Electromagnetic Field Coupling Between Over-Head Power Lines and Nearby Metallic Pipelines in Case of Direct Lightning

Denisa Stet, Levente Czumbil and Dan D. Micu
Technical University of Cluj-Napoca/ Electrotechnics and Measurement Department, Cluj-Napoca, Romania
e-mail: Denisa.Stet@ethm.utcluj.ro, Levente.Czumbil@ethm.utcluj.ro, Dan.Micu@ethm.utcluj.ro

Abstract - **Lightning-induced voltages in power systems are nowadays one of the causes of the main power quality and electromagnetic compatibility issues. In recent years, due to the increasing demand by customers for good quality in the power supply along with the widespread use of sensitive devices connected to distribution lines, the protection against lightning-induced disturbances became of primary importance. Installing pipelines in energy utility corridors containing high-voltage AC transmission lines subjects the pipelines to induced AC voltages which are a real and serious problem which can place both operator safety and pipeline integrity at risk. In case of a lightning strike on power line, the electromagnetic field produce by this pulse induces voltages in the nearby metallic structures. An electromagnetic interference analysis has been performed in case of a metallic gas pipeline that runs nearby a 110 kV/ 50 Hz power line. Different scenarios regarding the lightning strike on HVPL were investigated. Due to high value of the separation distance between HVPL and MP, only the effect of inductive and capacitive coupling is taking into account. Professional software for power system transients (EMTP-RV) is used to create an original transient state equivalent electrical circuit model of the system and to perform simulation of the transient process during lightning strike and compute the induced voltages in the metallic pipeline.**

Keywords: *electromagnetic interferences, AC induced voltages, gas pipeline, lightning stroke, EMTP-RV*

I. INTRODUCTION

Due to fast development of economy, energy demand is gradually pressing and the power transmission line and oil/gas pipelines are in the construction of rapid development. In many cases, these utilities have been forced to share the same distribution corridors for their networks. The main reasons for that were the strict environmental regulations that made it very difficult and time consuming to choose another corridor and the higher financial costs a new corridor would inflict. This resulted in situations where gas, water or oil supply utilities are sharing the same rights-of-way with overhead power lines or AC railway systems for several kilometers and in proximity to each other [1, 2].

Installing pipelines in energy utility corridors containing high-voltage AC transmission lines subjects the pipelines to induced AC voltages which is a real and serious problem which can place both operator safety and pipeline integrity at risk.

The electromagnetic fields generated by high voltage power line (HVPL) result in AC interference to nearby metallic structures, in the form of three mechanisms, namely inductive, conductive and capacitive. Capacitive coupling especialy afects the aboveground pipeline since it has both a capacitance to the transmission line and earth. İnductive coupling is caused by the time-varying magnetic field produced by the transmision line curents. Aerial and underground pipelines are both afected by inductive coupling. Resistive coupling is only relevant during the grounding fault and lighting strike when significant level of current flow into the earth. This will raise the potential of the tower base and of the neighboring soil with regard to the remote earth, and results in considerable stress voltage across the coating of the pipeline, which can lead to arcing that damages the coating or even the pipeline itself. When the lightning strikes the HVPL, both the inductive and resistive coupling will take place and put the pipeline at severe risk [1, 3, 4].

Lightning is an important phenomenon that implies an extremely high current, high voltage and transient electric discharge. It is caused by the accumulation of charges on clouds which, when sufficient potential is reached with respect to the ground (minimum 3×106 V to maximum 1010 V [5]); breaks down the air insulation gap and a discharge spark results. The current of the lightning discharge can be of the order 3-200 kA, about 1% is 140 kA or more whilst about 50% exceeded 32 kA [6, 7].

Interference from a lightning discharge is sometimes referred to as a lightning electromagnetic pulse. The field from this pulse induces currents and voltages in any conducting material in the vicinity [7].

Gas-pipes generaly are made of steel and polyethylene sheath is widely adopted as the gas-pipeline's outside corrosive protection material. When a high structure such as a power transmission tower is installed near the gas-pipeline route, there is a possibility that dielectric breakdown of polyethylene occurs especialy in case of lightning strike on HVPL.

Lightning overvoltages could be produced by direct lightning strokes to phase wires or by back flashover, when the lightning stroke hits the tower or the sky wire and the voltage across the phase wire insulator string exceeds its withstanding capability.

Direct strike rather than indirect is researched on because the insulation level of overhead line is of higher magnitude in the transmission line systems. Most lightning strikes on transmission lines are direct strikes. Indirect strike will have little impact on the transmission and therefore voltages produced may not be severe. Pipelines are mainly running parallel with transmission lines. For distribution lines, the distance between the shield wire and the insulator is less; therefore induced voltages due indirect strike are also very important to assess for low voltage and medium voltages systems [8].

Therefore a proper study of lightning performance of the transmission lines running parallel with pipelines or any other metallic structures is crucial in order to ensure the required electrical safety and electromagnetic compatibility.

This paper investigates the induced voltages in a metallic gas pipeline (MP) that runs near a 110 kV/ 50 Hz power line, when a single lightning strokes on the tower respectively on phase wire of the HVPL. Since the distance between pipeline and HVPL, along the common distribution corridor, is significantly large (25m), the resistive and capacitive couplings are neglected and only the effect of inductive coupling is taking into account.

II. HELPFUL HINTS

An existing gas stream pipeline shares the same parallel distribution corridor (5 km), on a significant part of its lengths, with a 110 kV/50 Hz single circuit overhead high voltage power line. Fig. 1 presents a cross-section of the studied problem. The HVPL consists of 3 copper phase wires placed in delta configuration electrical towers at 18 m respectively 22 m above ground and 1 aluminum-steel sky wire placed at a height of 27 m.

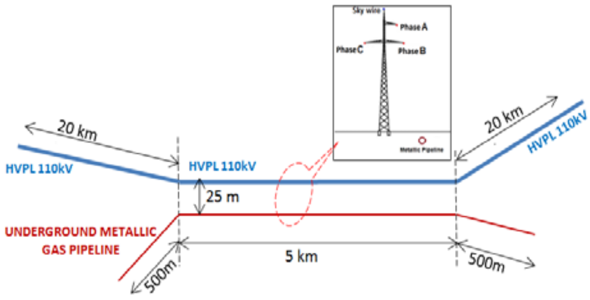

Fig. 1. Over view of the investigated right-of-way

In order to increase accuracy of the EMTP-RV simulation, the implemented geometrical model, takes into account a 20 km section of HVPL, on both sides of the parallel common corridor (see Fig.1).

The considered underground pipeline is part of a natural gas transmission main. The burial depth of the pipeline is 1.4 m; its outside diameter is 800 mm and its wall thickness 10 mm. The pipeline is coated with fused bonded epoxy primer and three-layer extruded polyethylene. The resistivity of the coating material is considered to be 25 $M\Omega \cdot m$ (see Fig. 2).

A. *Transmission Line Tower Modell*

One of the most important steps in the evaluation of fast front overvoltages produced by lightning strikes to overhead power lines is the accurate modelling of transmission transmission line towers.

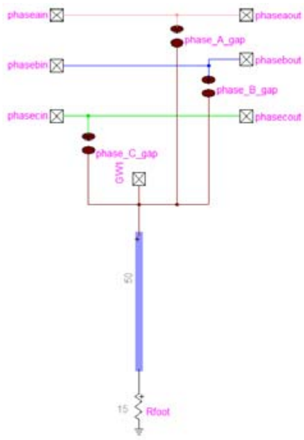

Fig. 3. Model circuit of the 110kV tower

Although the lightning response of a transmission line tower is an electromagnetic phenomenon, the representation of a tower is usually made in circuit terms. The simplest representation of power line tower is a lossless distributed-parameter transmission line, characterized by its surge impedance and travel time (see Fig. 3).

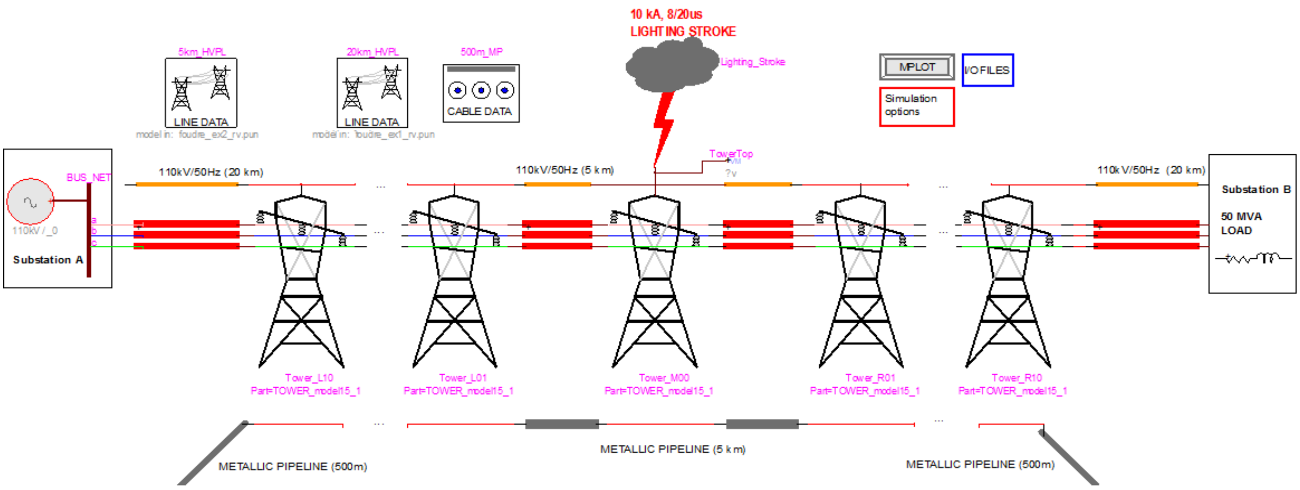

Fig. 2. Part of the EMTP_RV Model of the analyzed system.

The surge impedance would be obtained by defining a weighted average of the tower radius. This approach has been adopted also by CIGRE in 1991 [9] and IEEE in 1993 as standard method to evaluate transmission line tower equivalent surge impedance

$$Z_T = 60 \cdot \ln\left(\cot\left(1/2 \cdot \arctan\left(R_{Avg} / H\right)\right)\right) \quad (1)$$

where:

$$R_{Avg} = \left(r_1 \cdot h_2 + r_2 \cdot h + r_3 \cdot h_1\right)/ H \quad (2)$$

In order to take into account soil ionization phenomena, tower footing could be represented by a current dependent variable resistance driven by equation (3) proposed by CIGRE [10] and IEEE [11]:

$$R_T = R_0 / \sqrt{1 + I / I_C}\ ;\ I_C = (1/2\pi)\cdot(E_0 \cdot \rho)/ R_0^{\,2} \quad (3)$$

where:

- R_T - the current dependent tower footing resistance,
- R_0 - the low current and low frequency footing resistance,
- I_C - the limiting current to initiate soil ionization,
- I - the strike current,
- ρ - the soil resistivity,
- E_0 - the soil ionization gradient.

B. Lightning Current Modelling

The lightning current produced by a lightning stroke to an overhead transmission line could be model using a variable current source in parallel with a 400 Ω resistance representing the air path between the clouds and the transmission line.

To describe the lightning impulse current usually manufactures use a Ramp, eq. (4), or a Double Exponential, eq. (5), function which are easier to implement in test equipment.

$$I_{Ramp}(t) = \begin{cases} \dfrac{I_{LC}}{t_f}\cdot t & t \le t_f \\ \dfrac{I_{LC}}{2\cdot(t_h - t_f)}\cdot(2t_h - t_f - t) & t > t_f \end{cases} \quad (4)$$

$$I_{DExp}(t) = I_{LC}\cdot\left(e^{-A\cdot t} - e^{-B\cdot t}\right) \quad (5)$$

where: ILC is the amplitude of the lightning current, tf is the time to front, th is the time to half, while A and B are exponential coefficients for the double exponential model.

In 1991 based on statistical analysis of recorder lightning strikes around the world CIGRE [10] proposed a more complex formulation of lightning current which to take into account the concave form of the rise up part:

$$I_{CIGRE}(t) = \begin{cases} A_1\cdot t + A_2\cdot t^n & t \le t_c \\ B_1\cdot\exp\left(-\dfrac{t-t_c}{t_1}\right) - B_2\cdot\exp\left(-\dfrac{t-t_c}{t_2}\right) & t > t_c \end{cases} \quad (6)$$

where: tc is the time to crest, t1 and t2 are time parameters and A_1, A_2, B_1, B_2 are coefficient parameters which describe the front and the tail part of lightning current waveform [10].

Recently in literature the Heilder lightning current function [12] is used for the study of fast front overvoltages produced by lightning strikes to overhead power lines:

$$I_{Heidler}(t) = \frac{I_{LC}}{\eta}\cdot\frac{\left(\dfrac{t}{t_f}\right)^n}{1+\left(\dfrac{t}{t_f}\right)^n}\cdot\exp\left(-\frac{t}{t_h}\right) \quad (7)$$

where: n is the order of the implemented Heidler function and η is a scaling coefficient.

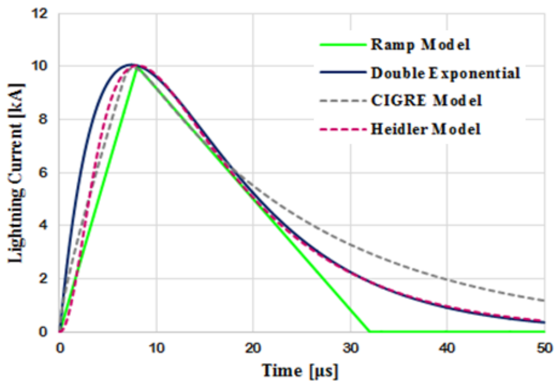

Fig. 4. 10 kA, 8/20 µs lightning current implementation with different mathematical functions.

Recently, in literature, the Heilder lightning current function [12, 13] is used for the study of fast front overvoltages produced by lightning strikes to overhead power lines (I_{LC} is the amplitude of the lightning current, t_f is the time to front, t_h is the time to half):

$$I_{Heidler}(t) = \frac{I_{LC}}{\eta}\cdot\frac{(t/t_f)^n}{1+(t/t_f)^n}\cdot\exp(-t/t_h) \quad (8)$$

with:

$$\eta = \exp\left[-\left(t_f/t_h\right)\cdot\left(n\cdot t_h/t_f\right)^{1/n}\right] \quad (9)$$

where:

- n - the order of the implemented Heidler function,
- η - a scaling coefficient.

III. EMTP-RV SIMULATON RESULTS

A. Steady State HVPL Operating Conditions

In the first stage, the HVPL-MP electromagnetic interference study was carried out for HVPL steady state operating conditions, in order to act as a comparison for the investigated lightning stroke scenarios.

As normal operating condition a 50 MVA symmetrical three phase load is considered for the power line (250 A on each phase wire).

Fig. 5 presents the evaluated RMS value of the induced voltage along pipeline length in case of steady state

HVPL operating conditions.

It can be observed that the highest induced voltage RMS values (12.23 V) are recorded at the two ends of the common distribution corridor HVPL-CM. For a more detailed analysis, Fig. 5 presents the obtained induced voltage waveforms, through EMPT-RV simulation, at different locations along pipeline length.

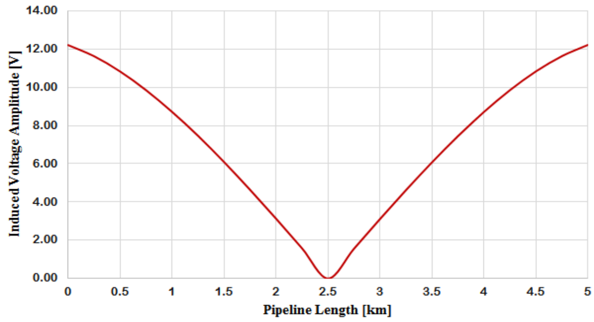

Fig. 5. Induced voltage along pipeline length.

According to Fig.5, for a specific time moment the induced voltage on the pipeline has opposite sign at the two ends (at 0 km and 5 km) and it is almost zero in the middle of common HVPL-MP right of way (at 2.5 km).

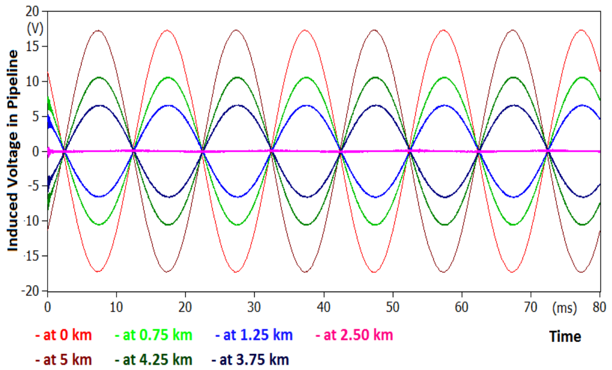

Fig. 6. Induced voltage waveform at different location along the common HVPL-MP right of way.

B. Lightnig Strike to Sky Wire with Back Flashover

In case of a lightning stroke to the HVPL sky wire, the lighting current flows towards the ground through the nearest power line towers, producing a potential rise along the towers and in nearby earth.

If the voltage difference between a tower cross arms and the adjoining phase conductor is higher than the withstand voltage of the insulator string then a back flashover phenomena appears and a part of the lighting current will flow toward the phase wire.

Due the fact that the insulator string may fail to withstand a lower transient voltage with a longer duration, but could withstand high overvoltage values for a short duration, the volt-time characteristic proposed by CIGRE [10] has been implemented for the back flashover simulations:

$$V_{WIns} = K_1 + K_2 / t^{0.75} \tag{10}$$

with:

$$K_1 = 400 \cdot L\,,\; K_2 = 710 \cdot L \tag{11}$$

where:

- V_{WIns} - the insulator string withstand voltage in (kV),
- L - the length of the insulator string in (m),
- t i- the elapsed time in (μs) from the lighting stroke occurring.

The worst case scenario is investigated when the lightning stroke hits the sky wire at the middle of the common distribution corridor, near to a power line tower. A 100 kA 8/20 μs lightning current is considered to strike at simulation time 5 ms, when phase A (the upper phase wire) voltage reaches its peak value and a back flashover phenomena occurs.

Most of this lightning stroke current flow through the power line tower into the earth and due to back flashover phenomena into phase wire A, whereas a part of it flows through the sky wire towards the neighboring towers (see Fig. 7).

Fig. 8 highlights the evaluated overvoltage waveforms on phase A (the upper phase wire) and phase B (the closest phase wire to the pipeline) in case of back flashover, respectively on the sky wire (tower top) at fault location and at the neighboring towers.

It may be noted that almost no overvoltage is recorded on the sky wire at the 5th tower numbered from the fault location.

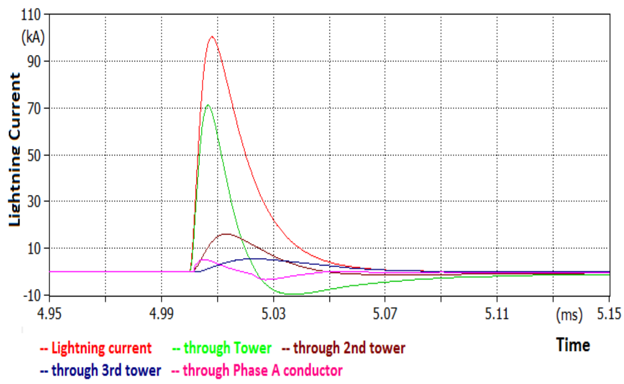

Fig. 7. Produced fault current due to lightning stroke.

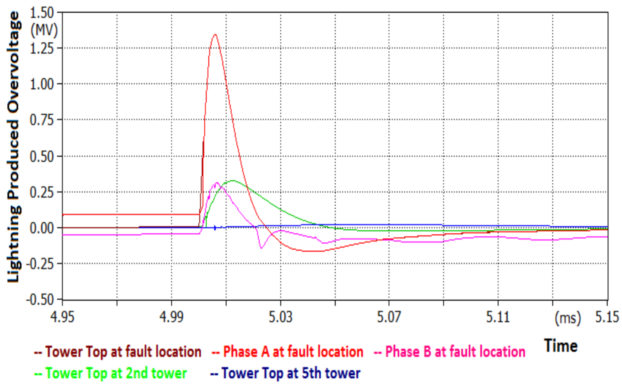

Fig. 8. Produced overvoltage waveforms on power line towers.

Due to inductive and capacitive coupling phenomena the transient overvoltages produced by the lightning strike in the power line phase and sky wires are transferred also to the nearby MP.

Fig. 9 emphasizes the induced voltage waveforms recorded at different locations along the underground pipeline.

The induced voltage waveform in the underground metallic pipeline propagates from the fault location in both directions and reaches the ends of common distribution corridor with a 65% attenuation and a 10 μs time delay (according to Fig. 9). The induced voltage in the underground pipeline dissipates in less than 1 ms.

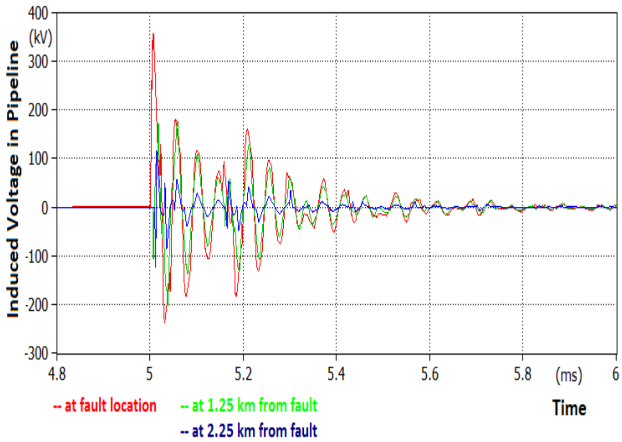

Fig. 9. Induced voltage waveforms in case of lightning stroke to sky wire with back flashover phenomena.

A harmonic analysis of the induced voltages in the can be done according to [14].

C. Lightnig Strike to Sky Wire without Back Flashover

The second investigated high voltage power line fault operating condition scenario refers to a much lower lightning stroke on the overhead sky wire and no back flashover phenomena is triggered. This kind of situation is most common in real life.

Therefore, a 15 kA lightning current is considered to strike the sky wire in the middle of the right of way (details in Fig. 2).

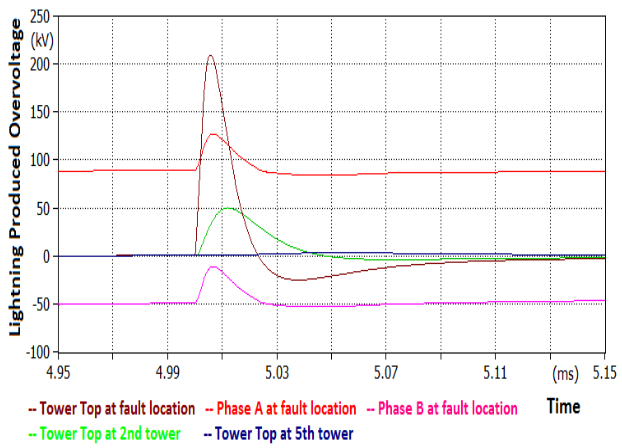

Fig. 10. Produced overvoltage waveforms on power line towers in case of lightning stroke to sky wire with no back flashover triggered.

Fig. 10 shows the evaluated overvoltage waveforms on the sky wire (tower top) at fault location and at the neighboring towers, and on phase wire A and B at fault location in case of no back flashover phenomena, respectively.

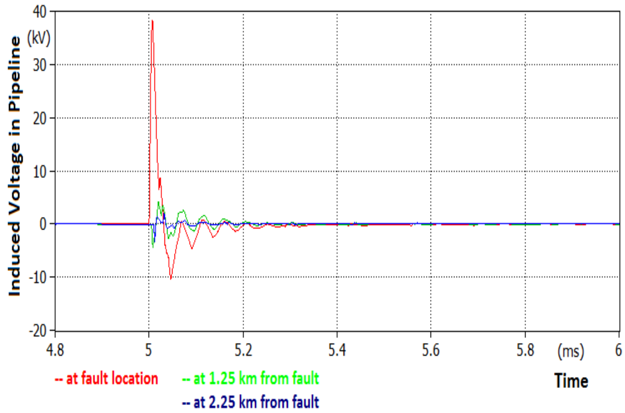

Fig. 11. Induced voltage waveforms in case of lightning stroke to sky wire with no back flashover phenomena triggered.

For the second investigated lightning strike to sky wire scenario the obtained induced voltage waveforms in the underground pipeline, through EMTP simulation are emphasized in Fig. 11. In this case the induced voltage waveform dissipates in less than 300 μs.

D. Lightnig Strike to Phase Wire

The sky wires of a HVPL are designed in order to protect the phase conductors form direct lightning strikes. However, a relatively low magnitude lightning strike may bypasses the sky (shield) wire and attaches to one of the transmission lines phase conduct ors, situation when a shielding failure occurs [15].

In order to evaluate the induced voltage waveforms in the underground pipeline in case of a shielding failure a 3 kA lightning strike is considered hitting the upper phase wire (phase A) at the middle of the common distribution corridor nearby a power line tower.

Fig. 12 presents the produced overvoltage waveforms in the transmission line phase conductors in case of a 3 kA 8/20 μs lightning strike hitting the upper phase wire at simulation time 5 ms when the phase voltage reaches its peak value.

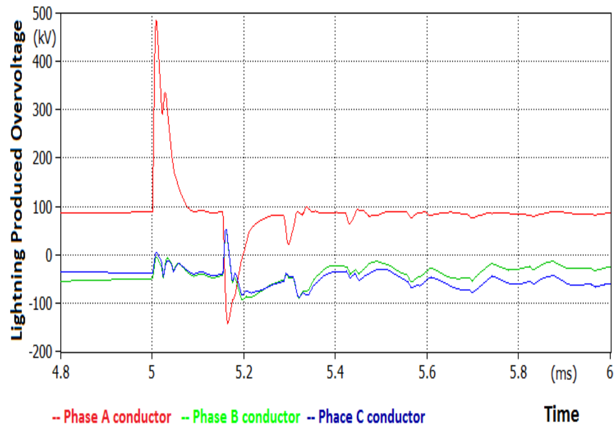

Fig. 12. Induced voltage waveforms in the underground pipeline in case of lightning strike to the upper phase wire.

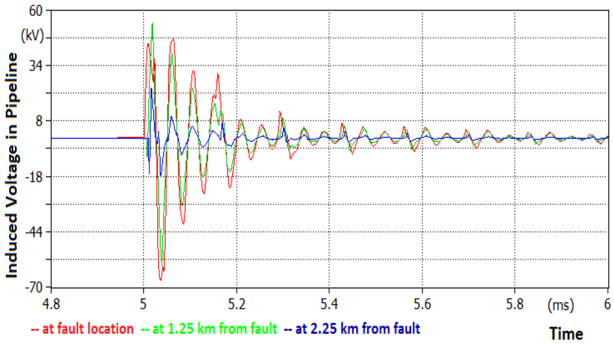

Fig. 13. Induced voltage waveforms in the underground pipeline in case of lightning strike to the upper phase wire.

The obtained induced voltage waveforms in the underground pipeline are showed in Fig. 13.

E. *Effect of Mitigation Wire*

The mitigation technique consists of a long buried wire parallel to the transmission line, often on the side of the transmission line opposite to the pipeline. With proper positioning, the voltages induced in the wire are out-of-phase with voltages induced into the pipeline [16].

For the present study a mitigation copper wire with 4 mm diameter was considered placed at 0.5 m from the gas pipeline.

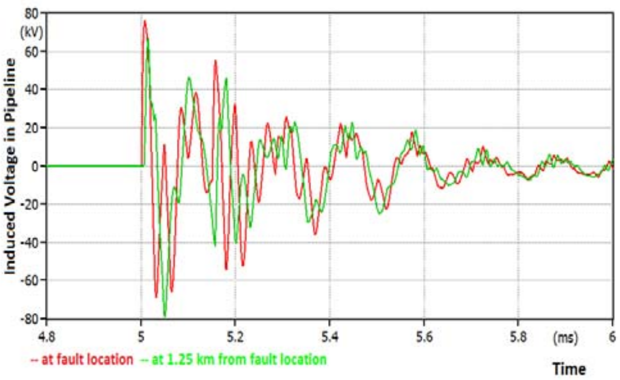

Fig. 14. Induced voltage waveforms in the presence of a mitigation wire for the case of the lightning strike to sky wire with back flashover.

The induced voltage waveforms in the underground pipeline evaluated in the presence of a mitigation wire, for the case of the 100 kA 8/20 μs lightning strike to sky wire, with back flashover phenomena on the upper phase wire (see paragraph III.B) are presented in Fig. 14.

In the presence of the mitigation wire the peak of the induced voltage waveform in the pipeline due to lightning strike to HVPL sky wire is reduced with more than 75%.

IV. CONCLUSIONS

An electromagnetic interference analysis has been performed in case of a metallic gas pipeline that runs nearby a 110 kV/ 50 Hz power line. Different scenarios regarding the lighting stroke on HVPL were investigated. Due to high value of the separation distance between HVPL and MP, only the effect of inductive and capacitive coupling is taking into account. An original transient state equivalent electrical circuit model was implemented in EMTP-RV software, in order to compute the induced voltages in the nearby pipeline.

The obtained results highlight the fact that the underground gas pipeline is subjected to very high induced voltage values. Although the induced voltage waveform dissipates quickly (less than 1 ms), the metallic structures is exposed to the electromagnetic corrosion phenomena.

Received on July 17,2015
Editorial Approval on November 15, 2015

REFERENCES

[1] H. Yuan, L.Qi, Y. Wu, X. Cui and L. Wang, "Lighting Induced Voltage on the Underground Pipeline near Overhead Transmission Line", *Proceedings of 7th Asia-Pacific International Conference on Lighting,* pp.411-415, November 2011.

[2] D.D. Micu, G.C. Christoforidis and L. Czumbil, "AC Interference on Pipelines due to Double Circuit Power Lines. A Detailed Study", *Electric Power Systems Research,* vol.103, pp.1-8, Oct. 2013.

[3] D. □te□ , L. Czumbil., D.D. Micu and O. Miron,"Evaluation and Mitigation on Metallic Pipelines", *Proceedings of the 2012 International Conference and Exposition on Electrical and Power Engineering,* EPE 2012.

[4] L. Darabant, M. Cretu and A. Darabant, 'Magnetic Stimulation of the Spinal Cord: Experimental Results and Simulations', IEEE Transactions on Magnetics, Vol. 49, Issue 5, pp. 1845-1848, May 2013.

[5] M.A. Uman, *Lightning*, Mcgraw-hill Advanced Physics Monograph Series pp. 214, 1969.

[6] M Ahsanul Alam and H Ahmad, "Some features lightning Ground Flashes in Malaysia", *National Technical Seminar*, KL, November 1996.

[7] D. Caulker, H. Ahmad and M. S Mohamed Ali, "Effect of Lightning Induced Voltages on Gas Pipelines using ATP-EMTP Program", *2nd IEEE International Conference on Power and Energy (PECon 08)*, December 1-3, 2008, Johor Baharu, Malaysia.

[8] D. Caulker, "Induced voltages on a gas pipeline due to lightning strikes on nearby overhead transmission line", 2011 http://www.sps.utm.my/sps-ir/id/eprint/1828.

[9] *** Guide to Procedures for Estimating the Lightning Performance of Transmission Lines, CIGRE Technical Report 063, October, 1991.

[10] CIGRE, *Guide to Procedures for Estimating the Lightning Performance of Transmission Lines*, CIGRE Technical Report 063, October, 1991.

[11] *** IEEE Working Group, "Estimating Lightning Performance of Transmission Lines. II. Updates to Analytical Models", *IEEE Trans. on Power Delivery*, vol. 8, no. 3, pp. 1254-1267, 1993.

[12] A. Ceclan, V. Topa, D. D. Micu and A. Andreotti, "Lightning-Inverse Reconstruction by Remote Sensing and Numerical-Field Synthesis," *IEEE Trans. on Magnetics,* vol. 49, no. 5, pp. 1657 - 1660, May, 2013.

[13] A. Ametani, and T. Kawamura, "A Method of a Lightning Surge Analysis Recommended in Japan Using EMTP," *IEEE Trans. on Power Delivery,* vol. 20, no. 2, pp. 867 - 895, April, 2005.

[14] C. Muresan, F. Dragan and V.D. Zaharia, "Total Harmonic Distortion Computation in Nonsyncronized Sampling conditions", *Acta Electrotehnica*, No. 2/2011, pg. 114-118, 2011.

[15] P. N. Mikropoulos, T. E. Tsovilis, "Lightning Attachment Models and Maximum Shielding Failure Current of Overhead Transmission Lines: Implications in Insulation Coordination of Substations", *IET Generation, Transmission & Distribution*, vol. 4, pp. 1299-1313, December, 2010.

[16] D. Markovic, V. Smith and S. Perera, "Evaluation of gradient Control Wire and Insulating Joints as Method of Mitigation Induced Voltages in Gas Pipelines", *Proc. AUPEC(1)05*, Hobart, Australia Paper S01.5, September 2005.