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Lightning Protection of Pipeline Systems

G. Peppas[1*], T.Tsovilis[2], E.Pyrgioti[1], Z. Politis[3]
[1]Electrical and Computer Engineering, University of Patras, Greece
[2] Raycap Group, Ljubljana, Slovenia
[3] Raycap S.A, Athens, Greece
*peppas@ece.upatras.gr

D. Micu[4], I. Gonos[5]
[4] Electrical Engineering dept., Technical University of Cluj-Napoca, Romania
[5] School of Electrical and Computer Engineering, National Technical University of Athens, Athens, Greece

***Abstract*—In this paper a full scale simulation analysis is done for the interference of a High Voltage Transmission line and a underground/aboveground pipeline system. Herein, a coupled system of 400kV transmission line and a nearby pipeline is simulated by means of ATP-EMTP for the case of direct lightning strike to transmission line. Simulation results are presented and possible issues and suggestions are commentated. The necessity of a detailed integrated standard prescribing the lightning and surge protection of pipelines in combination with cathodic protection system is essential.**

Keywords-* *lightning induced overvoltage, transmission line, pipeline, electromagnetic coupling, ATP-EMTP

I. INTRODUCTION

Over the last few decades, due to the huge growth of energy demands, power transmission lines and pipelines are expanding rapidly. Therefore, a profound interaction between the transmission line (TL) and the pipeline is inevitable. Based on the aforementioned parallelism Ametani et al. [1-3] investigated the induced voltages from TL to pipelines, wherein they studied the AC and impulse induced voltages [4-9]. Particularly for the AC induced voltages on a pipeline, various models and software are available [10-11]. The effect of a direct lightning strike on a LV overhead line network close to a buried pipeline has been studied with respect to realizing the safety distance between a buried pipe and the grounding electrode of a LV grid [12]. In this paper a full scale simulation analysis is done for the computation of the electromagnetic interference of 400kV transmission line and an underground/aboveground pipeline network in case of a direct lightning strike to the line.

A mandatory issue for a reliable pipeline system is the cathodic protection installation. A buried pipeline with cathodic protection is usually connected to grounding electrodes via several highly capacitive AC coupling mitigation devices placed at various locations along the pipeline in order to decrease the AC voltage interference. According to the latter, AC corrosion may dilapidate the pipeline with enormous repair cost (i.e replacement under utilization).

II. MODELLING APROACH

Within this framework we simulated a 4km typical double-circuit 400kV TL of the Greek power grid (S-15 type Fig. 1) according to the J. Marti's frequency-depended overhead line model [1]. The matching impedances (Table I) for the transmission line were calculated into [13], wherein the double circuit line was adopted according to [2, 4]. Flashover of transmission line insulator string was modeled by implementing the voltage-time curve flashover model. Lightning strike on the TL mid tower was modeled by means of a Heidler type15 current source producing 1.2/50μs and 10/350μs lightning waveforms of 100kA amplitude; by considering these standards waveforms we investigate the effect for different di/dt of the direct lightning strike.

TABLE I. R, L, C AND Z PARAMETERS OF THE TRANSMISSION LINE TOWER EQUIVALENT CIRCUIT [13] AS SHOWN IN FIGURE 1.

C_T	1.48nF	**L_2**	5.17μH
R_1	17.76Ω	**L_3**	4.87μH
R_2	17.26Ω	**L_4**	4.60μH
R_3	16.24Ω	**Z_{T1}**	220 Ω
R_4	15.33Ω	**Z_{T2}**	220 Ω
R_f	10.00Ω	**Z_{T3}**	220 Ω
L_1	5.32μH	**Z_{T4}**	150 Ω

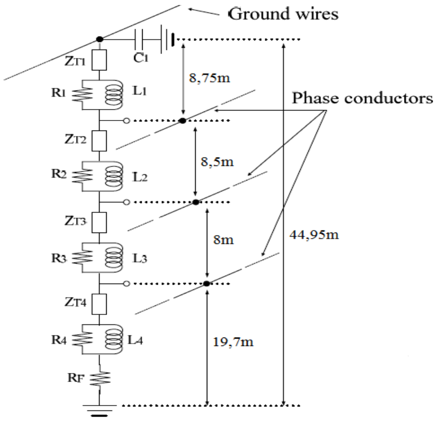

Figure 1. Equivalent circuit of S-15 transmission line tower

The pipeline system is modeled with a typical π-circuit model for short transmission lines. The per unit length values needed for the EMTP RLC model were calculated according to [8]. The equivalent circuit parameters per 100 meter are [13]:

$$L_{pipe}=4.05\mu H,\ C_{pipe}=1.65\mu F,\ R_{pipe}=0.25\Omega$$

Pipeline of 4km in length was simulated according to [1]; it is grounded every 400 m with R_g=150 Ω for aboveground case and underground, while R_g= 10Ω was considered at the ends of the pipeline [3, 8]. The latter parameters for grounding were selected in order to simulate a good grounding system (10Ω) and a poor grounding (150Ω). For the aboveground pipeline case study 2m height was selected while for the underground 1.5m depth. The underground pipeline was investigated for three different case studies, with grounding only at the ends of the pipeline, grounding for each 400m and grounding for each 400m along with annular insulating joints (flanges). The grounding points represent the conducting path through the AC coupling mitigation devices; it should be noted that the pipeline system is not directly grounded in order to maintain the anti corrosion protection system (cathodic protection). It is mandatory to clarify that cathodic protection of pipelines defines ungrounded system in normal conditions; the grounding systems is connected to the metallic part of the pipeline only through a mitigation coupling device, which enables the pass-through (switching) to the ground over a certain threshold voltage (-20~+20V).

According to [7, 13] the coupling between TL and pipeline is capacitive, inductive and resistive; the latter occurring through the soil equivalent resistance between the tower and the pipeline. The above ground pipeline was modeled with these three parameters according to [13]. However, for the underground pipeline capacitive coupling was negligible i.e C_{mutual}≈1.2pF/m, wherein by the addition of the vide ante parameters the simulation results are similar. The underground pipeline parameters were calculated according to [14] which is referring to the interference between and underground and above ground conductor wherein:

$$Z_m = j\omega\left(\frac{\mu_0}{2\pi}\right) exp\left(\frac{-h_2}{h_e}\right) ln\left(\frac{S}{D}\right) \qquad (1)$$

$$For:\ h_e = \frac{1}{m}, m = \sqrt{j\omega\mu_0\sigma}\ , S = \sqrt{H^2 + y^2}\ ,$$

$$H = h_1 + h_2 + 2h_e\ \ , D = \sqrt{(h_1 + h_2)^2 + y^2}$$

h_1: Height of the above ground conductor

h_2: Depth of the underground conductor (herein underground pipeline)

r_1: Radius of the above ground conductor

r_2: Radius of the underground conductor

y: Horizontal distance between above and underground conductor

Thus, following a simplified approach, only resistive coupling was considered as described in [13] with R_{mutual}=50Ω/m and L_{mutual}≈0.1μH/m was used for the coupling between the TL and the underground pipeline.

The induced voltages on the pipeline have been computed from location -2000m to location +2000m, every 400m, at the towers of the transmission line (i.e 11 towers with 400m span). The forthcoming results depicted are corresponding to the 50m distance from the TL, for two different current waveforms 10/350μs and 1.2/50μs for 10Ω grounding resistance, 150Ω grounding resistance, without grounding system and with grounding along with insulation joints. The color sequence is applied in the impending curves as well (**0m, +400m, +800m, +1200m, +1600m, +2000m**).

III. SIMULATION AND RESULTS

A. *Equivalent circuit of the system understudied.*

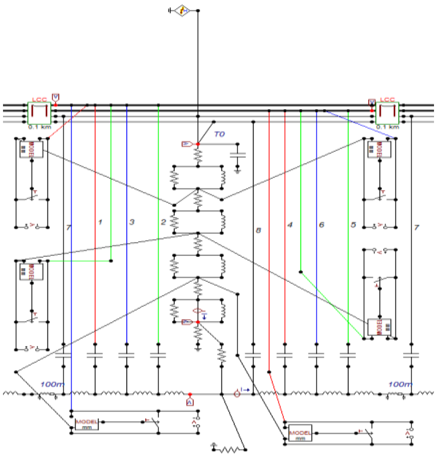

Figure 2. The mid module of aboveground pipeline model with grounding every 400m and with annular insulating joints. [15]

The above ground pipeline mid module (11 modules) wherein the lightning strike is injected is depicted in Fig.1. The underground pipeline model was studied for three case studies, for ungrounded pipeline, grounded every 400m and grounded with insulating joints [16].

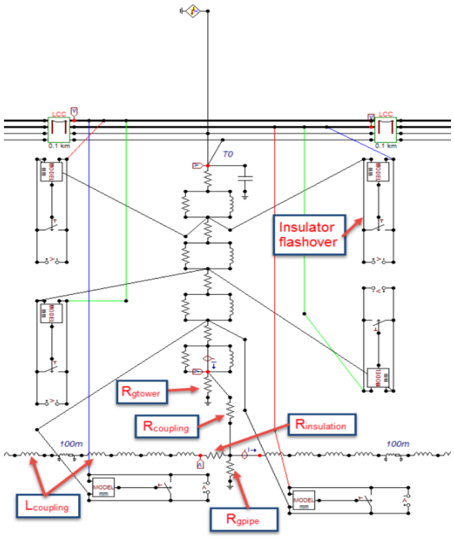

Figure 3. The mid module of aboveground pipeline model with insulator flashover model. [17]

B. *Induced overvoltages due to lightning strikes.*

Table II summarizes the exported simulation results for all the case-studies.

TABLE II. SIMULATION RESULTS FOR BOTH 1.2/50 AND 10/350 WAVEFORMS (ABOVE AND UNDERGROUND PIPELINE)

DISTANCE (m)	**1.2/50µs**							**10/350µs**							
	Above Ground		**Underground Pipeline**					**Above Ground**		**Underground Pipeline**					
	Grounded		Grounded		Ungrounded	Grounded and insulator joints		Grounded		Grounded		Ungrounded	Grounded and insulator joints		
	10Ω	**150Ω**	**10Ω**	**150Ω**	-	**10Ω**	**150Ω**	**10Ω**	**150Ω**	**10Ω**	**150Ω**	-	**10Ω**	**150Ω**	
0m	12.5kV	126kV	704.9V	6.9kV	97.2kV	384.4V	5.3kV	6.3kV	124kV	446V	4.5kV	68.5kV	396V	8.2kV	**Potential (kV)**
+400	10.3kV	121kV	479.0V	1.5kV	38.8kV	152.9V	1.9kV	5.7kV	119kV	215V	680V	28.5kV	168V	3.7kV	
+800	8.1kV	83kV	259.3V	0.9kV	15.1kV	60.4V	1.1kV	3.4kV	81kV	164V	480V	12.2kV	46V	1.5kV	
+1200	5.2kV	55kV	245.5V	0.4kV	43.2kV	171.0V	2.3kV	1.4kV	51kV	133V	190V	8.9kV	165V	2.3kV	
+1600	4.8kV	49kV	164.3V	1.6kV	47.7kV	189.5V	2.8kV	1.6kV	50kV	116V	1.3kV	12.7kV	33V	47.8kV	

Figures 4-9 depict typical waveforms of the induced voltages on the pipeline for a lightning strike of 100kA 1.2/50µs waveform.

Typical induced voltage waveforms for the case of 100kA, 10/350µs lightning strike to the transmission line are shown in Figs. 10-15.

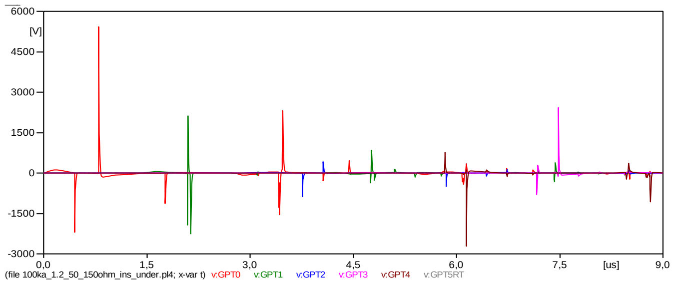

Figure 4. Induced Voltages to the **underground** pipeline for 100kA, 1.2/50µs, R_{gpipe}=150Ω with annular insulating joints.

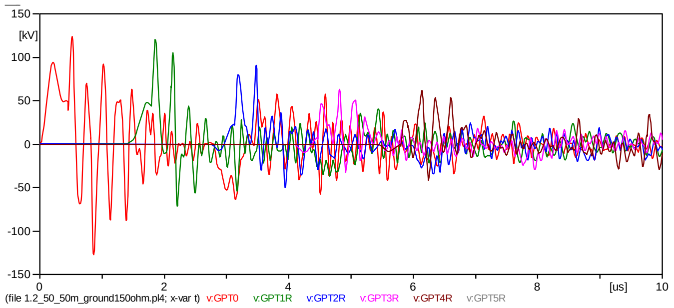

Figure 5. Induced Voltages to the **aboveground** pipeline for 100kA, 1.2/50µs, R_{gpipe}=150Ω with annular insulating joints.

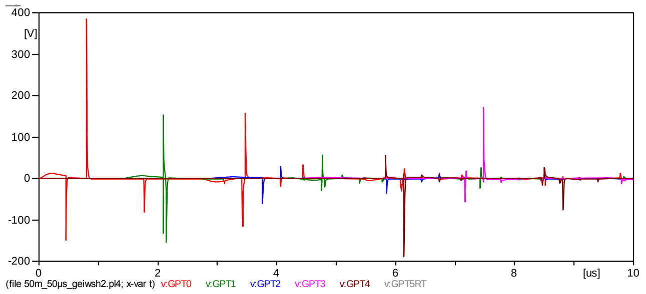

Figure 6. Induced Voltages to the **underground** pipeline for 100kA, 1.2/50µs, R_{gpipe}=10Ω with annular insulating joints.

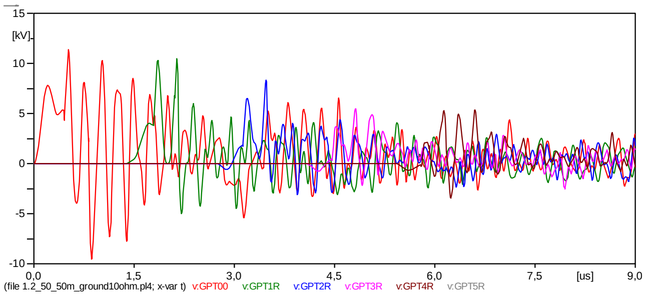

Figure 7. Induced Voltages to the **aboveground** pipeline for 100kA, 1.2/50µs, R_{gpipe}=10Ω with annular insulating joints.

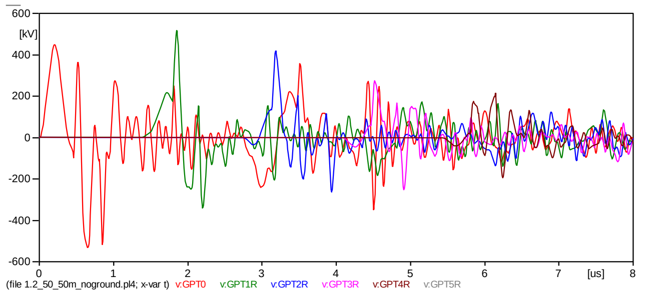

Figure 8. Induced Voltages to the **aboveground** pipeline for 100kA, 1.2/50µs, **without grounding**.

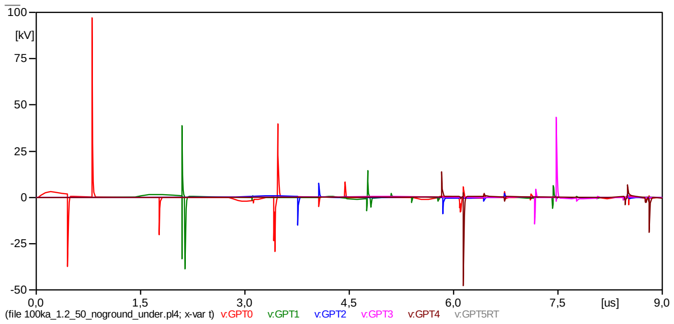

Figure 9. Induced Voltages to the **underground** pipeline for 100kA, 1.2/50µs, **without grounding**.

The 10/350µs lightning current waveform for 100kA is studied in Figs. 10-15.

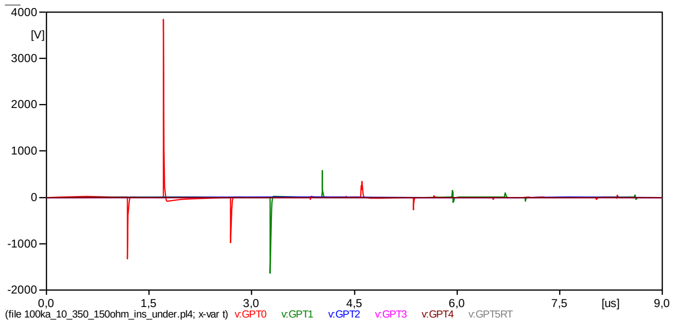

Figure 10. Induced Voltages to the **underground** pipeline for 100kA, 10/350µs, R_{gpipe}=150Ω with annular insulating joints.

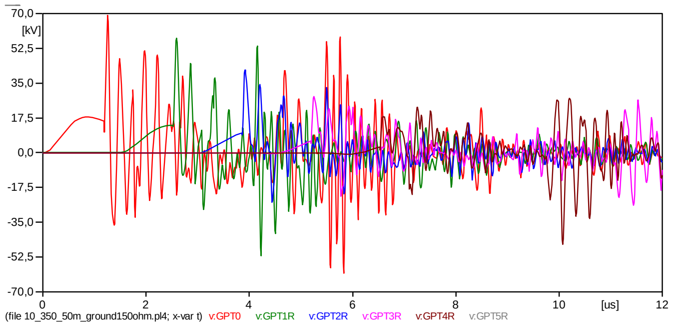

Figure 11. Induced Voltages to the **aboveground** pipeline for 100kA, 10/350µs, R_{gpipe}=150Ω with annular insulating joints.

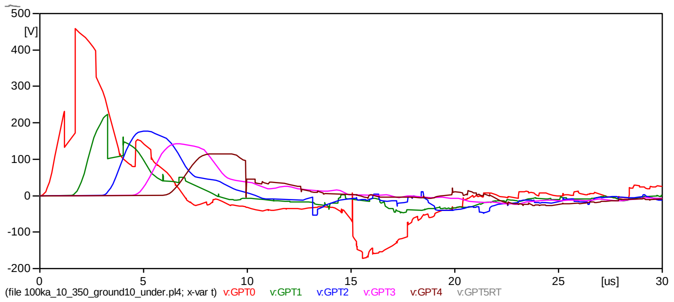

Figure 12. Induced Voltages to the **underground** pipeline for 100kA, 10/350µs, R_{gpipe}=10Ω with annular insulating joints.

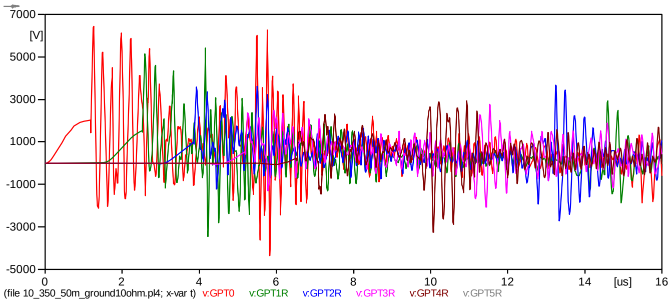

Figure 13. Induced Voltages to the **aboveground** pipeline for 100kA, 10/350µs, R_{gpipe}=10Ω with annular insulating joints.

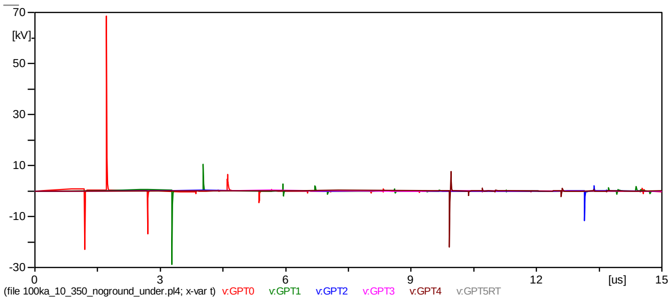

Figure 14. Induced Voltages to the **underground** pipeline for 100kA, 10/350µs, **without grounding**.

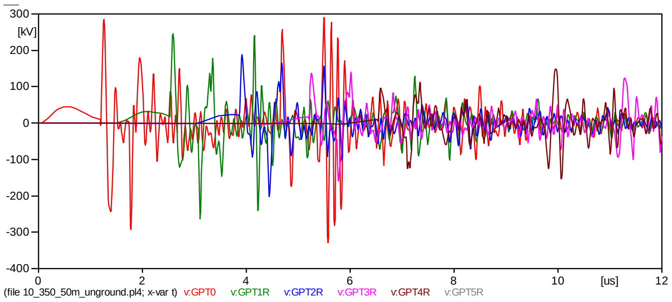

Figure 15. Induced Voltages to the **aboveground** pipeline for 100kA, 10/350µs, **without grounding**.

IV. DISCUSSION AND CONCLUSIONS

Pipeline systems are not directly connected to ground in order to avoid corrosion issues. The cathodic protection station supplies a direct current (dc) in order to maintain a cathodic pipe-to-soil potential and ensure the pipe-to-soil potential anti-corrosion behavior; in case of low frequency induced voltages at the pipelines the coupling mitigation devices installed periodically across the pipelines ensuring that the elevation of the pipeline potential with respect to the soil is limited to a pre-set voltage level above which are triggered and force conduction. The cathodic protection equipment, including DC decoupling devices, should be protected against fast-front surges. This study has demonstrated that:

A. The duration of the induced overvoltages is lower than 100μs (Fig. 12-14), due to nearby lightnings stikes (TL); this waveform may be bigger in case of direct lightning strike to the pipeline as reported in [18,19]; nevertheless it should be noted that the time to half of direct negatice lightning strikes has a median value of 77.5 μs [20].

B. Induced overvoltages peak can be up to around 100kV; the higher the grounding resistance the higher the overvoltage (Table II).

C. It is of great importance that ungrounded pipeline sytems are exposed to the highest induced overvoltages; thus, the open circuit failure mode of the AC mitigation devices combined with their surge protection circuit is not preferable with respect to short circuit failure mode. Short circuit failure mode of AC mitigation devices should preferably be combined with remote monitoring system so as not to affect the long term performance of the cathodic protection system.

D. AC coupling (mitigation) devices should combine surge withstand capabilities and should be in line, apart from BS 15280 [21], with IEC 61643-11[22] standard for SPDs, ensuring safe failure mode; this is of great importance in hazardous oil/gas industry applications.

According to the aforementioned, the scientific community and manufacturers of pipeline protection systems should come up with mandatory requirements on the surge withstand capability and safe failure mode on the devices that are installed in the field.

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