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Paper A02 - HVAC interference on pipeline networks
Modeling and optimization of mitigation techniques

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ABSTRACT

Sharing of common corridors by gas pipelines and overhead power transmission lines is becoming quite common. However, electrical energy can be transferred from power transmission lines to pipelines through inductive, conductive and capacitive coupling. When a power transmission line runs in parallel with a pipeline for a considerable length, induced AC voltages may appear on the pipeline.

While there are significant benefits in sharing a corridor between pipelines and power transmission lines, e.g. joint land use, there are also many concerns. The main ones are safety considerations for operation and maintenance personnel on pipelines, direct effects on the pipeline, such as corrosion and coating damage and effects on the electrical devices associated with the pipeline related to cathodic protection, metering and monitoring. AC induced corrosion is a significant threat to integrity of buried pipelines, due to its very high localized corrosion rate which can and has resulted in metal loss of more than 1 mm per year. AC corrosion mainly occurs at small coating holidays on well coated pipelines when the pipeline suffers from induced ac voltages.

This paper presents a technology for the prediction and mitigation of induced voltages on buried pipeline networks in the neighborhood of high voltage transmission lines. It will be demonstrated that this technology can deal with any configuration (no limitation on number of pipes, transmission lines, bonds, groundings, coating and soil resistivity) and that there is no need to separate the problem in sections where the pipe is parallel or not to the transmission line(s). In addition, the effect of phase wire changes and hanging catenaries can be taken into account.

In this paper, practical results of simulations on different configurations will be presented and compared with analytical solutions and experimental data for the design and mitigation stage.

Keywords: simulation software, HVAC, induced EMF, induced voltages, mitigation techniques.

INTRODUCTION

Increased difficulty in obtaining utility right-of-way and the concept of utility corridors have brought many underground structures, and pipelines in particular, into close proximity with electric power transmission and distribution systems. Any metallic object subjected to the alternating electromagnetic field of the transmission system will exhibit an induced voltage. In addition, power conductor faults to ground can cause substantial fault currents in the underground structure[1,2].

There are three basic methods by which AC currents and voltages can be induced on metallic structures near AC power lines. The first one is electrostatic coupling where the structure acts as one side of a capacitor with respect to ground. This is only of concern when the structure is above grade. Secondly, electromagnetic induction may occur when the structure is either above or below ground. In this case, the structure acts as the single-turn secondary of an air-core transformer in which the overhead power line is the primary. Finally, resistive coupling is caused by fault currents from AC power towers that flow on and off the underground structure.

Stray currents due to these induced voltages can cause corrosion of metallic structures although the amount of metal loss is less than an equivalent amount of DC current discharge would produce. The magnitude of AC stray current is often large – hundreds of amperes under electromagnetic induction and thousands of amperes during power line faults. These high current and voltage levels can produce a shock hazard for personnel and can damage the structure and related equipment, such as cathodic protection facilities. According to NACE International Recommended Practice RP0177, "Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems"[3], potentials in excess of 15 volts should be considered hazardous and steps should be taken to reduce the hazardous potential level.

Therefore, it is not surprising that there is an industrial need for the availability of a user-friendly simulation software that would provide capabilities for predicting and mitigating inductively coupled voltages on buried pipelines paralleling high voltage electric power transmission lines[4]. However, most available computer programs limit the modeling capabilities to parallel or near parallel geometries such as the CORRIDOR[5], ECCAPP[6] and PRCI[4] program. This limitation to pseudo-parallel geometries requires a subdivision of the pipeline(s) in a number of sections that are more or less parallel to the transmission line, which seriously reduces flexibility and can lead to important errors if the distances vary strongly along the influence zone. In addition, most of the available programs are restricted in the number of pipelines, transmission lines and (direct) bonds that can be modeled. This is a serious restriction since in many corridors a large number of pipelines are bonded together, e.g. for cathodic protection purposes.

Elsyca developed a software tool for AC predictive and mitigation techniques that allows to model any number of pipelines, high voltage transmission lines and bonds without any restriction at all on the complexity of the geometry, as described in full detail in reference[7].

VALIDATION OF THE MODEL - COMPARISON WITH ANALYTICAL SOLUTIONS

In what follows, the model will be evaluated by comparison with analytical solutions obtained in the literature. These analytical solutions are the best means to evaluate the accuracy of the developed model.

In order to be able to find an analytical solution, the following assumptions will be made:

- the pipeline is parallel to the transmission line,
- the leakage admittance of the pipeline is constant, i.e. the coating resistance per unit length of the pipeline is uniform and independent of the applied voltage,
- the soil resistivity along the parallel route is constant.

Under these conditions the induced EMF is constant along the pipeline and the governing equations can easily be solved. This has been done for three different cases as outlined below.

Case 1 : The pipeline extends for a few kilometres beyond the parallel route without earthing

Consider the configuration of Figure 1. A pipeline parallels a single horizontal 50 Hz, 345 kV transmission line for 10 km at a constant distance of 25 m. The pipeline lays at a constant depth of 5 m in a 100 Ωm resistivity soil, has a diameter of 50 cm and a coating resistance of 10.000 Ωm^2. Beyond the parallel route, the pipeline extends for 5 km without earthing.

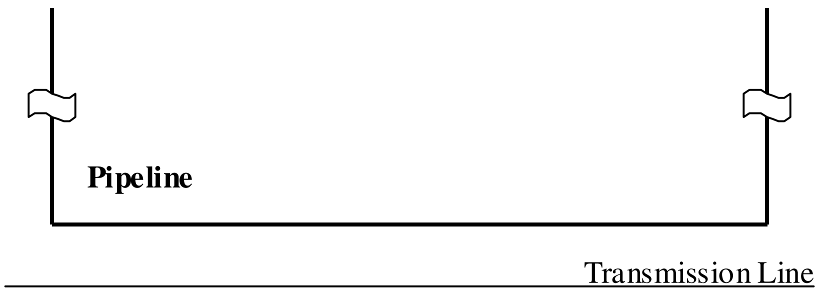


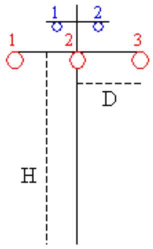
FIGURE 1 – Case 1 : The pipeline extends for a few kilometres beyond the parallel route without earthing.

Calculation of the induced EMF

Let us first concentrate on the calculation and verification of the induced EMF on the pipeline. The configuration of the 345 kV transmission line tower with specification of the phase wires is given in Figure 2. The currents in the phase wires are perfectly balanced and given by:

$$I_1 = I, I_2 = aI, I_3 = a^2 I,$$
$$a = e^{-j\frac{2\pi}{3}}, a^2 = e^{-j\frac{4\pi}{3}}. \quad (1)$$

Do note that the effect of the shield wires is not taken into account.



Phase Wires :

No	D [m]	H [m]	I [A]	Phase [deg]
1	-7.62	18.288	500	120
2	0	18.288	500	-120
3	7.62	18.288	500	0

FIGURE 2 – Single horizontal 345 kV tower with phase wire specifications.

The analytical formulation for the induced EMF p.u.l. on a parallel pipeline due to a perfectly balanced three-phase system without shield wires is given by the Carson-Clem formula[8]:

$$E_o = -jf\frac{\mu_o I}{2}\left[\ln\frac{d_{2p}d_{3p}}{d_{1p}^2} + j\sqrt{3}\ln\frac{d_{2p}}{d_{3p}}\right], \quad (2)$$

where d_{ip} represents the distance between phase conductor *i* and the pipeline *p*. Note that formula (2) is only valid for relatively short distances $d \leq 90\sqrt{\rho / f}$ ($d \leq 127m$) between a phase wire and the pipeline as will become clear.

The model as used in the simulations is given in Figure 3 below. Based on the specifications as given above, the induced EMF has been calculated using the technique as outlined in reference[7]. Results are presented in Figure 4. As expected, a constant EMF is observed along the parallel exposure which drops to zero at both sides beyond the parallel exposure.

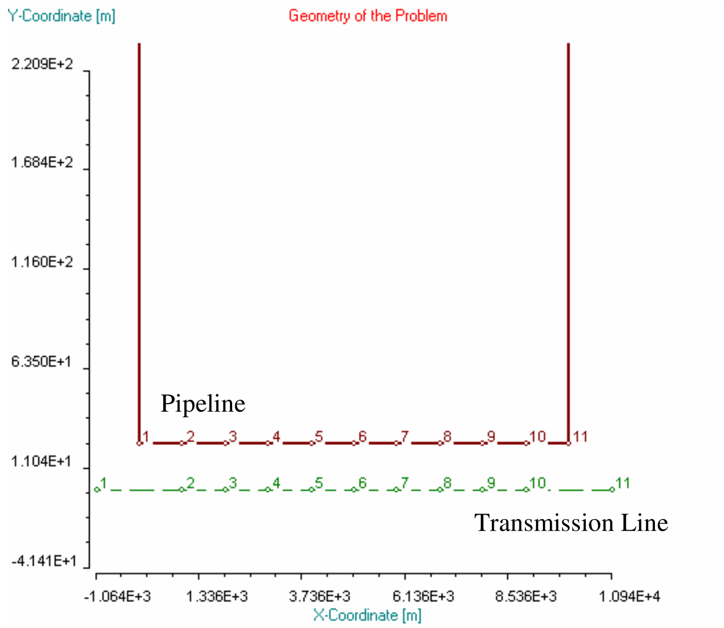


FIGURE 3 – Numerical model for case 1.

In addition, similar calculations have been done for a wide range of distances from 0 to 1000 m. A comparison between Carson-Clem predictions and numerical calculations as used here is given in Table 1. One can easily see that for small distances a very good agreement between the Carson-Clem and numerical results is found. However, as the distance increases, the error increases and once beyond about 100 m, the error increases rapidly. This is in perfect agreement with the observation that equation (2) should only be used for distances below 127 m. The EMF is calculated using a two-dimensional numerical integration scheme since the integrand involved is too complex to find an analytical solution. However, in the case of a perfectly parallel exposure, an exact solution has been found using Mathematica® 4.0 (referred to as "M4"). A comparison between the numerical and "M4" values is added in Table 1 and it can be observed that the general method adopted here gives perfect results regardless of the spacing between transmission line and pipeline.

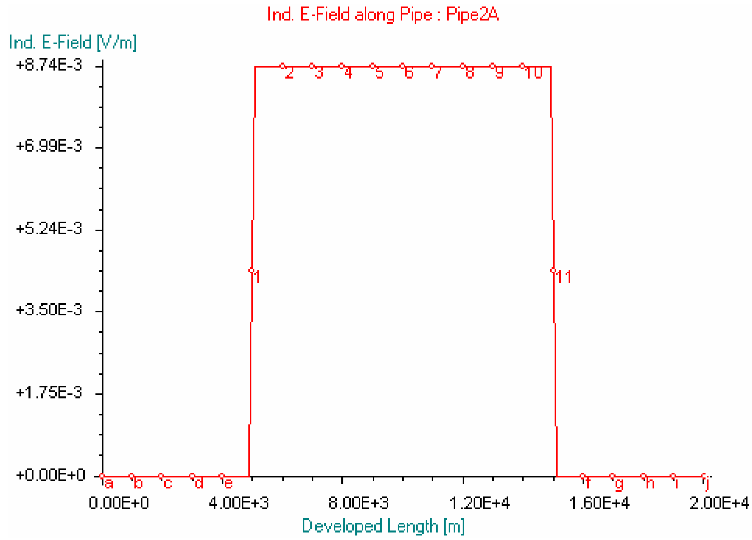


FIGURE 4 – Numerical simulation of the induced EMF per unit length (case 1).

Distance [m]	E,CC [mV/m]	E,num [mV/m]	E,error, CC[%]	E,M4 [mV/m]	E,num [mV/m]	E,error, M4 [%]
0	1.5977	1.5970	0.04	1.5963	1.5970	0.04
5	3.6188	3.6160	0.08	3.6152	3.6160	0.02
10	6.0952	6.0880	0.12	6.0873	6.0880	0.01
15	7.7546	7.7420	0.16	7.7421	7.7420	0.00
20	8.5630	8.5460	0.20	8.5461	8.5460	0.00
25	8.7489	8.7280	0.24	8.7278	8.7280	0.00
30	8.5637	8.5390	0.29	8.5388	8.5390	0.00
40	7.7425	7.7110	0.41	7.7108	7.7110	0.00
50	6.8293	6.7920	0.55	6.7915	6.7920	0.01
100	3.9396	3.8750	1.64	3.8748	3.8750	0.00
200	2.0465	1.9390	5.25	1.9380	1.9390	0.05
500	0.8275	0.6451	22.05	0.6442	0.6451	0.13
1000	0.4144	0.2039	50.81	0.2032	0.2039	0.33
2000	0.2073	0.0334	83.90	0.0332	0.0334	0.59

TABLE 1 – Comparison between Carson-Clem ("CC"), numerical and Mathematica® 4.0 ("M4") values for the induced EMF per unit length.

Many conventional calculation methods consider a zone of about $200\sqrt{\rho}$ (i.e. 2 km) parallel to both sides of the transmission line in which its influence is considered to be "significant"[8]. From the results obtained above, it is clear that the use of equation (2) for the calculation of the induced EMF, can give a serious overestimation of the EMF, hence introducing errors on the safe side.

Calculation of the induced voltage and current

Let us now go back to the original case with a 25 m spacing between the pipeline and transmission line. Based on the calculated induced EMF as specified in Figure 7, the transmission line model for the induced voltages and currents will be solved. To that purpose, a characteristic impedance is placed at the beginning and end of the pipeline to simulate an electrically long pipeline at both ends. The calculation of the pipeline impedance and admittance p.u.l. is based on the formulas listed in reference[7] with $\rho_p = 1.7\ 10^{-7}\ \Omega$m, $\mu_r = 300$ and $\varepsilon_r = 5$.

The analytical solution for this configuration is given by[8]:

$$V(x) = \frac{E}{2\gamma}\left(e^{-\gamma(L-x)} - e^{-\gamma x}\right), \tag{3}$$

$$I(x) = \frac{E}{2z}\left(2 - e^{-\gamma(L-x)} - e^{-\gamma x}\right). \tag{4}$$

The maximum potential $V_{\max} = E/(2\gamma)(1-e^{-\gamma L})$ occurs at the ends of the parallel routing at km 5 and 15. Beyond the exposure, the pipeline potential and current decrease according to the following exponential function:

$$V(x) = V_{\max} e^{-\gamma x}, \tag{5}$$

$$I(x) = \frac{V_{\max}\gamma}{z} e^{-\gamma x}. \tag{6}$$

with x the co-ordinate outside the parallel section.

In Figures 5 and 6, the calculated values for the induced voltage and current are compared with the analytical solutions as obtained from (3). A perfect agreement for the induced voltage and the induced current, both for the parallel section and for the section beyond the parallel exposure can be observed. The average error made is about 0.16% for the induced voltage and about 0.01% for the induced current. Detailed information on the obtained numerical and analytical values is given in Table 2.

The current flowing at both ends of the pipeline at 5 km beyond the parallel exposure is about 2.4A. It is not necessary to extend the pipeline for 5 km beyond the parallel exposure when the characteristic impedance is used to close both ends. This is only done to demonstrate the exponential decay of the induced voltage and current beyond the parallel exposure. Although not presented here, simulations done with a characteristic impedance at very short extensions give exactly the same results.

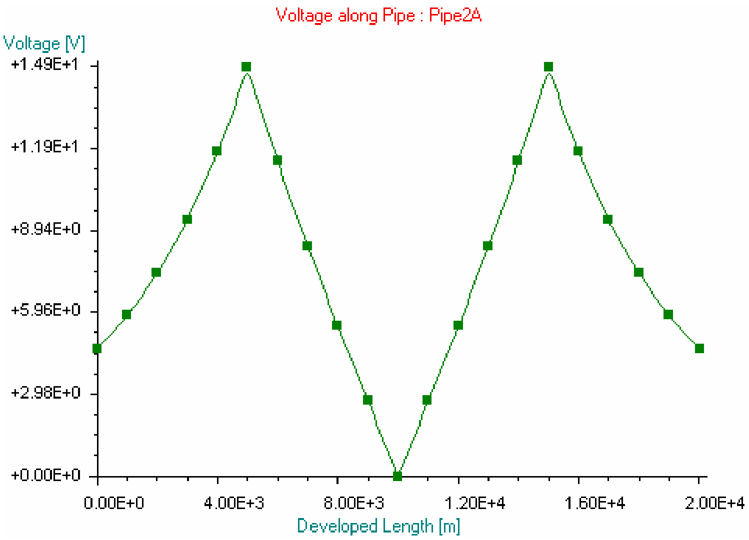


FIGURE 5 – Comparison between numerical and analytical (full square) voltages (case 1).

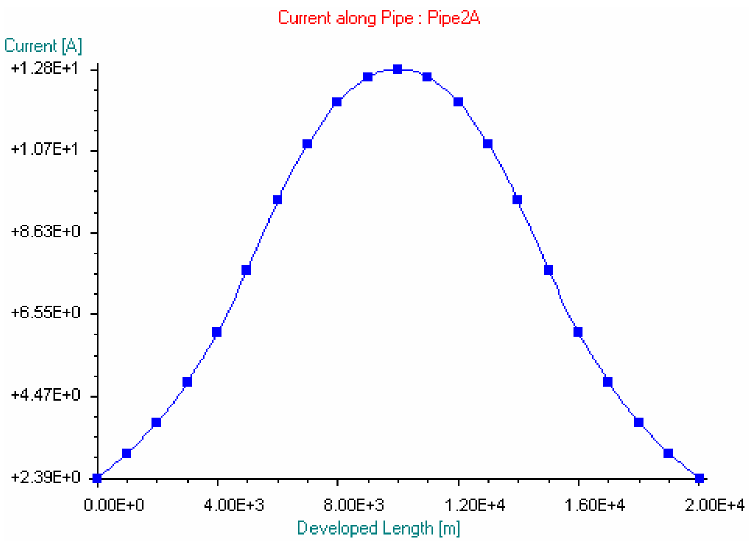


FIGURE 6 – Comparison between numerical and analytical (full square) currents (case 1).

Case 2 : The pipeline extends beyond the parallel routing at one extremity and stops at the other extremity without earthing

Next consider the configuration of Figure 7. The pipeline extends beyond the parallel routing at one extremity and stops at the other extremity without earthing. This case is modeled by putting a characteristic impedance at the beginning of the pipeline and by doing nothing at the end.

The pipeline and transmission line parameters are exactly the same as for the previous case. Therefore the calculated EMF will be exactly the same as for the first 15 km of Figure 4.

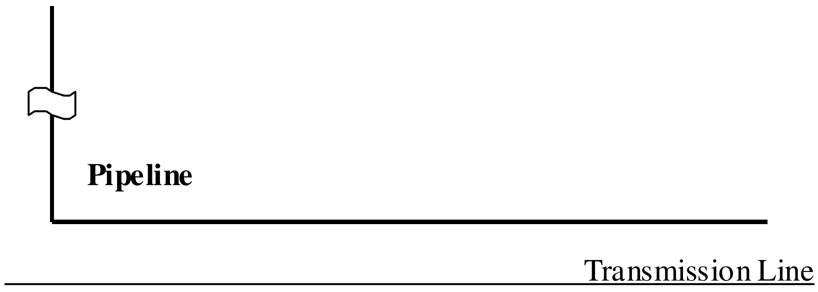


FIGURE 7 – Case 2 : The pipeline extends beyond the parallel routing at one extremity and stops at the other extremity without earthing.

The analytical solution for this configuration is given by[8]:

$$V(x) = \frac{E}{2\gamma}\left[e^{\gamma x}\left(2e^{-\gamma L} - e^{-2\gamma L}\right) - e^{-\gamma x}\right], \quad (7)$$

$$I(x) = \frac{E}{2z}\left[2 + e^{\gamma x}\left(2e^{-\gamma L} - e^{-2\gamma L}\right) + e^{-\gamma x}\right], \quad (8)$$

again with an exponential decay of both the voltage and current beyond the parallel exposure at the beginning of the pipeline.

The calculated and analytical values for the induced voltage and current are presented in Figures 8 and 9. Again, a perfect agreement along the entire developed length of the pipeline can be seen, indicated by the detailed information in Table 2, presenting an average error of about 0.12% for the induced voltage and about 0.01% for the induced current.

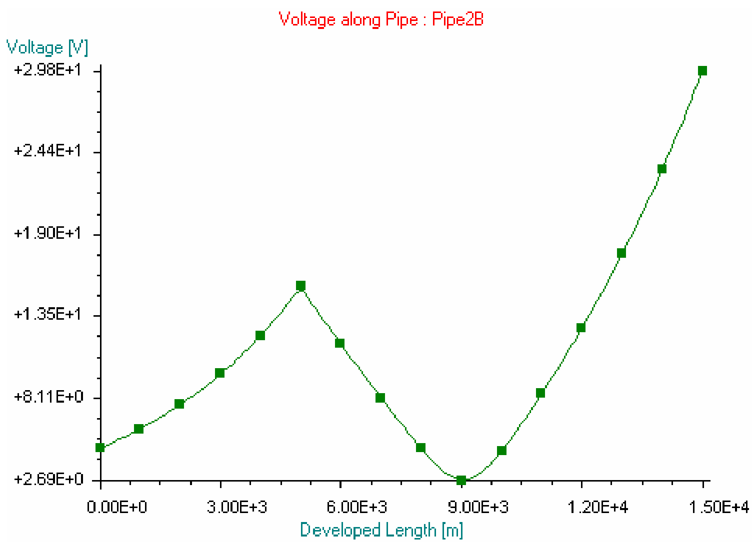


FIGURE 8 – Comparison between numerical and analytical (full square) voltages (case 2).

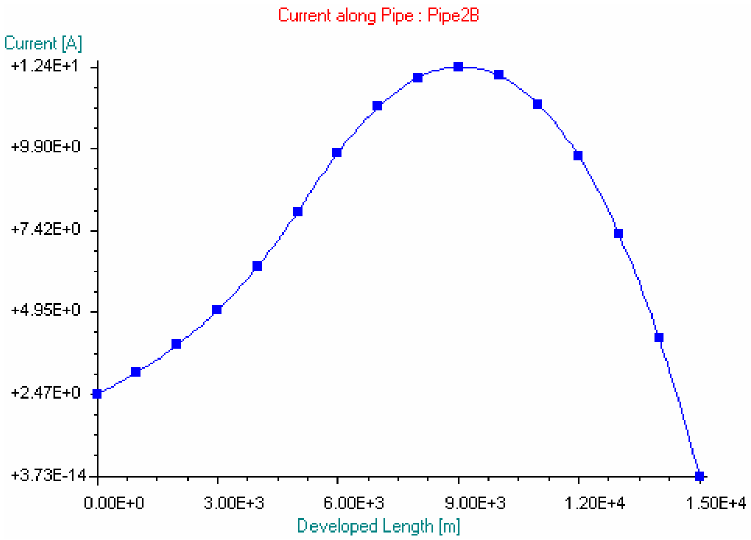


FIGURE 9 – Comparison between numerical and analytical (full square) currents (case 2).

Case 3 : The pipeline extends beyond the parallel routing at one extremity and is perfectly earthed at the other extremity

Finally, consider the configuration of Figure 10. This example is exactly the same as the one before, except that the pipeline is now perfectly earthed at the end of it. This case is modeled by putting a characteristic impedance at the beginning of the pipeline and a zero impedance at the end.

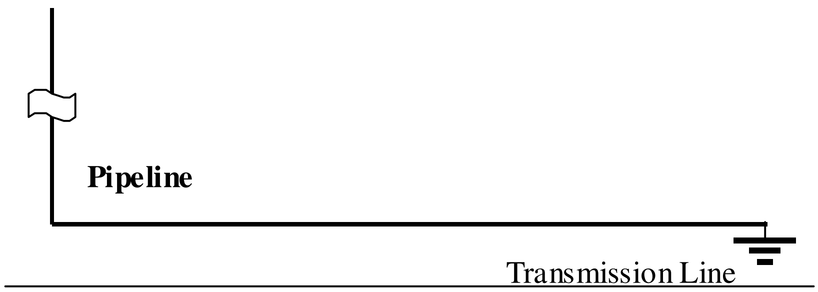


FIGURE 10 – Case 3 : The pipeline extends beyond the parallel routing at one extremity and is perfectly earthed at the other extremity.

For this configuration, the analytical solution is given by[8]:

$$V(x) = \frac{E}{2\gamma}\left(e^{\gamma(L-x)} - e^{-\gamma(L-x)}\right)e^{-\gamma L}, \tag{9}$$

$$I(x) = \frac{E}{2z}\left[2 - \left(e^{\gamma(L-x)} + e^{-\gamma(L-x)}\right)e^{-\gamma L}\right], \tag{10}$$

again with an exponential decay of both the voltage and current beyond the parallel exposure at the beginning of the pipeline.

The calculated and analytical values for the induced voltage and current are presented in Figures 11 and 12. Again, a perfect agreement along the entire developed length of the pipeline can be seen, indicated by the detailed data in Table 2, presenting an average error of about 0.1% for the induced voltage and about 0.01% for the induced current. The positive effect of the earthing when compared to the previous case can be seen by the fact that the maximum induced voltage along the pipeline drops more than 50% from about 29.8V to only 14.4V. The current that is drained away via the earthing at this locating is about 15.4A.

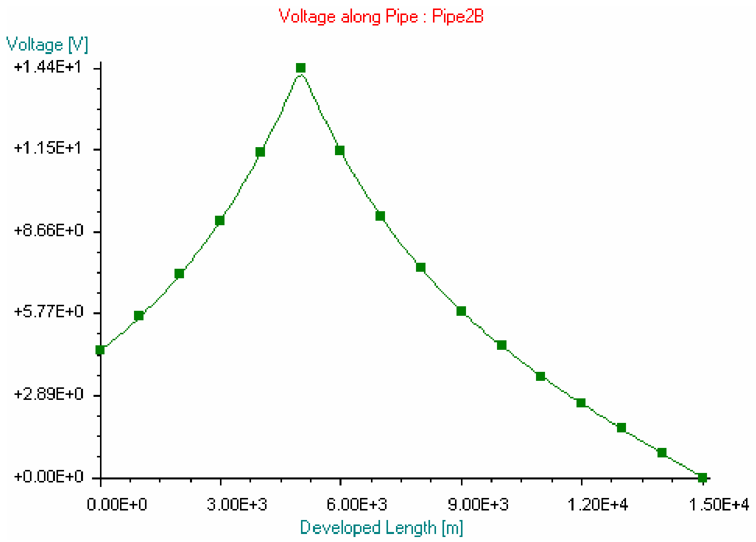


FIGURE 11 – Comparison between numerical and analytical (full square) voltages (case 3).

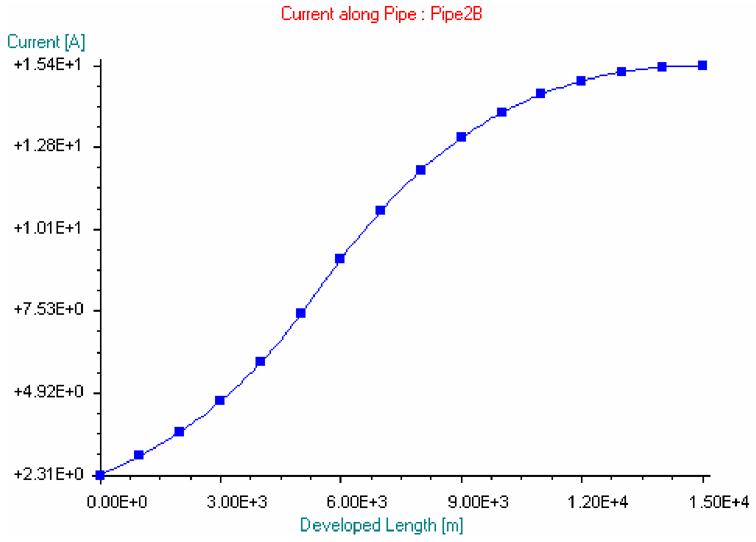


FIGURE 12 – Comparison between numerical and analytical (full square) currents (case 3).

Length [m]	V,anal [V]	V,num [V]	V,error [%]	I,anal [A]	I,num [A]	I,error [%]
0	4.6286	4.6288	0.0053	2.3854	2.3856	0.0055
1000	5.8484	5.8487	0.0051	3.0141	3.0142	0.0044
2000	7.3896	7.3900	0.0045	3.8084	3.8086	0.0040
3000	9.3371	9.3374	0.0038	4.8120	4.8122	0.0035
4000	11.7977	11.7981	0.0030	6.0802	6.0804	0.0031
5000	14.9069	14.6694	1.5931	7.6826	7.6820	0.0071
6000	11.4658	11.4663	0.0046	9.4269	9.4250	0.0204
7000	8.3738	8.3743	0.0048	10.8822	10.8800	0.0198
8000	5.4908	5.4911	0.0053	11.9397	11.9376	0.0180
9000	2.7210	2.7212	0.0057	12.5758	12.5736	0.0173
10000	0.0000	0.0000	0.0000	12.7876	12.7855	0.0166
11000	2.7210	2.7212	0.0057	12.5758	12.5736	0.0173
12000	5.4908	5.4911	0.0053	11.9397	11.9376	0.0180
13000	8.3738	8.3743	0.0048	10.8822	10.8800	0.0198
14000	11.4658	11.4663	0.0046	9.4269	9.4250	0.0204
15000	14.9069	14.6694	1.5931	7.6826	7.6820	0.0071
16000	11.7977	11.7981	0.0030	6.0802	6.0804	0.0031
17000	9.3371	9.3374	0.0038	4.8120	4.8122	0.0035
18000	7.3896	7.3900	0.0045	3.8084	3.8086	0.0040
19000	5.8484	5.8487	0.0051	3.0141	3.0142	0.0044
20000	4.6286	4.6288	0.0053	2.3854	2.3856	0.0055
			<0.1631>			<0.0111>

Length [m]	V,anal [V]	V,num [V]	V,error [%]	I,anal [A]	I,num [A]	I,error [%]
0	4.8134	4.8140	0.0115	2.4807	2.4810	0.0115
1000	6.0819	6.0826	0.0113	3.1345	3.1348	0.0108
2000	7.6848	7.6856	0.0107	3.9605	3.9609	0.0100
3000	9.7100	9.7109	0.0099	5.0042	5.0047	0.0098
4000	12.2689	12.2700	0.0089	6.3230	6.3236	0.0094
5000	15.5022	15.2520	1.6141	7.9894	7.9891	0.0035
6000	11.7150	11.7168	0.0155	9.7601	9.7584	0.0179
7000	8.1421	8.1443	0.0264	11.1507	11.1489	0.0158
8000	4.7991	4.8016	0.0505	12.0372	12.0356	0.0136
9000	2.6892	2.6909	0.0630	12.3699	12.3684	0.0118
10000	4.6286	4.6279	0.0146	12.1126	12.1115	0.0093
11000	8.3988	8.3975	0.0156	11.2248	11.2239	0.0081
12000	12.7574	12.7559	0.0114	9.6529	9.6522	0.0072
13000	17.6550	17.6534	0.0089	7.3255	7.3251	0.0065
14000	23.2505	23.2488	0.0075	4.1486	4.1484	0.0061
15000	29.8138	29.8115	0.0076	0.0000	0.0000	0.0000
			<0.1180>			<0.0095>

Length [m]	V,anal [V]	V,num [V]	V,error [%]	I,anal [A]	I,num [A]	I,error [%]
0	4.4807	4.4809	0.0042	2.3092	2.3093	0.0042
1000	5.6615	5.6617	0.0039	2.9178	2.9179	0.0032
2000	7.1535	7.1538	0.0033	3.6867	3.6868	0.0028
3000	9.0388	9.0390	0.0026	4.6583	4.6584	0.0023
4000	11.4208	11.4210	0.0017	5.8859	5.8861	0.0019
5000	14.4306	14.2097	1.5308	7.4371	7.4367	0.0051
6000	11.5014	11.5018	0.0035	9.1774	9.1759	0.0165
7000	9.1912	9.1916	0.0039	10.7379	10.7362	0.0156
8000	7.3536	7.3539	0.0046	12.0285	12.0269	0.0133
9000	5.8663	5.8666	0.0050	13.0543	13.0528	0.0116
10000	4.6286	4.6288	0.0051	13.8460	13.8446	0.0101
11000	3.5601	3.5603	0.0044	14.4386	14.4373	0.0090
12000	2.6001	2.6001	0.0022	14.8642	14.8630	0.0080
13000	1.7049	1.7048	0.0035	15.1489	15.1479	0.0069
14000	0.8449	0.8447	0.0206	15.3120	15.3110	0.0068
15000	0.0000	0.0000	0.0000	15.3651	15.3600	0.0333
			<0.1000>			<0.0094>

TABLE 2 – Comparison between analytical and numerical values for the induced voltage and current for cases 1 to 3 (from top to bottom).

VALIDATION OF THE MODEL WITH FIELD DATA

In a second step the software has been validated by means of existing field data. The case that has been studied is a double HVAC system (780 A and 810 A) as presented in Figure 13. The pipeline parallels the HVAC system for about 12 km with a minimum distance between both routings of about 200 m.

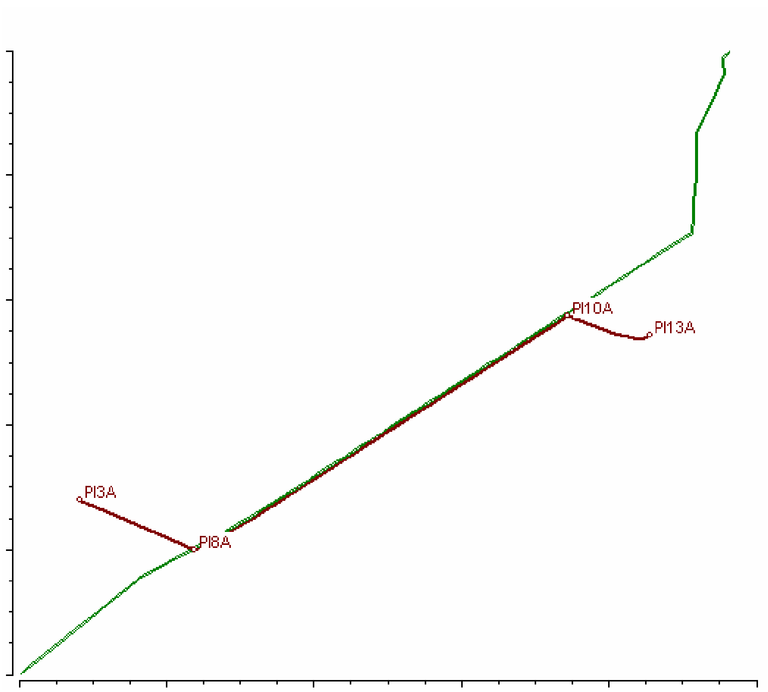


FIGURE 13 – Twin HVAC circuit parallel to pipeline (field case).

The average measured coating quality of the pipeline is 20.0 kΩm^2, the average measured soil resistivity is 62.0 Ωm.

Figure 14 presents a comparison between the calculated and induced pipeline voltages.

It can be observed that there is a very good agreement between both data. As expected, the maximum induced voltages are found where the pipeline crosses the HVAC line.

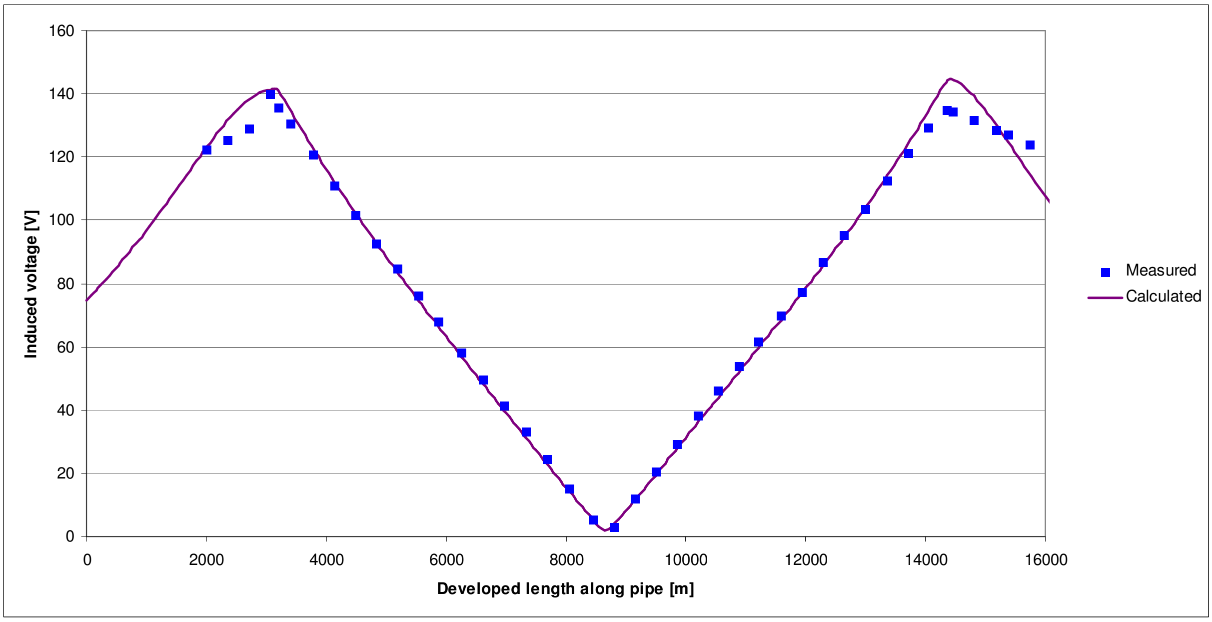


FIGURE 14 – Comparison between measured and calculated induced voltages.

CONCLUSIONS

This paper presents a simulation software that predicts and mitigates inductively coupled voltages on buried pipelines paralleling high voltage electric power transmission lines. To that purpose, a general applicable formulation for the induced EMF on the pipeline has been introduced. This formula can be used for any configuration between transmission line and pipeline and does not require an a priori (and artificial) division of the pipeline in sections parallel or not to the transmission line.

With the obtained values for the EMF, the induced voltages and currents are calculated by solving the well-known transmission line model that represents the pipe-earth circuit. This has been done using a numerical technique based on the one-dimensional finite element method. This approach is very flexible since it allows to specify the pipeline parameters (diameter, coating, soil resistivity, …) for each individual section of the pipeline.

As a first evaluation, the simulated results have been compared with available theoretical test cases. It has been found that the calculated values for the induced electromotive force and the induced voltage and current are in perfect agreement with these theoretical test cases. In addition, it has been proven that commonly used formulas for the induced EMF need to be handled with care, especially when the distance between the transmission line and the pipeline becomes bigger.

In a second step, the calculated induced voltages have been compared with experimental data for two transmission lines that run parallel to a buried pipeline for about 12 km. Also here very good agreement has been obtained.

REFERENCES

1 "Cathodic Protection Level 1 Training Manual", NACE International, 2000.

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