HVAC interference assessment on a buried gas pipeline

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Abstract. A pipeline, railway or telecommunication cable (referred to as victim line) sharing a common corridor with ac power transmission or distribution lines captures a portion of the electromagnetic field energy surrounding the power lines in the air and soil. This captured energy, often designated as ac interference, can result in an electrical shock hazard for people touching the victim lines or metallic structures connected to them. Furthermore, excessive stress voltages across rails, telephone pairs or pipe walls and coating surfaces can result in degradation or damage to equipment and puncture of pipe coating, leading to accelerated corrosion and can damage insulation flanges and rectifiers. The main objective for this study is to analyse proximity effect from a proposed double circuit transmission lines in different scenarios, which are steady-state, fault conditions and lightning strike. Induced voltage and currents on a gas pipeline to be determined using Current Distribution, Electromagnetics and Soil Structure Analysis (CDEGS) software.

1. Introduction
In general, the primary objectives of an interference study are (1) to determine mitigation required to reduce victim lines potentials to less than a given maximum level throughout the right-of-way during worst case steady-state conditions, (2) to determine the maximum stress voltages occurring during fault conditions along the victim lines; and (3) to develop gradient control grid designs to protect exposed appurtenances, such as pipeline valve sites, during fault conditions, according to IEC Standard 479 or IEEE Standard 80 safety criteria. Touch voltages at these installations to be verified as less than 15V during worst case steady-state conditions (as per NACE RP0177 Section 4: Design Considerations for Protective Devices, Section 5: Personnel Protection, Section 6: AC and Corrosion Considerations and Section 7: Special Considerations in Operation and Maintenance of CP System and Safety Systems [1].

2. Modelling and Simulation
Perspective views of the transmission line and pipeline system in this study are shown in Figure 1 and Figure 2. The 36” diameter pipeline enters the right-of-way in a near perpendicular direction (at angle of 88° 40'45", 11.44 km from Substation A. There are no other crossings of pipeline within the right-of-way of the transmission line. The system being modelled is shown in Figure 3.
The system consists of the following four major components:

1. A power system network consisting of a 500kV overhead transmission lines.
2. Two substations (terminals) from which power is fed to the transmission line network.
3. A buried 36" diameter (about 2.6m below ground) high pressure gas pipeline.
4. The characteristics of the soil along the right-of-way under study.

The modelled line is about 44.5 km long, where the towers are of steel-lattice construction. The line uses ACSR Curlew four bundled phase conductor per phase, ACSR Skunk earthwire and an average of 450m span length. Fault current magnitude is based on a bolted fault assuming a zero ohm equivalent earth impedance at Substation A.
For the gas pipeline, it is made of 36” diameter steel pipe with wall thickness of 10.88mm and coated with fusion bonding epoxy (FBE) of coating resistance approximately 5000Ωm². The coating electrical strength is between 3 – 5 kV as per NACE SP0177-2007, Para 4.13.2. The pipe was buried at 2.6m depth below ground. The average soil resistivity measured within the vicinity of the pipeline crossing is 58 Ωm. Tower footing resistance (TFR) is 5.0Ω based on TFR value specified in transmission tower technical specifications for 500kV. The earthing resistances of the two substations (A and B) earthing systems are 0.50 Ω and 0.43 Ω, respectively.

3. Results and Discussions

Study on the effects of electrical interference from the proposed 500kV HVAC double circuit transmission lines in different scenarios, which are steady-state, fault conditions and lightning strike on the buried gas pipeline were carried out using Current Distribution, Electromagnetics, Grounding and Soil Structure Analysis Software (CDEGS) module TLC. Local lightning data were used as one of the inputs in this study. Induced voltage and currents on a pipeline were determined.

One of the major variables affecting AC interference study is the soil resistivity profile of the site. Soil resistivity measurements are an extremely important first step when site data is being collected. Soil resistivity measurements are performed using the Wenner four-electrode method. By recording resistivity measurements for various electrode spacings, the depth and resistivity of each layer of a multilayer soil model can be deduced [2]. Multiple soil resistivity tests were carried out within the vicinity of the gas pipeline crossing. The soil resistivity measurements were analyzed using computer simulation and the resulting composite multilayer soil model is shown in Table 1.

| Soil Layer | Soil Model Resistivity (Ωm) | Thickness (m) |
|------------|----------------------------|---------------|
| Top        | 156.52                     | 0.4348        |
| Middle     | 58.59                      | 14.88         |
| Bottom     | 94.68                      | ∞             |

3.1. Steady-state condition. During steady-state condition, the proposed 500kV overhead transmission lines from Substation A to Substation B will experience a minimum of 840A and a maximum of 1317A load currents per phase. This is based on the data for the duration from 1st January 2013 until 31st December 2013. Summary of simulation results for steady-state condition are given in Figure 4, Figure 5 and Figure 6.
Figure 4. Steady-state Condition - Victim Line Potential Magnitude (Inductive)

Figure 5. Steady-state Condition - Victim Line Coating Stress Voltage
Both maximum inductive voltage and coating stress voltage occur at pipeline distance of 160m away from overhead line with magnitudes of 37.95 mV. The maximum pipeline voltage is within the 15V steady-state touch voltage safety limit given in NACE Standard SP0177-2007 (Section 5.2.1.1). Test post located at about 198.6 m from the right of pipeline center will experience possible induced voltage of 37.71 mV and induced current of 18.25 mA. Block valve station which is located at 3.98 km from the center of pipeline crossing will experience possible induced voltage of 5.172 mV and induced current of 3.133 mA. Induced voltages at these locations are below the safety limit 15V given in NACE Standard SP0177-2007 (Section 5.2.1.1). The probability of AC corrosion is primarily a function of the AC current density at the steel / earth interface and is delineated with regard to the following current density thresholds [3]:

1. AC-induced corrosion does not occur at AC densities less than 20 A/m²
2. AC corrosion is unpredictable for AC densities between 20 to 100 A/m²
3. AC corrosion occurs at current densities greater than 100 A/m²

A preventive coating is applied to the surface to prevent corrosion. Damage or puncture in the preventive coating may occur due to manufacturing process or any other reason. The damage in this coating is called ‘holiday’. Diameter of pipeline coating holiday refers to the diameter of damage / puncture in the coating. Default value is 0.0113 m [3]. For a circular coating holiday, the AC current density is related to the induced AC voltage by the following equation [3]:

\[ i = \frac{V_{AC}}{\rho \cdot d} \]

where; \( i \) = AC current density, \( V_{AC} \) = induced AC voltage with respect to remote earth, \( \rho \) = soil resistivity at steel/earth interface, \( d \) = diameter of circular holiday. For a worst case condition of 1 cm² surface area of circular coating holiday (i.e. diameter of 0.0113 m), current density calculated for maximum possible inductive voltage of 37.95 mV during steady-state condition is 0.1475 A/m². Thus, there is no risk of AC-induced corrosion on the pipeline.

3.2. Fault conditions at Substation B. In this section, the ac interference on the pipeline caused by a single-phase-to-earth fault on the 500kV transmission line is investigated. A single-phase-to-earth fault current magnitude of 26 kA, 0.3s duration occurring at Substation B is modelled. The distribution of the currents in the faulted phase and earth wires are calculated. The interference levels on the pipeline such as induced potentials (inductive and conductive) and coating stress voltages are
computed. Summary of potentials during fault condition occurring at Substation B are given in Figure 7, Figure 8 and Figure 9.

![Figure 7. Fault Condition (Substation) - Victim Line Potential (Inductive)](image)

![Figure 8. Fault Condition (Substation) - Victim Line Potential (Conductive)](image)
Summary of currents during fault condition occurring at Substation B are given in Figure 10.

Maximum inductive voltage occurs at pipeline distance of 1020m away from overhead line with magnitudes of 2.245 V. Maximum conductive voltage occurs at pipeline crossing with magnitude of 1.142V while maximum coating stress voltage occurs at 795m to the right of pipeline crossing with magnitude of 3.042V. The maximum pipeline voltages are within the 15V steady-state touch voltage safety limit given in NACE Standard SP0177-2007 (Section 5.2.1.1). Test post located at about 198.662m from the right of pipeline center will experience possible induced voltage of 1.252V and induced current of 3.887A. Block valve station which is located at 3.98km from the center of pipeline crossing will experience possible induced voltage of 1.958V and induced current of 25.29mA. Induced voltages at these locations are below the safety limit 15V given in NACE Standard SP0177-2007 (Section 5.2.1.1). For a worst case condition of 1cm$^2$ surface area of circular coating holiday (i.e. diameter of 0.0113m), current densities for calculated for maximum possible inductive voltage of 2.245V during steady-state condition is 8.772 A/m$^2$. Thus, there is no risk of AC-induced corrosion on the pipeline.
3.3 Fault due to lightning strike conditions. The proximity effect on the pipeline caused by the transmission line during a fault due to lightning strike occurring at tower closest (worst case condition) to the pipeline is investigated. The interference levels on the pipeline such as induced potentials (inductive and conductive) and coating stress voltages are computed. Lightning activity profile for the proposed transmission line was plotted using available data from 1st January 2004 until 31st December 2013 collected by TNBR Lightning Detection System Network as shown in Figure 11. There was a total of 37,640 lightning strikes detected within 5km radius from center of the transmission line during this period with peak current minimum, average and maximum of 2.02kA (2%, 752 occurrences), 22.10kA (50%, 18,820 occurrences) and 252.03kA (0.01%, 4 occurrences) respectively. The proposed transmission line resides within the areas which experience between 8 and 9 lightning strokes per km² per year (i.e. yellow bounded areas).

3.3.1 Average peak current of 22kA. The simulation results potentials occurring during fault caused by lightning strike to tower top with an average current of 22kA are given in

3.3.2 Table 2 and Table 3.

| Distance from Center of Line (Left) | Inductive Voltage Magnitude (V) | Inductive Voltage Angle (°) | Conductive Voltage Magnitude (V) | Conductive Voltage Angle (°) | Coating Stress Voltage Magnitude (V) | Coating Stress Voltage Angle (°) |
|------------------------------------|---------------------------------|-----------------------------|---------------------------------|-------------------------------|------------------------------------|----------------------------------|
| 0                                  | 0.2172                          | 74.825                      | 155.3                           | 6.625                         | 155.3                              | 6.700                            |
| 148                                | 0.2447                          | 70.873                      | 130.1                           | 5.394                         | 130.2                              | 5.492                            |
| 296                                | 0.2574                          | 66.737                      | 108.4                           | 3.964                         | 108.5                              | 4.085                            |
| 444                                | 0.2653                          | 62.544                      | 93.27                           | 2.711                         | 93.40                              | 2.851                            |
| 592                                | 0.2695                          | 57.563                      | 82.25                           | 1.649                         | 82.40                              | 1.804                            |
| 740                                | 0.2681                          | 52.108                      | 73.80                           | 0.739                         | 73.97                              | 0.901                            |
| 888                                | 0.2626                          | 46.756                      | 67.05                           | -0.054                        | 67.23                              | 0.110                            |
| 1036                               | 0.2551                          | 41.682                      | 61.49                           | -0.752                        | 61.68                              | -0.592                           |

Figure 11. Lightning ground stroke density map (2004 - 2013)
Table 3. Potentials during fault due to lightning strike at tower top, 22kA (to the right of the pipeline)

| Distance from Center of Line (Right) | Inductive Voltage Magnitude (V) | Inductive Voltage Angle (°) | Conductive Voltage Magnitude (V) | Conductive Voltage Angle (°) | Coating Stress Voltage Magnitude (V) | Coating Stress Voltage Angle (°) |
|-------------------------------------|---------------------------------|----------------------------|---------------------------------|----------------------------|-------------------------------------|-------------------------------|
| 0                                   | 0.1382                          | 71.811                     | 155.2                           | 6.609                      | 155.3                              | 6.655                         |
| 148                                 | 0.09596                         | -79.121                    | 130.0                           | 5.364                      | 130.1                              | 5.322                         |
| 296                                 | 0.1796                          | -96.124                    | 158.4                           | 3.393                      | 108.3                              | 3.840                         |
| 444                                 | 0.2215                          | -104.263                   | 93.20                           | 2.681                      | 93.14                              | 2.550                         |
| 592                                 | 0.2451                          | -110.053                   | 82.19                           | 1.619                      | 82.10                              | 1.460                         |
| 740                                 | 0.2612                          | -115.524                   | 73.75                           | 0.709                      | 73.63                              | 0.526                         |
| 888                                 | 0.2703                          | -121.780                   | 67.00                           | -0.083                     | 66.86                              | -0.281                        |
| 1036                                | 0.2724                          | -127.521                   | 61.45                           | -0.782                     | 61.28                              | -0.986                        |

The simulation results of currents during fault caused by lightning strike to tower top with an average current of 22kA is given in Table 4 and Table 5.

Table 4. Currents during fault due to lightning strike at tower top, 22kA (to the left of the pipeline)

| Distance from Center of Line (Left) | Shunt Current Magnitude (mA) | Shunt Current Angle (°) | Longitudinal Current Magnitude (A) | Longitudinal Current Angle (°) |
|-------------------------------------|-----------------------------|-------------------------|-----------------------------------|------------------------------|
| 0                                   | 18.49                       | 74.825                  | 0.4463                            | 24.486                       |
| 148                                 | 20.83                       | 70.873                  | 0.4347                            | 22.610                       |
| 296                                 | 21.91                       | 66.737                  | 0.4211                            | 20.494                       |
| 444                                 | 22.58                       | 62.544                  | 0.4063                            | 18.262                       |
| 592                                 | 22.94                       | 57.563                  | 0.3904                            | 15.948                       |
| 740                                 | 22.83                       | 52.108                  | 0.3736                            | 13.611                       |
| 888                                 | 22.35                       | 46.756                  | 0.3560                            | 11.323                       |
| 1036                                | 21.72                       | 41.682                  | 0.3381                            | 9.126                        |

Table 5. Currents during fault due to lightning strike at tower top, 22kA (to the right of the pipeline)

| Distance from Center of Line (Right) | Shunt Current Magnitude (mA) | Shunt Current Angle (°) | Longitudinal Current Magnitude (A) | Longitudinal Current Angle (°) |
|-------------------------------------|-----------------------------|-------------------------|-----------------------------------|------------------------------|
| 0                                   | 11.77                       | 71.811                  | 0.4543                            | 25.577                       |
| 148                                 | 8.168                       | -79.121                 | 0.4523                            | 24.576                       |
| 296                                 | 15.29                       | -96.124                 | 0.4447                            | 22.882                       |
| 444                                 | 18.86                       | -104.263                | 0.4336                            | 20.895                       |
| 592                                 | 20.86                       | -110.053                | 0.4202                            | 18.746                       |
| 740                                 | 22.23                       | -115.524                | 0.4050                            | 16.493                       |
| 888                                 | 23.01                       | -121.480                | 0.3882                            | 14.219                       |
| 1036                                | 23.19                       | -127.521                | 0.3703                            | 11.997                       |

For an average lightning peak current of 22kA, a strike at the tower nearest to the pipeline will cause the following:

a) a maximum inductive voltage occurs at pipeline distance of 1036 m away from overhead line with magnitudes of 0.2724 V,
b) a maximum conductive voltage and coating stress voltages occur at pipeline crossing with magnitude of 155.3V, and
c) a maximum longitudinal current at pipeline crossing is 0.4543A.

The maximum inductive pipeline voltages are below 15V steady-state touch voltage safety limit given in NACE Standard SP0177-2007 (Section 5.2.1.1). The maximum coating stress voltages is
below the FBE electrical strength (3 – 5kV). Test post located at about 198.662m from the right of pipeline center will experience possible induced voltage of 0.2447V and induced current of 0.4523A. Block valve station which is located at 3.98km from the center of pipeline crossing will experience possible induced voltage of 0.2237V and induced current of 28.6mA. Induced voltages at these locations are below the safety limit 15V given in NACE Standard SP0177-2007 (Section 5.2.1.1). Current density at worst case condition of 1cm² circular holiday, calculated for maximum possible inductive voltage of 0.2724 V during fault due to lightning condition is 1.058A/m². Thus, there is no risk of AC-induced corrosion on the pipeline.

4. Summary and Conclusions

Study on the effects of electrical interference from TNB proposed 500kV HVAC double circuit transmission lines in different scenarios, which are steady-state, fault conditions and lightning strike were carried out using Current Distribution, Electromagnetics, Grounding and Soil Structure Analysis Software (CDEGS). Induced voltage and currents on a pipeline were determined.

For steady-state conditions, both maximum inductive voltage and coating stress voltage occur at 160m away from overhead line with magnitudes of 37.95mV. The maximum pipeline voltage is within the 15V steady-state touch voltage safety limit given in NACE Standard SP0177-2007 (Section 5.2.1.1). Calculated current density at worst case condition of 1cm² circular holiday, for maximum possible inductive voltage of 37.95mV is 0.1475 A/m². Thus, there is no risk of AC-induced corrosion on the pipeline.

For fault conditions at 500kV Ayer Tawar substation, maximum inductive voltage occurs at 1.02km away from overhead line with magnitudes of 2.245V. The maximum pipeline voltage is within the 15V steady-state touch voltage safety limit given in NACE Standard SP0177-2007 (Section 5.2.1.1). Calculated current density at worst case condition of 1cm² circular holiday, for maximum possible inductive voltage of 2.245V is 8.722A/m². Thus, there is no risk of AC-induced corrosion on the pipeline.

For fault conditions due to lightning strike of average peak current of 22kA, maximum inductive voltage occurs at 1.036km away from overhead line with magnitude of 0.2724V. The maximum pipeline voltage is within the 15V steady-state touch voltage safety limit given in NACE Standard SP0177-2007 (Section 5.2.1.1). Calculated current density at worst case condition of 1cm² circular holiday, for maximum possible inductive voltage of 0.2724V is 1.058A/m². Thus, there is no risk of AC-induced corrosion on the pipeline.

For fault conditions due to lightning strike of average peak current of 252kA, maximum inductive voltage occurs at 1.036km away from overhead line with magnitudes of 3.12V. The maximum pipeline voltage is within the 15V steady-state touch voltage safety limit given in NACE Standard SP0177-2007 (Section 5.2.1.1). Calculated current density at worst case condition of 1cm² circular holiday, for maximum possible inductive voltage of 0.2724V is 1.058A/m². Thus, there is no risk of AC-induced corrosion on the pipeline.

5. References

[1] NACE 2007 NACE SP0177-2007 Standard Practice Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems (USA: NACE International)

[2] IEEE 2012 IEEE 81–2012 Guide for Measuring Earth Resistivity, Ground Impedance and Earth Surface Potentials of a Grounding System (USA: IEEE)

[3] Gas/Electric Partnership Conference XIX 2011 Induced AC Mitigation for Safety and Corrosion Control (Texas, USA).