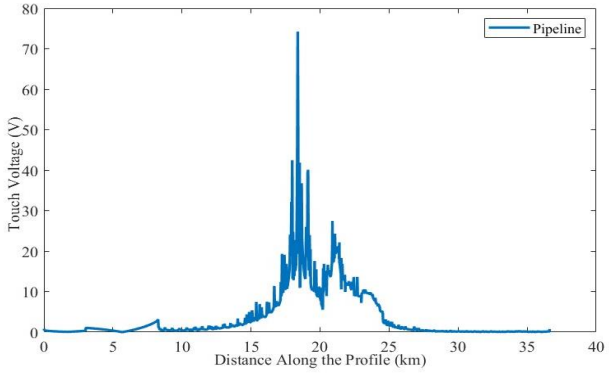


Fig. 10. Changes in touch voltage obtained under fault conditions.

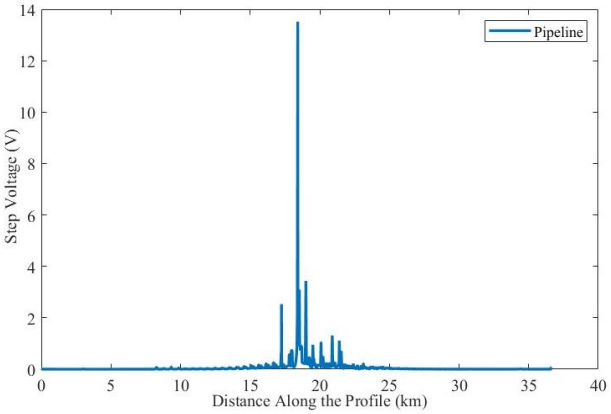


Fig. 11. Changes in step voltage obtained under fault conditions.

Step voltage refers to the voltage a person experiences between their feet due to the potential difference on the ground surface during an electrical fault, and its compliance with international standards is critical for human safety. When the cathodic protection system is active, the touch voltage at the 18.63 km point is measured at 74.24 V, while the step voltage is measured at 13.518 V. This indicates that a specific section of the pipeline is exposed to high touch voltages, which presents a significant safety risk for that area. This information is crucial for implementing safety measures and reducing potential risks.

International standards have been established to keep electromagnetic interference in pipelines within safe limits. ISO 18086 [20] recommends maintaining the current density below 100 A/m² and the touch voltage within the range of 15-25 V RMS to prevent AC-induced corrosion in embedded pipelines. EN 50443:2011 [21] sets the limits for electromagnetic interference effects at a current density of 100 A/m², and a touch voltage limit of 50 V RMS. EN 50443 emphasizes that the touch voltage should not exceed 50 V RMS under normal operating conditions and 1500 V under fault conditions. These standards have been developed to ensure both safety and minimize corrosion risks under pipeline operating conditions. The criteria aimed at preventing hazardous currents on individuals in contact with the pipeline have been compared with the analysis results to assess the compliance of pipeline safety with the standards.

V. CONCLUSIONS

In this study, the electromagnetic interference effects on the Baku-Tbilisi-Ceyhan (42") Oil Pipeline have been examined in detail under both steady-state and fault conditions. The findings obtained can be summarized as follows:

Steady State Analyses

- When the cathodic protection system is active, the current density decreases by approximately 73.75%, and the touch voltage decreases by 74.2%.
- Values obtained are below the limits of 100 A/m² current density and 50 V RMS touch voltage set by the EN 50443:2011 standard. This indicates that the system operates within safe working limits.

Fault Condition Analyses

- Three-phase short-circuit fault scenarios are examined, and significant increases are observed in both step voltage and touch voltage parameters.
- Although the touch voltage momentarily reached levels as high as 74 V, it remained below the limit values of 1500 V or 2000 V set for pipelines in the TS EN 50443 standard.
- It is determined that both step voltage and touch voltage don't exceed the safety limits of international standards, and therefore, the system is assessed as safe.

In future studies, it is recommended to investigate the effect of the pipeline's physical dimensions on the induced voltage, as well as to examine in detail different fault scenarios, such as line-to-ground short circuits.

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