ACCURATE SIMULATION OF AC INTERFERENCE CAUSED BY ELECTRICAL POWER LINES: A PARAMETRIC ANALYSIS

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Abstract

AC interference caused by high voltage power lines on non-energized utility lines (such as pipelines, rail tracks, etc.) sharing a common corridor with the electric lines is a serious concern because it can result in electric shocks and can threaten the integrity of the utility lines. This paper compares and discusses two different methods devoted to AC interference studies. A circuit approach and an electromagnetic field approach are used to carry out a parametric analysis for various configurations of the network, grounding systems, fault current contributions and locations, and soil structures. In the circuit approach, inductive and capacitive interference components are computed first and independently from the conductive components. The overall interference is then obtained by adding all components. Two methods are used to model ground impedances with the circuit approach. The coupled-ground method accounts for the coupling between grounds and the classical method ignores the coupling by assuming that each grounding system is very far from all others. On the other hand, the electromagnetic field theory approach models the complete network and the inductive, capacitive and conductive interference effects are simultaneously taken into account. Computation results based on the various approaches and methods are then compared and discussed. Noticeable differences are found in some cases between the various approaches.

Keywords

AC Interference, Computer Simulation, Transmission Lines, Power System Planning, Grounding

1. Introduction

AC power lines and non-energized utility lines (such as pipelines, rail tracks or low voltage conductors) often share a common corridor. As a result, these utility lines may be subject to electrical interference due to inductive, conductive and capacitive effects. The inductive interference component is caused by the alternating magnetic field generated by current flowing in the power line conductors and is particularly strong when a single phase-to-ground fault occurs on the power line. The conductive interference is due to currents discharged into the various power line grounding systems during faults occurring at locations near the utility lines. Usually, the capacitive coupling effect is negligible for grounded or buried metallic conductors or pipes. In most interference cases, inductive and conductive effects are almost in phase and therefore will add up and may lead to severe interference levels that can result in an electrical shock hazard for people touching the utility line (touch voltage) or simply standing nearby (step voltage) and furthermore, damage to utility line, such as pipeline's coating, insulating flanges, rectifiers or even direct damage to the pipeline's wall itself can occur. Therefore, this proximity effect is a major concern that requires a thorough analysis to evaluate the AC interference levels and determine if mitigation is required.

Previous studies have already been carried out on this subject [1-6]. This paper expands on all topics related to this area. In principle, both circuit and field approaches can be used to carry out the AC interference study. In the circuit approach, the line parameters, such as longitudinal self and mutual inductive impedances of the various metallic paths (conductors, pipelines, etc.), and lumped parameters, such as tower and substation grounds are calculated first in order to build a circuit model representing the entire network. In this procedure, the entire network is subdivided into small segments and the piece-wise parallelism approximation is made to assume that all conductors are parallel to each other within any given section (usually a span). Note that the lumped ground impedances that are needed in the circuit model must be determined individually by measurements or using an appropriate formula or software package. Two methods are used here to compute the ground impedances required in the circuit approach. The coupled-ground method that accounts for conductive coupling effects between grounds normally requires the use of a grounding software package. The classical method ignores this conductive coupling and assumes that each grounding system is very far from all others, making it possible to use simple formulae to derive the required ground resistances. Once the circuit model is built, the shunt currents that are discharged into the lumped ground impedances, as computed by the circuit model, are then used in an appropriate frequency-domain grounding software (earth conduction model that accounts for frequency and current phase shifts) to energize the various grounding systems that are present in the right-of-way.

The field approach is based on electromagnetic field theory. By solving Maxwell's electromagnetic field equations, it takes induction effects fully into account and allows the computation of the self inductance of arbitrary circuits and of the mutual inductances between any two such circuits. The computation results contain the combined effects of the inductive, conductive and capacitive interference. However, it requires more computation time, since the network model must represent all above ground and buried conductors (including grounding systems) simultaneously.

Various scenarios are analyzed in detail and the results for different approaches and methods are compared. All computer simulations are performed using the computer software described in references [7-9].

2. Computer Models

This study is based on a reference computer model, from which several simulations are created by varying one parameter at a time. The reference computer model under consideration is illustrated in Fig. 1.

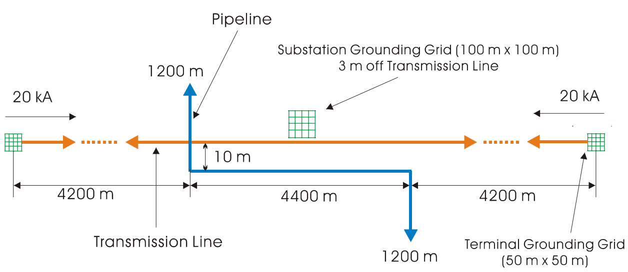

Fig. 1. Reference computer model.

A 16 inch (about 0.4 m) steel pipeline with 500,000 ohm-m^2 coating leakage resistance is buried at a depth of 3 m and runs parallel to a 230 kV transmission line for a distance of 4400 m. At each end of corridor exposure the pipeline turns abruptly and perpendicularly to the transmission line and extends another 1200 m beyond the end. The separation distance between the pipeline and the center of the transmission line is 10 m. The transmission line is 12800 m long. The phase conductors (266.8 MCM ACSR Partridge) are 11 m above ground. The shield wire (OPGW 52 mm/646) is located at the center of the transmission line and is 18 m above ground. It is grounded by means of a 2 m ground rod at each tower. The span length is 400 m. A substation is located midway along the transmission line, just 3 m off the transmission line center line. The substation grounding system is a 100 m by 100 m copper grid, which is connected to the shield wire. Both terminal substation grounding systems are 50 m by 50 m copper grids. The grids are buried at a depth of 0.5 m. The pipeline is not connected to any grounding grid or transmission tower grounds. The soil is assumed to be uniform with a resistivity of 100 ohm-m. The available phase-to-ground fault current magnitude is 40 kA with equal contributions of 20 kA from each terminal, for a fault modeled midway along the transmission line. Note that for simplicity, only the faulted phase conductor (side phase) was modeled.

The following is a list of the parameters of the computer model that were varied in the parametric study:

- The pipeline is connected to the substation grid;
- The substation grid is removed;
- The exposed pipeline is at an angle of 30, 45, and 60 degrees with respect to the transmission line;
- The fault occurs at the second tower from the left terminal substation;
- The soil resistivity is changed to 1000 ohm-m;
- The fault current contribution is 30 kA from the left terminal and 10 kA from the right terminal.

3. Computation Results

The components of the inductive and conductive interference are computed for each scenario using the circuit and field approaches. Earth potentials are computed at observation points located on the surface of the soil along a profile that parallels the pipeline, within the shared corridor. The profile is above the pipeline. Therefore touch voltages along the pipeline can be calculated as the difference between the pipeline ground potential rise (GPR) and the potential of the observation point above it. The spacing between adjacent observation points is 5 m.

3.1 Reference Scenario

Figs. 2 and 3 show the touch voltages along the pipeline caused by the inductive and conductive components for the reference scenario.

The peak value of the touch voltage caused by the inductive component occurs midway along the pipeline, as shown in Fig. 2, and is 6332 V or 6310 V based on both methods used in the circuit approach, or about 16 % larger than the 5448 V computed by the field approach. The reason for this is attributed to the sudden reversal of the magnetic field (fault current flow reversal) at the fault location that applies in the circuit model. In the field approach, the magnetic field change is progressive (smooth transition) across the fault location. Therefore the circuit model predicts higher touch voltages at the fault location than the field model. Note that the difference between the fields on coupled-ground and classical circuit approaches is quite small, suggesting that the methods are equivalent.

Fig. 3 indicates that the maximum value of the conductive component of the touch voltages computed using the classical circuit approach methodology (6365 V) is slightly lower than the 6474 V computed by the field approach. This is to be expected because the circuit model approach, within its abrupt transition of magnetic field, reduces more effectively, by induction on the shield wire, the flow of current into the earth from the towers and substation near the fault site than is seen in the field approach and this despite the fact that the lumped grid and tower impedances that are computed individually in the classical method are lower than the values that are calculated using the field or coupled-ground method. Lower ground resistances would of course result in a greater share of the total fault current being injected into the earth near the fault, thereby increasing nearby touch voltages. The effect of this coupling is clearly illustrated in Fig. 4. It shows that the tower grounds in the vicinity of the fault location exhibit higher ground resistances (51.25 ohms) than all other tower grounds (as low as 46 ohms), due to the influence of the substation grid. Note that the tower ground resistance computed individually (i.e., no other grounds in the vicinity) is 44.89 ohms. On the other hand, the substation grounding grid is much less influenced by this proximity effect. Its ground resistance is 0.45 ohm when coupling effects are accounted for and 0.447 ohm when these effects are ignored. This is why when the coupled-ground method is used in the circuit approach the results improve compared to the exact values computed by the field approach.

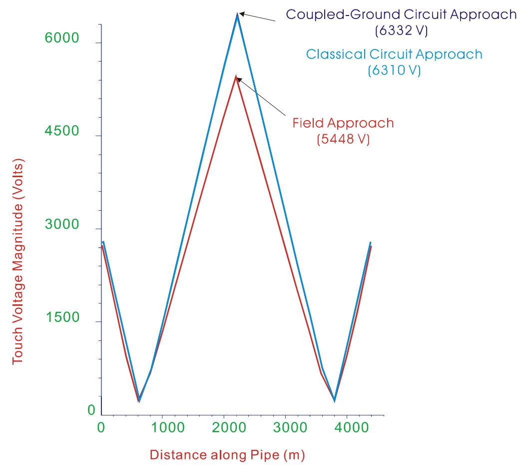

Fig. 2. Inductive pipe touch voltages for Reference Case.

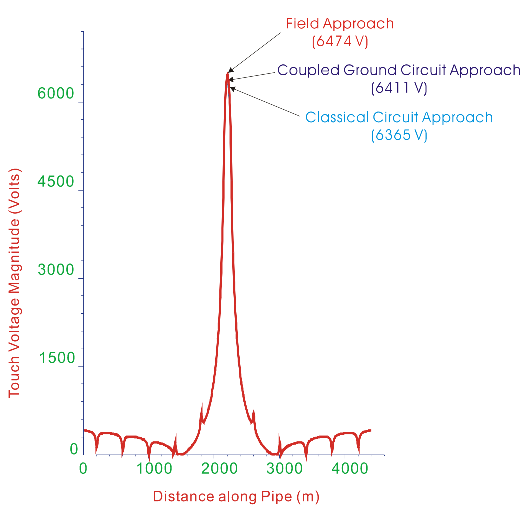

Fig. 3. Conductive pipe touch voltages for Reference Case.

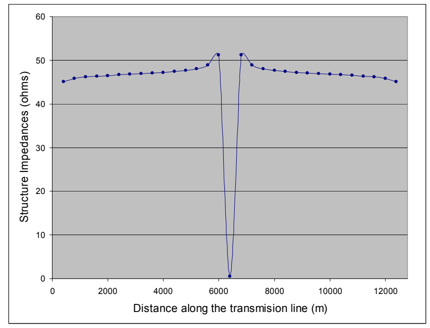

Fig. 4. Coupled-ground resistance values (towers and grid).

As can be seen from Fig. 3, the difference between the touch voltages computed by both approaches is only 0.97%. Note that this improvement applies to the conductive component only. It is important to note here that the coupled-ground method data is derived from the computation results obtained from the field model, i.e., the ground resistance is determined as the ratio of the computed tower (or grid) GPR over the current flowing through the tower (or grid). Therefore, it is not a practical method, because it requires the deployment of a field-based computer model that it is supposed to replace. It is discussed here to determine the extent of the inaccuracies that are caused by neglecting the conductive coupling effects between grounds.

3.2 Pipeline Connected to Substation Grid

When the pipeline is connected to the substation grounding grid (Scenario 1), the potentials along the pipeline are as shown in Fig. 5. Note that because in this case we have a direct connection to the pipeline, the pipe potentials include both inductive and conductive components. The values computed using the circuit approach are larger than those computed using the field approach everywhere except at the fault location. The difference however, is small. Note that the classical and coupled-ground methods results are essentially the same.

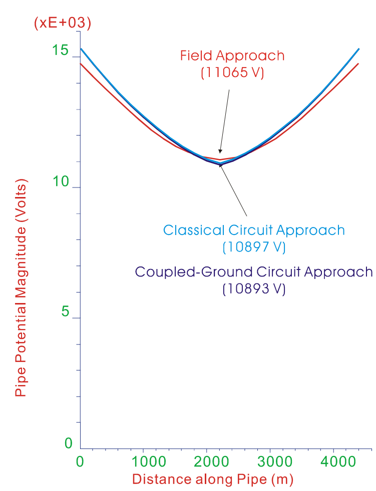

Fig. 5. Pipe potentials for Scenario 1.

3.3 No Substation Grounding Grid

When the substation grounding grid is removed (Scenario 2), less fault current is discharged into the earth and the pipeline touch voltages are lower for both inductive and conductive components. The difference between the touch voltages due to the inductive component at the fault location has decreased to about 10% as shown in Fig. 6.

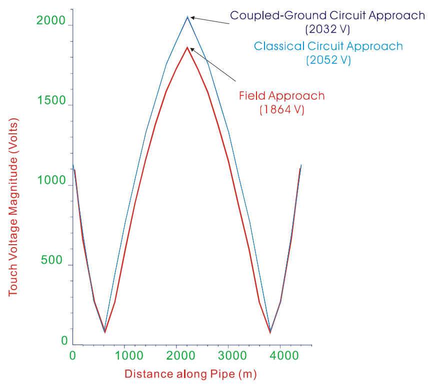

Fig. 6. Inductive pipe touch voltages for Scenario 2.

The amount of current injected into the earth is slightly larger in the circuit model than in the field model because all tower impedances used in the circuit model (44.89 ohms) are lower than the resistances that apply in the field model (45.74 to 46.7 ohms). However, the differences are marginal. That is why the touch voltages caused by the conductive component are 1.2% larger in the classical circuit model than in the field model. The coupled-ground circuit model results are 0.5% larger only as shown in Fig. 7.

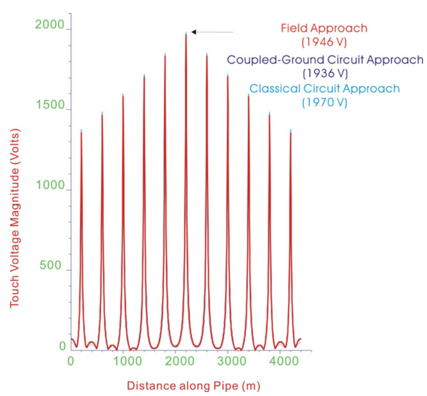

Fig. 7. Conductive pipe touch voltages for Scenario 2.

3.4 Pipeline Crossing the Transmission Line

Figs. 8 to 11 show what happens when the pipeline crosses the transmission line for three different crossing angles. In general, the circuit approach overestimates the inductive touch voltage on the pipeline. The influence of the crossing angle is significant at the fault location. The differences are 87%, 177% and 512% for angles of 30 (Scenario 3), 45 (Scenario 4), and 60 degrees (Scenario 5), respectively.

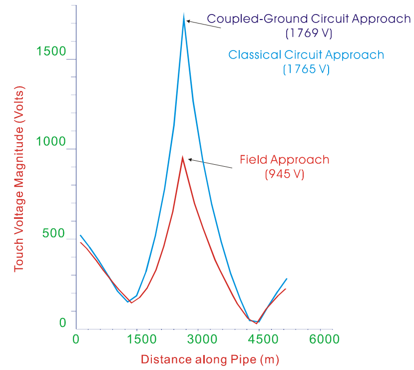

Fig. 8. Inductive pipe touch voltages for Scenario 3 (30 degrees).

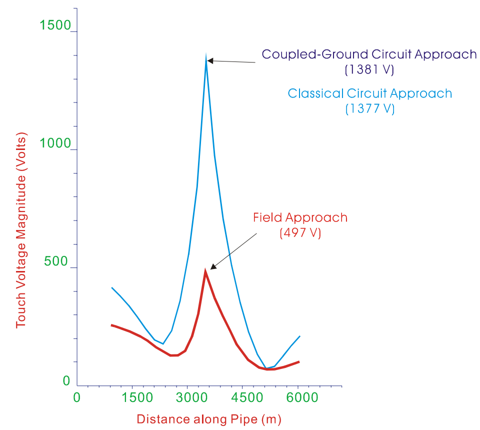

Fig. 9. Inductive pipe touch voltages for Scenario 4 (45 degrees).

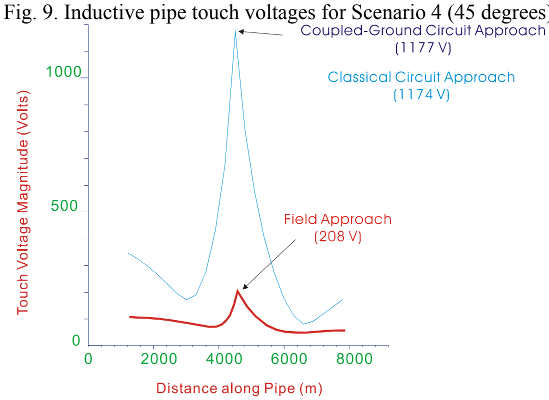

Fig. 10. Inductive pipe touch voltages for Scenario 5 (60 degrees).

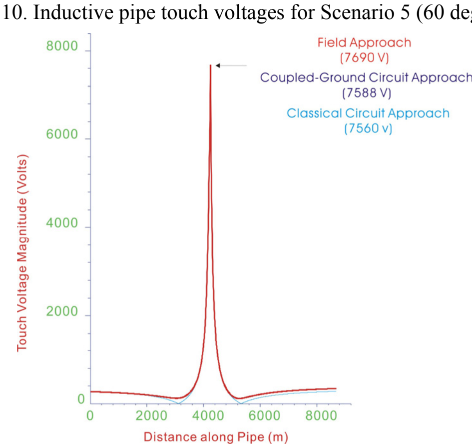

Fig. 11. Conductive pipe touch voltages for Scenario 5 (60 degrees).

The influence of the crossing angle is significant at the pipeline ends for angles exceeding 30 degrees. These results are consistent with those presented in [3] and [4]. As already stated, the magnetic field rapidly changes in magnitude and phase angle at the fault location, a fact that is not taken into account by the circuit approach. Note however that the overall interference includes also the conductive component shown in Fig. 11 (Scenario 5, 60 degrees). The conductive components for the other two angles exhibit a similar trend and behavior. Figs. 10 and 11 clearly show that the difference between the two approaches is not as dramatic if the overall interference levels are compared, because of the rather large magnitude of the conductive component.

3.5 Influence of Soil Resistivity

The objective of this scenario analysis (Scenario 6) is to investigate the effects of soil resistivity variations on the accuracy of circuit and field approaches. The results that pertain to a 1000 ohm-m soil resistivity are shown in Figs. 12 and 13. The soil resistivity affects the lumped ground resistance values much more than the transmission line and pipeline line parameter values. Therefore, significantly lesser currents are discharged into the earth, while more current flows in the shield wire towards both terminals. The discontinuity of the magnetic field at the fault location is larger and has a stronger influence on the computation results. Consequently, the maximum touch voltage difference between circuit and field models due to the inductive component increases from 16% for the reference scenario to about 29% in this case. The effect of high soil resistivity on the conductive components is significant. However, the relative differences of the conductive components between circuit and field models is still remaining the same as the references case, as shown in Fig. 13.

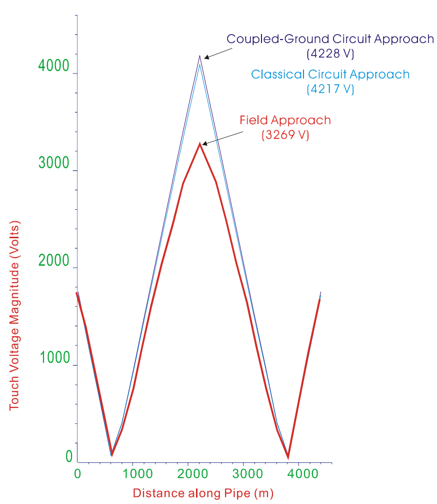

Fig. 12. Inductive pipe touch voltages for Scenario 6.

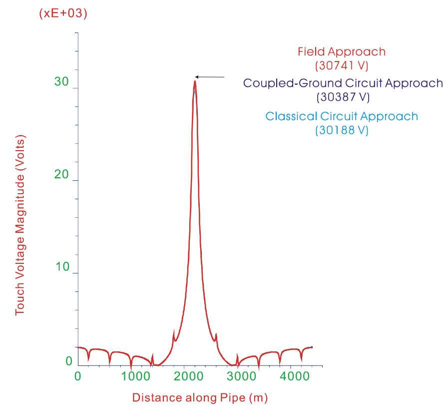

Fig. 13. Conductive pipe touch voltages for Scenario 6.

3.6 Influence of Fault Location

Assume now that the fault occurs on the second tower near the left terminal (Scenario 7), i.e., 5600 m away from the substation. The inductive and conductive components of the touch voltages computed using the circuit approach and field approach are similar. In this scenario, the pipeline is parallel to the transmission line and there is no significant abrupt magnetic field change along most of the right of way. The computation results are shown in Figs. 14 and 15.

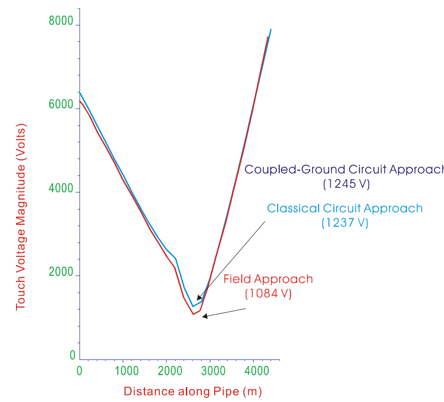

Fig. 14. Inductive pipe touch voltages for Scenario 7.

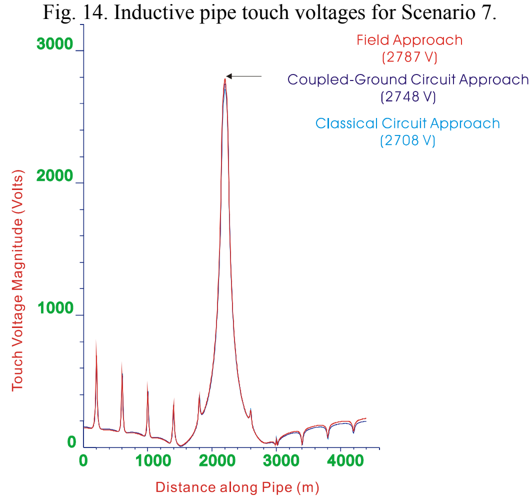

Fig. 15. Conductive pipe touch voltages for Scenario 7.

3.7 Influence of Fault Contributions

In this Scenario 8, it is assumed that the fault current contributions from the left and right terminals are 30 kA and 10 kA respectively. Figs 16 and 17 show the results that apply for this case. The conclusions are similar to the reference case except that the maximum peak is now about 8 kV and occurs near the left terminal because of the unequal fault contributions.

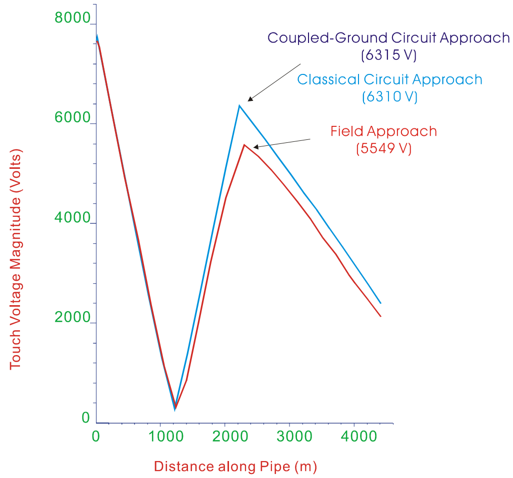

Fig. 16. Inductive pipe touch voltages for Scenario 8.

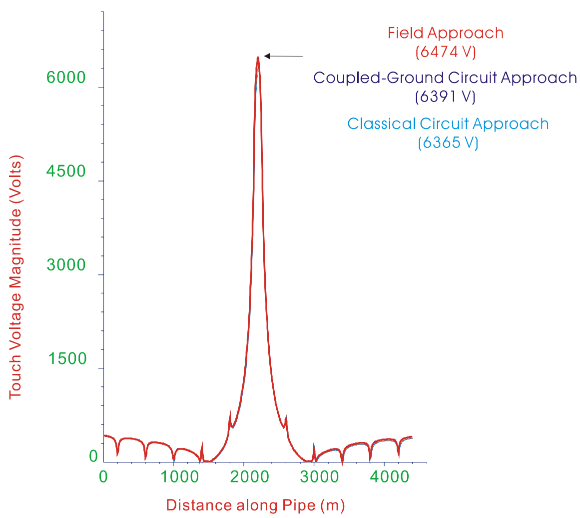

Fig. 17. Conductive pipe touch voltages for Scenario 8.

4. Conclusion

The AC interference from a high voltage power line on a nearby non-energized line has been analyzed for various scenarios, using the circuit and electromagnetic field approaches. The following parameters have been found to have a significant influence on the accuracy of the inductive component computed using the circuit approach:

- Angle between the inducing and induced lines;
- Current discontinuity at the fault location (i.e., relative magnitudes of the contributions from both ends);
- Fault location with respect to the transmission line feeding ends.

The following parameters have been found to have a relatively smaller influence on the accuracy of the inductive component computed using the circuit approach:

- Soil resistivity;
- Type of interconnection between the pipeline and the faulted structure;
- Size of the grounding system at the fault location;
- The method used to calculate the ground impedances along the right of way. More precisely, the coupled-ground method that accounts for conductive coupling among all grounds introduces small improvements.

Finally, the conductive component is accurately computed for all ranges of values that were examined in this parametric analysis. The importance of inductive interference, when compared with conductive effects near the fault location, decreases dramatically with increasing angle between the transmission line and the pipeline, so the inductive interference may not be a concern at all when the angle becomes large.

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References

[1] F. P. Dawalibi, J. Ma and Y. Li, Mechanisms of electromagnetic interference between electrical networks and neighboring metallic utilities, *American Power Conference*, Chicago, 1999.

[2] Y. Li, F. P. Dawalibi and J. Ma, Electromagnetic interference caused by a power system network and a neighboring pipeline, *Proceedings of the 62nd Annual Meeting of the American Power Conference*, Chicago, 2000, pp. 311-316.

[3] Y. Li, F. P. Dawalibi and J. Ma, Effects of conductor angle between transmission lines and neighboring utilities on the accuracy of inductive interference computations, *Proceedings of the IEEE-PES/CSEE International Conference on Power System Technology*, PowerCon 2002, Kunming, China, 2002, Vol. 4, pp. 2477-2481.

[4] Y. Li, F. P. Dawalibi, and J. Ma, Effects of the length and angle of conductors on the computation accuracy of inductive interference, *Proceedings of the 2001 IEEE/PES Transmission and Distribution Conference and Exposition*, Atlanta, Oct. 28 - Nov. 2, 2001.

[5] A. Taflove, M. Genge, J. Dabkowski, Mitigation of Buried Pipeline Voltages Due to 60 Hz AC Inductive Coupling, Part I - Design of Joint Rights-of-Way, *IEEE*

Trans. on Power Apparatus and Systems, Vol. PAS-98, No. 5, Sept/Oct 1979, pp. 1806-1813.

[6] M. Frazier, et. al., Transmission Line, Railroad and Pipeline Common Corridor Study, *IEEE Trans. on Power Delivery*, Vol. PWRD-1, No. 3, July 1986, pp. 294-300.

[7] F. P. Dawalibi and F. Donoso, Integrated analysis software for grounding, EMF, and EMI, *IEEE Computer Applications in Power*, 1993, Vol. 6, No. 2, pp. 19-24.

[8] F. P. Dawalibi and A. Selby, Electromagnetic fields of energized conductors, *IEEE Transactions on Power Delivery*, Vol. 8, No. 3, July 1993, pp. 1275-1284.

[9] A. Selby and F. P. Dawalibi, Determination of current distribution in energized conductors for the computation of electromagnetic fields, *IEEE Transactions on Power Delivery*, Vol. 9, No. 2, April 1994, pp. 1069-1078.

Biographies

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