Original Article

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Prediction and mitigation of AC interference on the pipeline system

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Abstract: The purpose of this paper is to predict and mitigate AC interference on buried pipeline systems due to transmission lines. Modeling and field verification of AC interference is done. The article also presents the issue of optimizing the mitigation measures. The paper uses the field data on soil resistivity, transmission line, and pipeline details to develop a model using current distribution electromagnetic interference grounding and soil structure analysis (CDEGS) software to predict the AC interference on the pipeline system. The model is validated with field measurements, and post-mitigation measures are considered. Mitigation measures are optimized to develop an economical mitigation plan. The case demonstrates the use of modeling techniques to predict and mitigate AC interference on pipelines. The field validation of modeling results helps improve the modeling results and plan optimized mitigation measures. The study requires providing comprehensive field data relevant to the pipeline system under consideration. The accuracy of the field data may have a bearing on the outcome of the study. The study enables designing and optimizing mitigation measures using modeling. Comparisons with field measurements help achieve desired pipeline system integrity against AC corrosion.

Keywords: coating stress voltage; leakage current density; modelling; prediction; simulation.

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Abbreviations

AC	alternating current
AF	alternating frequency
CDS	current distribution, electromagnetic fields, grounding, and soil structure analysis
CP	cathodic protection
DC	direct current
DFBE	dual fusion bonded epoxy
EMF	electromagnetic field
FGL	finished ground level
TLP	test lead post

1 Introduction

Transmission lines provide convenient means for electricity transportation in bulk from generation centers to demand centers. Increasing electricity demand requires laying more transmission lines to enable the timely availability of electricity at demand centers. Cross-country pipeline networks, on the other hand, provide an economical and safe mode of transport for highly inflammable hydrocarbons in bulk. Any pipeline operator needs to maintain the integrity of the pipeline networks against internal and external corrosion. Coatings provide primary protection against external corrosion to underground pipelines. Secondary protection is provided by suitably designed cathodic protection systems (Kim et al. 2004; Thakur 2017; Thakur et al. 2021).

The instances of pipelines sharing corridors with transmission lines (Jacquet 1995) are common. Being linear systems, pipeline networks, and transmission lines either cross one another or run parallel at many places.

Proximity with transmission lines influences/accelerates the external corrosion in pipeline systems (Adedeji et al. 2018; Guo et al. 2015) due to AC interference. In the presence of AC, the effectiveness of CP systems to prevent external corrosion of pipelines is impacted severely. Harmonics in induced voltage may further diminish the performance of CP systems (Charalambous et al. 2018; Chen et al. 2018) to prevent external corrosion. Coating stress voltage on pipelines on AC interference is required to minimize shock hazards and avoid coating failures.

AC interference on pipelines due to nearby transmission lines is influenced by factors like operating voltages, pipeline characteristics, soil resistivity, tower configurations, tower location, inter-distance between transmission lines and pipelines, earthling systems, operating high-voltage currents, and load currents (Brenna et al. 2014; Cole and Marney 2012; Lalvani and Lin 1994; Thakur et al. 2020). Soil resistivity is a function of soil properties such as pore size, particle size distribution, water content, connectivity, temperature, and medium (Kuang 2016). Soil resistivity measurement is vital for AC interference modeling and the success of mitigation measures.

Experimental studies (Büchler 2020; Chen et al. 2021; Goidanich et al. 2010; Kuang and Cheng 2014, 2015a,b, 2017; Shabangu et al. 2018; Zhu et al. 2014) are available to determine the dependence of AC corrosion on various factors, which vary with time and location. Computer-based simulation and modeling studies are performed considering single circuit configuration (Lucca 2018; M'ziou 2020; Popoli et al. 2021; Tiegna et al. 2013). A buried pipeline can be represented by an electrical circuit connected to the earth (Samouëlian et al. 2005). The mutual impedance between pipeline and power line can be determined by modeling pipeline as a loss transmission line (Carson 1926; De Lacerda et al. 2007).

The induced voltage on the pipeline can cause a shock hazard to people standing near the pipeline or touching the pipeline. Further increased stress voltage across the pipeline may cause puncture/degradation of the pipe coating and insulating joints.

Modeling studies help predict the coating stress voltage on the pipeline network and plan mitigation measures to minimize the coating stress voltage. A dual model considering circuit analysis (involving equivalent electrical circuits) and finite element method (numerical solution considering differential equations) helps predict the coating stress voltage (Christoforidis et al. 2005). Modeling can be helpful to predict and optimize mitigation measures (Cristofolini et al. 2018; Dabkowski and Taflove 1979; Markovic et al. 2005; Popoli et al. 2019). Depending upon the coating type, high coating stress voltage, especially during fault conditions, may result in the breakdown of the coating.

This study predicts the coating stress voltage on the pipeline system considering critical factors like transmission line loading, voltages, tower configuration, and soil characteristics. Soil characteristics are measured in the field and modeled in three layers. The circuit model includes transmission line loading parameters and conductors' orientation to predict coating stress voltage. Mitigation measures are incorporated in the model to determine post mitigation results. Field measurements using data loggers are compared with the model for validation. Based on the results, the model is revisited to optimize the mitigation measures.

2 Materials and methods

2.1 Materials

The electric circuit model approach and finite element method (FEM) have been used for AC interference analysis involving multiple soils and conductors. The pipeline system has been modeled on an electric circuit approach involving:

- Set up of circuit model
- Calculations of line parameters
- Analysis of circuit.

The circuit model setup included importing polylines from Google Earth. The polylines provided pipeline and transmission line route details. The pipeline's route consisted of various cross-sections, having details like phase-to-phase clearance, electrical characteristics of the pipeline, phase-to-shield wire distance, transmission line phase conductors, and shield wires.

The prediction and mitigation AC interference study has been conducted using modeling techniques combined with measurement in the field on a 105 km pipeline network in the Odisha state of India.

2.2 Software deployed

The study used CDEGS software to analyze problems involving earthing, electromagnetic fields accurately, and electromagnetic interference. Right-of-way (ROW) package of CDEGS is used for automated AC interference analysis. ROW pro package includes simulation of power lines, interconnections, and terminal stations (SPLITS), transmission line parameters (TRAIN), low and high-frequency grounding (MALZ), soil resistivity analysis (RESAP), and other engineering tools.

TRAIN and SPLITS modules model corridor, having multiple energized and de-energized power line circuits and other utilities, accounting for inductive and capacitive coupling throughout the corridor.

The conductive through earth coupling was addressed through the MALZ module. Electromagnetic field (EMF) energization feature of MALZ module provided combined conductive and inductive interference effects, imported directly from ROW.

RESAP module provided transformation of soil resistivity measurements into layered soil module, which MALZ then used.

AC interference studies were completed using the ROW pro package under fault conditions, considering conductive, inductive and capacitive couplings, accommodating variation in soil characteristics along the entire length of the pipeline (Figure 1).

2.3 Acceptable interference levels

Inductive, conductive, and capacitive couplings may exist between the power lines and underground pipelines. Under sinusoidal steady-

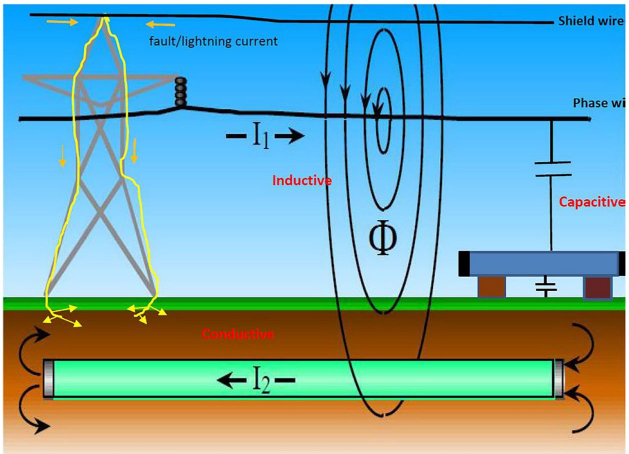

Figure 1: Inductive, capacitive, and conductive couplings.

state conditions, capacitive coupling is negligible, and the pipeline is simultaneously subjected to inductive and conductive couplings.

The following AC corrosion interference levels are considered:

Personal safety: (1) Steady-state conditions: maximum 15 V RMS AC touch voltage (NACE Standard SP0177-2014). (2) Fault conditions: permissible AC touch and step potential at above-ground portions (IEEE Standard 80-2013).

AC corrosion: (1) Steady-state conditions: AC density lower than 30 A/m^2 on a 1 cm^2 coupon (NACE Standard SP0169-2013). (2) Fault conditions: the coating stress voltage is limited to 3000 V AC to prevent coating damage and 5000 V AC to prevent structural damage to the pipeline (NACE Standard SP0177-2014).

The entire above criteria shall be satisfied post mitigation measures for acceptable AC interference on pipelines.

Table 1: Existing pipeline earthing locations.

Sl. no.	Chainage (km)	Type
1	105	DMV
2	112.8	DAC
3	119.5	DAC
4	119.5	DAC
5	123	DMV
6	152.2	DMV
7	172.9	DMV
8	175.1	DAC
9	177.2	DAC
10	180	DAC
11	181.5	DAC
12	184.5	DAC
13	207.4	DAC

DAC, decoupling AC; DMV, decoupling motor operated valve.

2.4 Model simulation

2.4.1 Input pipeline parameters: Pipeline parameters, such as the material of construction API 5LX70, OD 45.72 mm, WT 6.35 mm, average depth laid of 1.5 m from FGL were considered. The thickness of the DFBE coated pipeline is 0.6 mm with a coating leakage resistance of 23,000 Ω·m^2 (Specified by coating supplier) was evaluated. The pipeline was earthed at block valve locations at four TLPs for Valves and nine locations through TLPs for AC interference (Table 1).

2.4.2 Transmission line parameters: Details of six transmission lines consisting of several circuits, voltage level, normal load, and phase arrangement of 400/220/132 kV transmission lines in Odisha, India (Table 2) were provided as input to the software. The normal load on the transmission lines was substantially low as compared to the design load.

2.4.3 Soil resistivity measurements: The measurements of soil resistivity at electrode spacings of 0.5, 1, 2, 3, 5, 10, 20, 30, and 50 m were done at 21 locations along the pipeline using four pin Wenner method using calibrated soil resistivity meter. The soil resistivity measurements were transformed into a three-layer soil structure using the RESAP module (Figure 2).

2.4.4 Model simulation: Corridor details were provided using a 3D graphical Row CAD tool to import KMZ files and Google Earth to import Polylines. The electrical characteristics of the pipeline, transmission line phase conductors and shield wires were defined using a cross-section tab.

Each conductor of the 400 kV transmission line was represented by phase. In line with the circuit model approach, two shield wires were considered as one phase. Geometrical distances, heights, and electrical characteristics were also considered.

A phase conductor configuration had twin moose conductors with a spacing of 450 mm. The shielded wire configuration was identified as steel with a resistance of 2.5 Ω/km.

The configuration was done on similar lines for cross-sections of 220 and 132 kV transmission lines.

Each terminal was energized (Figure 3) with system voltages, load impedances, and terminal ground impedances.

Table 2: Details of transmission lines nearby/crossing the pipeline system.

Sl. no.	Name of transmission line	Utility owner	Transmission voltage (kV)	Number of circuits	Normal load (Amps) circuit 1/2/3/4	Phase arrangement
1	Mendhasal–Pandabili	PGCIL	400	Four	335/335/410/130	–
2	Meramundali–Mendhasal	OPTCL	400	Double	380/350	Centre line
3	Narendrapur–Mendhasal	OPTCL	220	Single	270	Centre line
4	Nayagarh–Chandaka	OPTCL	220	Double	260/230	Centre line
5	Khurda–Mendhasal	OPTCL	132	Single	100	–
6	Nuapatna LILO	OPTCL	132	Double	110/105	Centre line

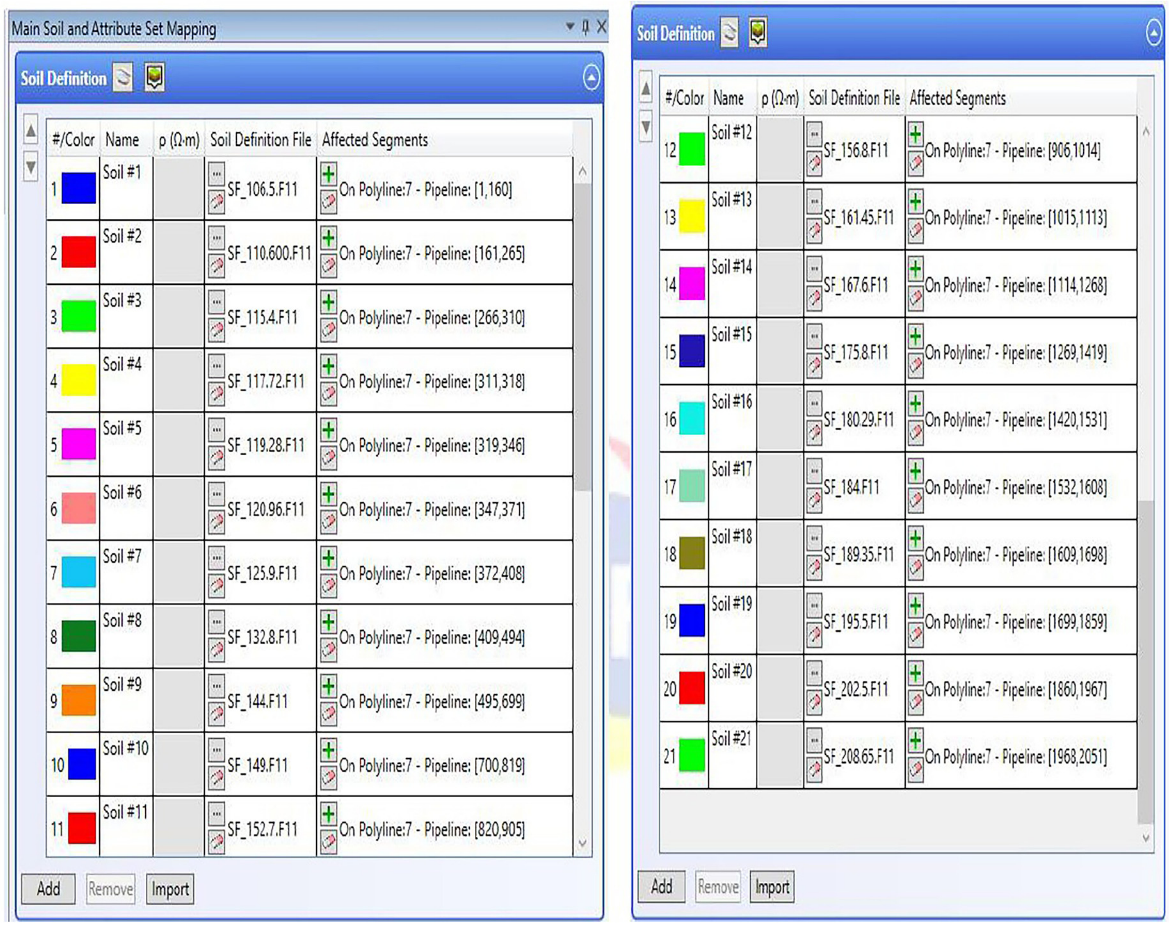

Figure 2: Soil resistivity mapping using RESAP module.

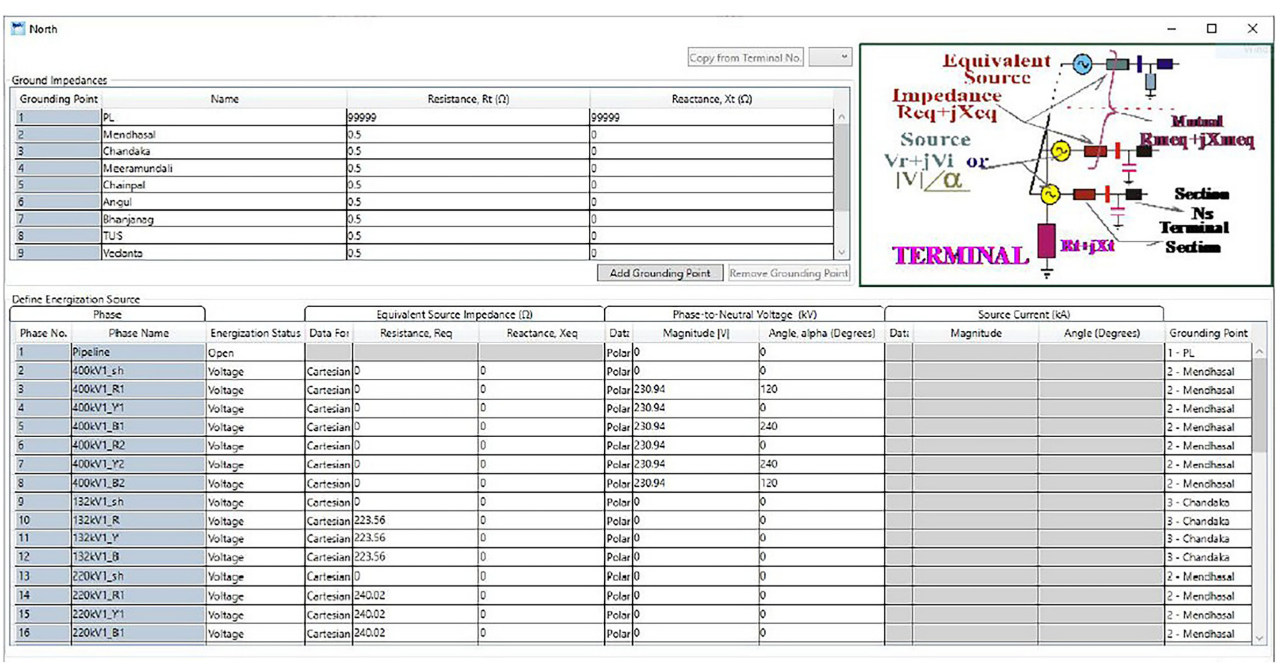

Figure 3: Terminal energisation.

2.4.5 Generating regions: Row CAD was used to subdivide the system into regions, which form the base unit for representing the system in circuit form (Figure 4). Each terminal has several areas provided as Row CAD output.

2.4.6 Modeling for steady-state: The scheme was modeled in CDEGS, showing the existing pipeline ground points (Figure 5).

Pipeline earth impedances were defined in software for all locations to generate a total interference model. Substation ground impedances and pipeline earthing were defined. The total interference calculations determined pipeline touch voltage. Touch voltage validation against baseline interference voltage (collected in the field using 24 h data loggers) was carried out.

Figure 4: Generating regions.

2.4.7 Mitigation for normal load: Mitigation measures using zinc ribbon were planned in the areas of high leakage current density. With mitigation measures in place model determined leakage current density and pipeline touch voltage. A mitigation plan is finalized for each location.

2.4.8 Modeling for fault conditions: The transmission lines are considered a two-terminal network, which acts as a source for the fault. The maximum stress voltage is determined under fault conditions with a mitigation plan for a normal load. The fault is configured to occur between the *R* phase and shield wire at identified towers. Total interference levels are computed under fault conditions. A mitigation plan with screening electrodes is added in software to reduce coating stress voltage within acceptable limits. The total interference levels are again computed and coating stress voltage determined.

3 Results and discussion

3.1 Steady-state conditions

The touch voltage is less than 15 V (Figure 6) in the pipeline system. The touch voltage was less than 2 V from

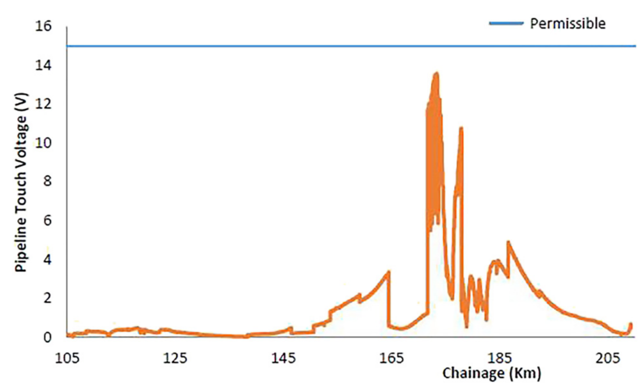

Figure 6: Pipeline touch voltage (chainage 105–210 km).

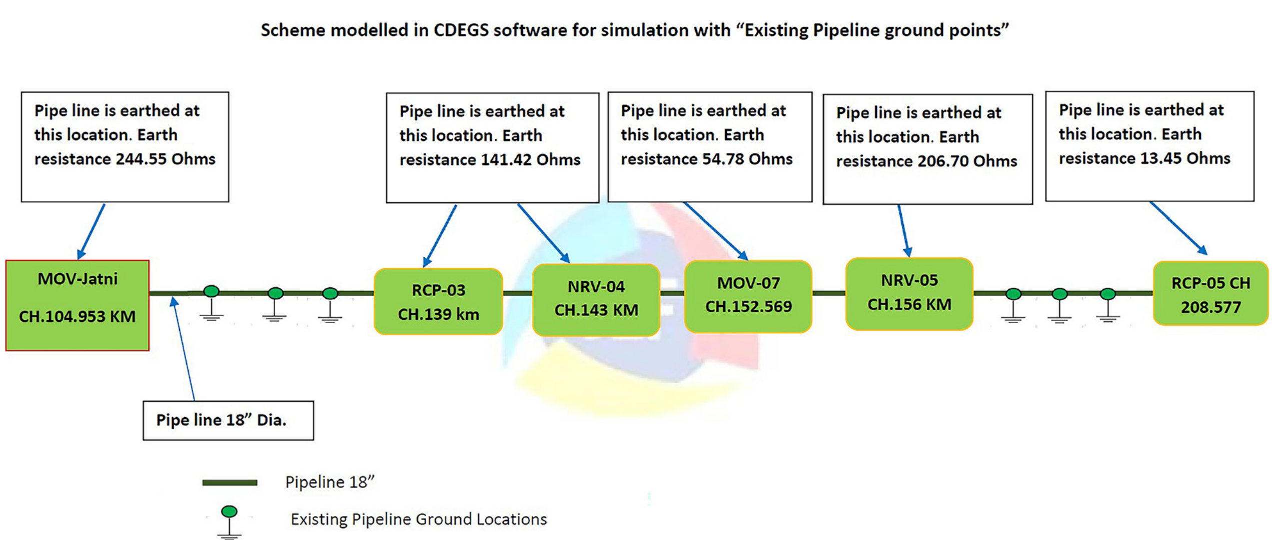

Figure 5: Scheme modeling in CDEGS.

chainage 105 km up to chainage 150 km. The maximum touch voltage was observed as 13.6 V (maximum) at chainage 173 km.

The baseline interference voltage was compared with the modeled touch voltage on the pipeline (Figure 7). The field measurements trend found similar to values as per model but lesser in absolute value. Maximum leakage current density (Figure 8) of 229.5 A/m^2 was observed at chainage 171.6 km. Such a high leakage current density indicates higher pipeline corrosion due to induced AC interference.

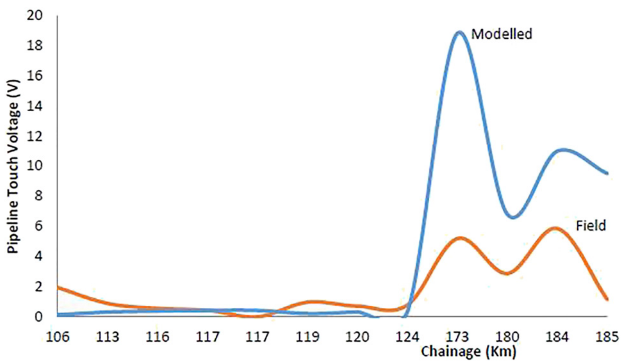

Figure 7: Modeled versus field induced voltage.

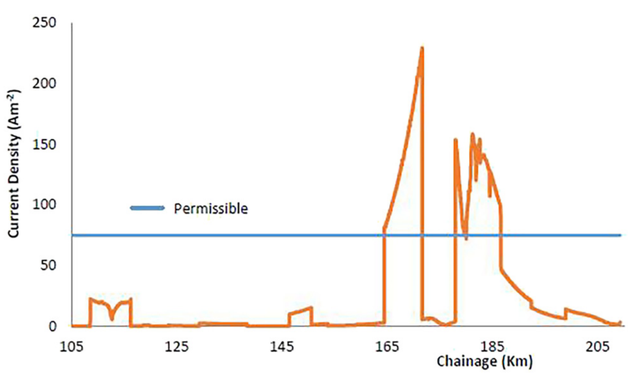

Figure 8: Leakage current density.

3.2 Fault conditions

A single-phase to ground fault for one transmission line is simulated. The section current with the position of the faulted wires flowing in the phase wire has been considered. The shield wire section current has also been considered. A very high shunt current in the tower earthing at the faulted towers (approximately 14,000 A) is observed (Figure 9).

Fault in the transmission line resulted in coating stress voltage of 5034.3 V at the chainage 243.5 km (Figure 10), which is unsafe.

A similar simulation is done for other transmission lines, and the results are within acceptable limits.

The following mitigation measures were identified (Table 3):

- High induced AC voltage and AC corrosion
- High touch and step potential at above ground MOV locations during fault conditions
- High touch and step potential at above ground TLP locations during fault conditions
- High coating stress voltage
- Arcing at locations with less separation distance.

Various mitigation measures were reviewed and optimized to bring touch potentials within acceptable limits.

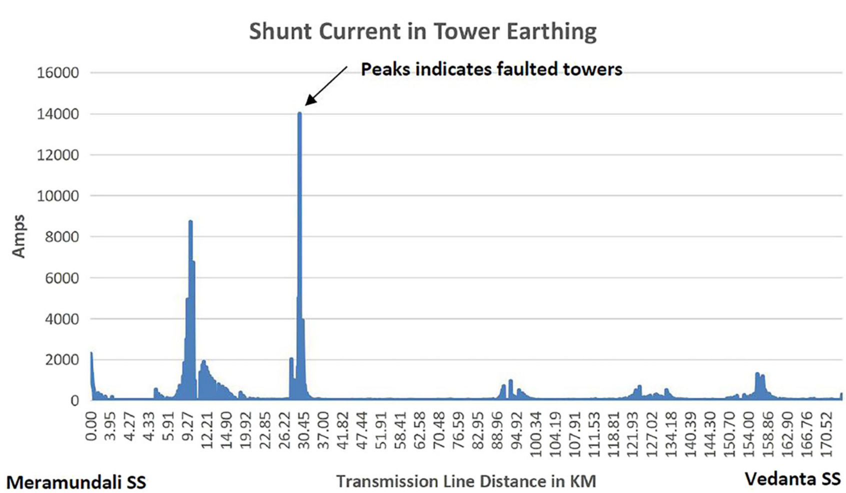

Figure 9: Shunt current in tower earthing.

Table 3: Identified risks and mitigation measures.

Sl. no.	Risk	Mitigation measure
1	Steady-state induced voltage and AC corrosion	Installation of Zn ribbons/rods of various lengths via decouplers (145 locations).
2	Touch potential and step potential at MOV locations during fault conditions	Step potential found within safe limits. Touch potential exceeds the permissible limits at few locations. A simple mitigation measure is to spread gravel to the thickness of 100 mm at identified locations.
3	Touch potential and step potential at TLPs during a fault condition	Touch potential and safe potential found within safe limits. No measure is required.
4	Coating stress voltage	Coating stress voltage under worst-case scenario found more minor than the limit of 5 kV. However, the implementation of mitigation measures for the steady state shall further reduce the coating stress voltage.
5	Arcing	Installation of screening electrodes at identified four locations, wherein pipeline falls short of minimum separation distance.

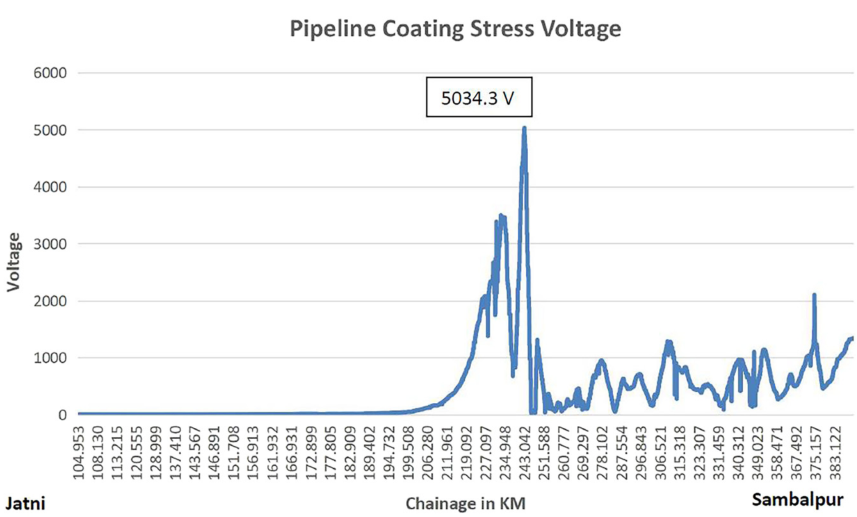

Figure 10: Pipeline coating stress voltage (pre-mitigation).

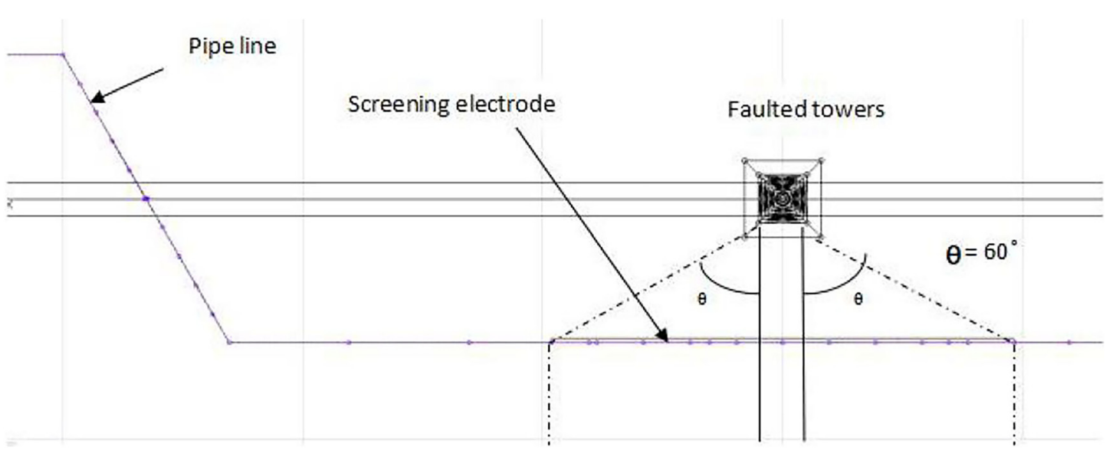

Figure 11: Screening electrode alignment.

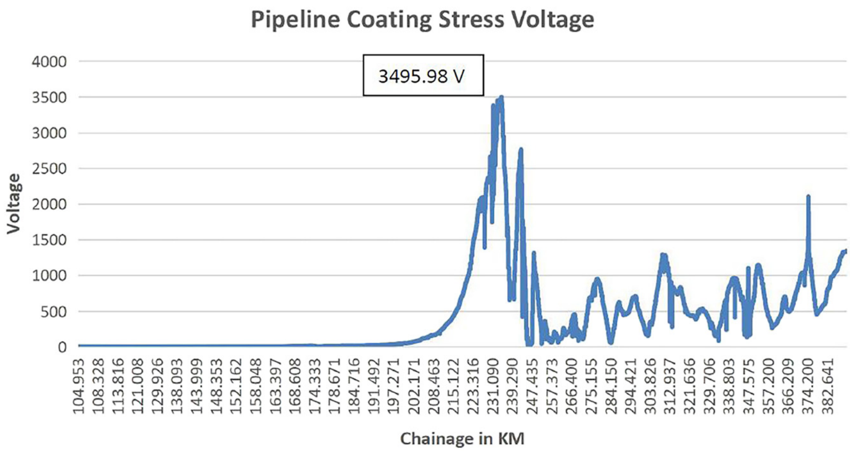

Figure 12: Pipeline coating stress voltage (post-mitigation).

A screening electrode was deployed (Figure 11) to reduce post-mitigation coating stress voltage within limits (Figure 12).

4 Conclusions

In the sinusoidal steady-state, the touch potential is within the acceptable limit of 15 V RMS. The pipeline touch potential in steady-state did not require any specific mitigation measures. Field measurements are less than the modeled values. The model considered the rated loads of transmission lines, while the transmission lines were running at substantially lower loads during field measurements. However, the trends in both modeled values and field measurements were similar, validating the model.

Mitigation measures were considered in the model, and maximum leakage current density was reduced post-mitigation. Mitigation measures required bringing down the leakage current density to less than 30 A/m^2 were quite substantial. The actual leakage current in the field is less than half of the modeled value. The modeled maximum leakage current density post-mitigation was brought down to 48.2 A/m^2. Field values post-mitigation are less than the acceptable limit of 30 A/m^2. Mitigation measures are planned to ensure that the AC interference quantum concerning touch potential and leakage current density is within acceptable limits, along with the management of other risks.

Under fault conditions, the coating stress voltage was very high due to the high shunt current and must be mitigated. Mitigation measures against the same are identified and modeled to obtain coating stress voltage within acceptable limits.

The modeling exercise continues for different mitigation measures to ensure that all the parameters are within acceptable limits for steady-state and fault conditions. Some identified mitigation measures are removed and remodeled to avoid over mitigation.

This study helped to predict AC interference and the performance of various mitigation measures. The study enabled validation of the modeled results with the field measurements for implementing economic mitigation measures.

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References

Adedeji, K.B., Ponnle, A.A., Abe, B.T., Jimoh, A.A., Abu-Mahfouz, A.M., and Hamam, Y. (2018). A review of the effect of AC/DC interference on corrosion and cathodic protection potentials of pipelines. Int. Rev. Electr. Eng. 13: 495.

Brenna, A., Lazzari, L., Pedeferri, M., and Ormellese, M. (2014). Cathodic protection condition in the presence of AC interference. La Metall. Ital. 106: 29–34.

Büchler, M. (2020). On the mechanism of cathodic protection and its implications on criteria including AC and DC interference conditions. Corrosion 76: 451–463.

Carson, J.R. (1926). Wave propagation in overhead wires with ground return. Bell Syst. Tech. J. 5: 539–554.

Charalambous, C.A., Demetriou, A., Lazari, A.L., and Nikolaidis, A.I. (2018). Effects of electromagnetic interference on underground pipelines caused by the operation of high voltage AC traction systems: the impact of harmonics. IEEE Trans. Power Deliv. 33: 2664–2672.

Chen, L., Du, Y., Liang, Y., and Li, J. (2021). Research on corrosion behavior of X65 pipeline steel under dynamic AC interference. Corrosion Eng. Sci. Technol. 56: 219–229.

Chen, M., Liu, S., Zhu, J., Xie, C., Tian, H., and Li, J. (2018). Effects and characteristics of AC interference on parallel underground pipelines caused by an AC electrified railway. Energies 11: 2255.

Christoforidis, G.C., Labridis, D.P., and Dokopoulos, P.S. (2005). A hybrid method for calculating the inductive interference caused by faulted power lines to nearby buried pipelines. IEEE Trans. Power Deliv. 20: 1465–1473.

Cole, I.S. and Marney, D. (2012). The science of pipe corrosion: a review of the literature on the corrosion of ferrous metals in soils. Corrosion Sci. 56: 5–16.

Cristofolini, A., Popoli, A., and Sandrolini, L. (2018). Numerical modelling of interference from ac power lines on buried metallic pipelines in presence of mitigation wires. *2018 IEEE international conference on environment and electrical engineering and 2018 IEEE industrial and commercial power systems Europe (EEEIC/ I&CPS Europe)*. IEEE, pp. 1–6.

Dabkowski, J. and Taflove, A. (1979). Mitigation of buried pipeline voltages due to 60 Hz AC inductive coupling part II: pipeline grounding methods. IEEE Trans. Power Apparatus Syst. 5: 1814–1823.

De Lacerda, L.A., Da Silva, J.M., and Lázaris, J. (2007). Dual boundary element formulation for half-space cathodic protection analysis. Eng. Anal. Bound. Elem. 31: 559–567.

Goidanich, S., Lazzari, L., and Ormellese, M. (2010). AC corrosion. Part 2: parameters influencing corrosion rate. Corrosion Sci. 52: 916–922.

Guo, Y.B., Liu, C., Wang, D.G., and Liu, S.H. (2015). Effects of alternating current interference on corrosion of X60 pipeline steel. Petrol. Sci. 12: 316–324.

Jacquet, B. (1995). Guide on the influence of high voltage AC power systems on metallic pipelines. CIGRE WG 36: 1–56.

Kim, D.K., Ha, T.H., Ho, Y.C., Bae, J.H., Lee, H.G., Gopi, D., and Scantlebury, J.D. (2004). The alternating current induced corrosion. Corrosion Eng. Sci. Technol. 39: 117–123.

Kuang, D. (2016). Pipeline corrosion and coating failure under alternating current interference.

Kuang, D. and Cheng, Y.F. (2014). Understand the AC-induced pitting corrosion on pipelines in both high pH and neutral pH carbonate/ bicarbonate solutions. Corrosion Sci. 85: 304–310.

Kuang, D. and Cheng, Y.F. (2015a). AC corrosion at coating defect on pipelines. Corrosion 71: 267–276.

Kuang, D. and Cheng, Y.F. (2015b). Study of cathodic protection shielding undercoating disbandment on pipelines. Corrosion Sci. 99: 249–257.

Kuang, D. and Cheng, Y.F. (2017). Effects of alternating current interference on cathodic protection potential and its effectiveness for corrosion protection of pipelines. Corrosion Eng. Sci. Technol. 52: 22–28.

Lalvani, S.B. and Lin, X.A. (1994). A theoretical approach for predicting AC-induced corrosion. Corrosion Sci. 36: 1039–1046.

Lucca, G. (2018). Different approaches in calculating AC inductive interference from power lines on pipelines. IET Sci. Meas. Technol. 12: 802–806.

Markovic, D., Smith, V., and Perera, S. (2005). Evaluation of gradient control wire and insulating joints as methods of mitigating induced voltages in gas pipelines.

M'ziou, N. (2020). Electromagnetic compatibility problems of indirect lightning stroke on overhead power lines. Math. Comput. Simulat. 167: 429–442.

Popoli, A., Cristofolini, A., and Sandrolini, L. (2021). A numerical model for the calculation of electromagnetic interference from power lines on nonparallel underground pipelines. Math. Comput. Simulat. 183: 221–233.

Popoli, A., Sandrolini, L., and Cristofolini, A. (2019). Finite element analysis of mitigation measures for ac interference on buried pipelines. *2019 IEEE international conference on environment and electrical engineering and 2019 IEEE industrial and commercial power systems Europe (EEEIC/I&CPS Europe)*. IEEE, pp. 1–5.

Samouëlian, A., Cousin, I., Tabbagh, A., Bruand, A., and Richard, G. (2005). Electrical resistivity survey in soil science: a review. Soil Tillage Res. 83: 173–193.

Shabangu, T.H., Shrivastava, P., Abe, B.T., and Olubambi, P.A. (2018). Stability assessment of pipeline cathodic protection potentials under the influence of AC interference. Prog. Electromagn. Res. M 66: 19–28.

Thakur, A.K. (2017). Corrosion control for above ground crude oil storage tanks. In: *CORROSION 2017. OnePetro*.

Thakur, A.K., Arya, A.K., and Sharma, P. (2020). The science of alternating current-induced corrosion: a literature review on pipeline corrosion-induced due to high-voltage alternating current transmission pipelines. Corrosion Rev. 38: 463–472.

Thakur, A.K., Arya, A.K., and Sharma, P. (2021). Analysis of cathodically protected steel pipeline corrosion under the influence of alternating current. Mater. Today Proc., https://doi.org/10.1016/j.matpr.2021.05.548.

Tiegna, H., Amara, Y., and Barakat, G. (2013). Overview of analytical models of permanent magnet electrical machines for analysis and design purposes. Math. Comput. Simulat. 90: 162–177.

Zhu, M., Du, C., Li, X., Liu, Z., Wang, S., Li, J., and Zhang, D. (2014). AC density on stress corrosion cracking behavior of X80 pipeline steel in high pH carbonate/bicarbonate solution. Electrochim. Acta 117: 351–359.