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Investigation of grounding resistance effect on the MV grid of Hellenic electromotive railway during lightning strikes

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***Abstract*— The paper discusses the effect of the grounding resistance on the transient response of MV railway grid during lightning strikes. For study purposes were modelled the electrified railway MV grid (ERMV) that the Hellenic electromotive suburban railway makes use, including the masts, consoles, the rails and the overhead medium-voltage transmission grid of 25kV dedicated for this purpose. For the simulation of the understudied model time-domain solver was adopted in ATP-EMTP software. The model Volt-Time Curve is used for the modeling of the insulator, but it was necessary to create a new equation for the specific model, because of the short length of the insulator in such projects. Two types of lightning are used for the simulation purposes, for fast and slow signal, with current value in 100kA and one measurement in 30kA. For fast signal, the values of front and tail time are 1.2/50µs and for the slow signal 10/350µs. In addition, for the ground resistance: 10Ω, 70Ω and 245Ω are used.**

Keywords- Electrified Railway Medium Voltage (ERMV); ATP-EMTP; suburban railway; medium-voltage (MV); overhead contact line (OHCL);

I. INTRODUCTION

The electromotive railway systems are separated in two categories, with alternative (AC) and direct current (DC) operated ones. The power supply to the train is implemented via two-line overhead line. In the DC operated railways the maximum nominal operating voltage is 3kV. In the DC systems with a third parallel line, the operation voltage is 600÷700V. For cost related purposes regarding the required infrastructure for the railway operation and for higher energy efficiency it is used AC system called electrified railway medium voltage (ERMV) grid. In Greece the underground railway system (metro) trains operate, basically with 750V DC, while they are prepared to operate at 25kVAC ERMV grid, when they have to use the same railway of Hellenic Suburban railway system [1]. In this paper the effect of earthing resistance in the ERMV during lightnings will be discussed in order to be evaluated its performance regarding current dissipation and voltage clearance. The results will be useful for future projects with poor soil conditions where low earthing resistance is not feasible to be achieved.

II. DESCRIPTION OF THE MODEL

The ERMV consists of two main circuits, the primary circuit supplies the train with power and the secondary one is for traffic control and grid protection purposes. The power supply on the primary circuit is provided via a 150kV/25kV step-down substation which is designed to support a two-phase system [2-7]. The main components of the specific substation are: 170kV two-phase disconnector 1250A with earthing switch installed on a pole on the 25kV ERMV substation, voltage transformer 150kV, current transformer 150kV, 150kV circuit-breaker used for protection of the 150kV/27.5kV main transformer, 150kV surge arrester, main (boost) transformer 150/27.5kV-15MVA, single-phase load-breaker switch 25kV-1250A, single-phase disconnector 25kV-1250A, current transformer 800/5-5-5A, voltage transformer 25kV/0.1kV, surge arrestor 36kV. The electrical system of the railway ERMV, that will be considered, consists of overhead line 25kVAC, poles of the ERMV with the earthing electrodes, single-direction railway used as return wire and mounting insulators of the OHCL. The system that is studied in the current paper consists of the following main components: 1) overhead contact medium voltage line (OHCL) which is connected with the train, 2) railways, 3) medium-voltage insulators, and 4) return wire, earthing including equipotential connection system [1]. The OHCL consists of overhead line mounting system, the touch wire with the train, the return circuit and electrical connections along the railway. Railways are used apart from the train path also for the development of a current return circuit. For that purpose it is important to be secured the electrical continuity. The typical railway of the Greek railway is 540mm^2 and 600mm^2 of steel [5]. Insulators are usually used in transmission grids of medium or high voltage in order to support, separate and include medium or high voltage wires. The return wire, the earthing and equipotential connection system is designed and constructed in such a way in order to be ensured the electrical continuity and the appropriate return path for the current which in parallel ensures the reliable operation of traffic control system and also personnel safety. Regarding the earthing, all live components of OHCL and all metallic mounting supports must be earthed in order touch voltages to be avoided and reliable and safe operation to be ensured [2]. The return circuit inside and outside the train stations is created by equipotential connection between poles in specific distances, for Greek railway is 63m [1]. All other metallic parts of the train station like fetches can be connected in the return wire. The earthing method that secures reliable operation against equipment failures and personnel safety is direct earthing. This method makes use of return circuits as main current used for train operation in case of failure. The electrical continuity is aparted of rails and return wire shall ensure the high percentage of current return to the substation. In the next section will be discussed a simplified model of the railway and will analyzed the effect of the earthing resistance of the pole in case of lightning strike [5]. An effective earthing of a railway system can prevent from serial damages of the equipment since in case of ground fault due to lightning insulators can be damaged near the line [3]. The lightning that affects the line can cause voltages which exceed the design and tolerance of the equipment resulting in line wire circuit trip [4]. In Fig.1 is depicted the real system that has been considered in the current paper.

Figure 1. Train of Hellinic Electromotive Suburban Railway [1].

A. Simulation software

In the current paper is discussed the effect of grounding resistance of railway in different type of lightning strikes. The model that has been developed by means of EMTP-ATP, consisted of impulse generator, overhead contact line (OHCL), poles and their earthing electrodes, single-way rail which is used also as return wire and mounting insulators of the OHCL.

B. Model components

The selected impulse generator in EMTP-ATP is Heidler type 15 with rated lightning current 100kA, 1.2/50μs for fast step and 10/350μs for the slow one. The selected OHCL is the one used in the Greek Suburban Railway network and is 25kVAC-50Hz. In the overhead line system is included also the return wire which is mounted on the external side of the pole as indicated in Fig.2. The catenary has been considered as a joint line since the insulators which are mounted on the poles have common connection with fixpoint anchor wire and contact wire. In the meantime, the fixpoint anchor wire is connected via hangers with the contact wire with maximum distance of 300cm. The line that has been simulated consists of 16 poles with 63m spacing meaning total length of 1008m. The left side of the line is the starting point of the OHCL and is the point where the 25kVAC-50Hz is applied. The right side of the line is the ending point of the 1008m line. As regards the poles these are used basically to keep mounted the insulators and the lines [1]. Each pole with total height of 8.01m is considered as typical metallic pole and electrically can be simulated as RLC π-equivalent circuit. In the model are used 17 poles in total. In the first pole starts the return wire and in the last terminates the catenary wire and the return wire. Each pole is grounded via earthing resistance which is calculated with the equation [8]:

$$R = \frac{\rho}{2\pi L} \times \ln\frac{4L}{1.36d} \times \frac{2h+L}{4h+L} \qquad (1)$$

ρ:soil resistivity (Ωm), was considered 200Ωm

L:length of earthing electrode (m)

h:distance from the ground surface (m)

d:electrode diameter (m), was considered 0,011m

For the paper purposes has been considered two type of electrodes installed in different way. For earthing electrode with length of L_1=0.6m and h_1=0.5m and as per Eq.1 was calculated R_1=245Ω. For earthing electrode L_2=3m and h_2=0.2m the earthing resistance was calculated R_2=70Ω.

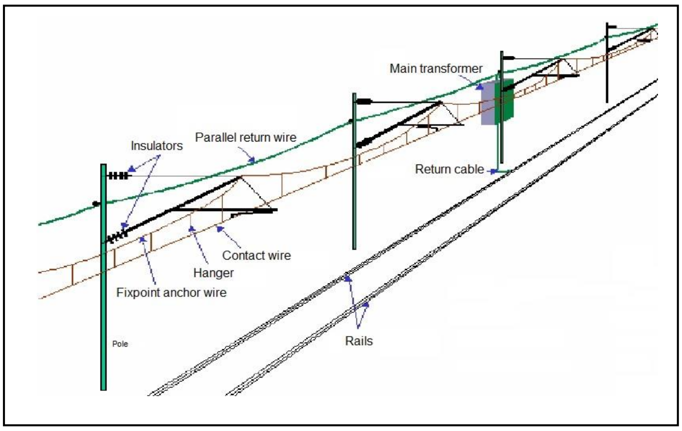

Figure 2. Single-way railway system representation [15].

The surge resistance of the pole is calculated by the equation [9]:

$$Z_p = 60 ln\sqrt{2}\frac{2h}{r} \qquad (2)$$

h:pole height(m)

r:pole radius (m)

The pole of the discussed model has a height of 8.01m and its radius is 0.22m. So the surge resistance of the pole (z_p) is Z_p=278.1Ω. The single-way rail has been considered as joint single-phase RLC π-equivalent. As it is aforementioned the distance between poles is 63m so the total rail circuit consists of 16 parts of 63m length each while the return wire is connected in every 700m. The rail surge resistance is calculated by the equation [9]:

$$Z_r = 60ln\frac{2h}{r} \qquad (3)$$

h:pole height(m)

r:pole radius (m)

For the rail of the current model, h=0.32m and r=13.12mm. So the resistance is calculated 233.7Ω.

The insulator projection is significantly low (36,73cm) wherein there is no adequate literature experimental flashover study for this insulator-string length (i.e EPRI); hence a voltage-time curve data is not available. For this purpose it was essential to find new formula which shall apply for the specific insulators adapted to their length and technical characteristics. In the High Voltage Laboratory of Patras' University and based on measurements in real conditions with equivalent air gaps specific formula has been developed and follows hereto[1, 10]. The eq.4 is derived from experimental data, plotted and fitted with the proposed formula:

$$V_{FO} = \left[224.2 + 31.3e^{-\frac{t}{5.47}}\right] \times 1000 \ \ (kV) \qquad (4)$$

t: the required time in order to have flashover (μs)

The vide ante voltage-time curve equation was adopted in the insulator flashover model and comprehended into the overall simulation approach (Fig. 3).

The total model that has been used is depicted in Fig.3.

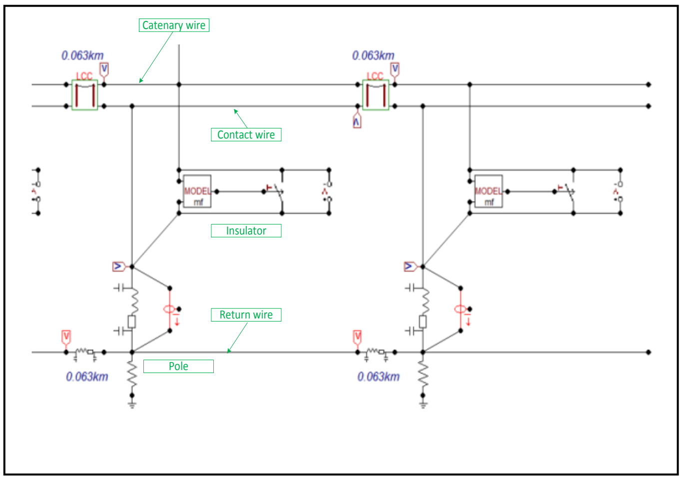

Figure 3. Single-way railway system representation.

III. SIMULATION RESULTS

The electrical equivalent model of the railway system is depicted in Fig.3. The scope of this paper is to be investigated the effect of earthing resistance in the railway network in case of lightning strikes. The main vulnerable points of the railway system are the direct lightning hit on the top of the pole and the catenary wire. The simulation was executed considering two types of lightning strike with different time parameters. The selected time parameters are 1.2/50μs and 10/350μs. The lightning currents that have been considered are of peak values 30kA and 100kA. In this section there will be presented and discussed the simulation results based on the applied lightning signals. The results include:

- Measured current in the poles due to lightning strike
- Measured voltage in the rails which are considered as the return wire of current to the substation.
- Measured voltage due to lightning strike in the catenary wire.
- Measured voltage on the insulators which are connected via droppers (or hangers) and connect the catenary and the contact wire
- Measured voltage on the top of the poles due to lightning strike

Apart from considering the earthing resistance of 70Ω and 245Ω, it was considered additionally an earthing resistance of 10Ω in order to be investigated the effect of earthing resistance to the reduction of the above voltages. It is important to be clarified that the lightning strike occurs in the catenary wire and on the top of the pole and is considered as point 0 for the simulation purposes. The starting point of the rail is the -504m and the end is point +504m while there are 17 poles installed in sections of 63m each. In other words in every 63m the rail is bonded with the pole and is earthed via earthing resistance. The catenary wire is a single-phase transmission line of 25kV rated voltage [1].

TABLE I. SIMULATION POINTS AND ACTUAL DISTANCE

Simulation points	**Actual distance (m)**
-8 / +8	-504 / +504
-7 / +7	-441 / +441
-6 / +6	-378 / +378
-5 / +5	-315 / +315
-4 / +4	-252 / +252
-3 / +3	-189 / +189
-2 / +2	-126 / +126
-1 / +1	-63 / +63
0	0

With zero position is considered the pole position which is hit by the lightning directly or its mounted catenary wire and is in the middle of the simulated rail system.

A. *Results of lightning strike on the catenary wire (1.2/50μs)*

The results depicted hereto are for fast time lightning strike (1.2/50μs). In Fig.4 are depicted the measured currents at poles -8,-1,0,+1 and +8 for lightning strike 30kA and earthing resistance 70Ω.

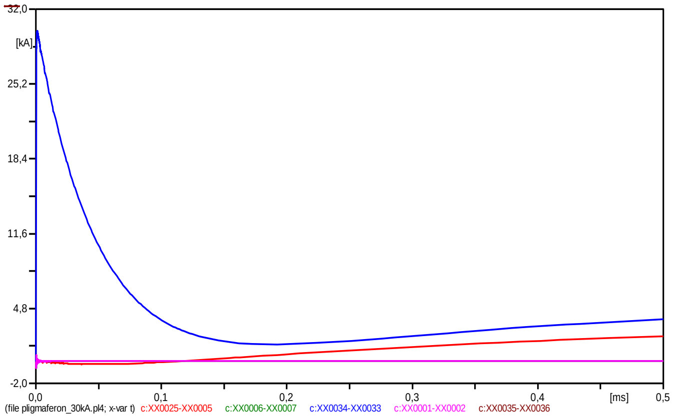

Figure 4. Pole currents for Ip=30kA, Rg=70Ω, 1.2/50μs.

From Fig.4 derives that the maximum current is at the central pole, the one which is hitted by the lightning. The measured voltages in the rail are depicted in Fig.5 with earthing resistance of 70Ω.

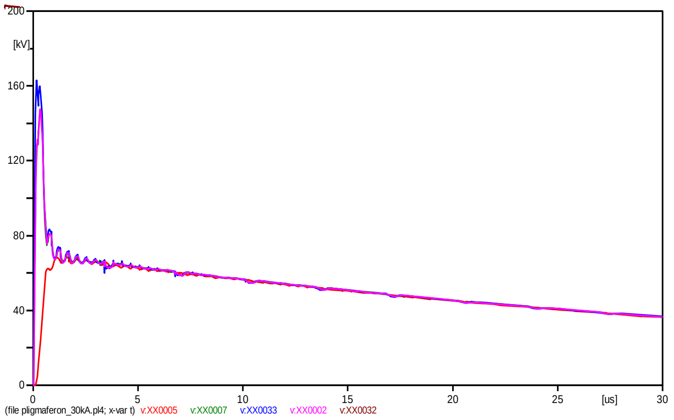

Figure 5. Rail voltages for I_p=30kA, R_g=70Ω,1.2/50μs.

The voltages in the catenary line are depicted in Fig.6 following a lightning strike of 30kA and with earthing resistance of 70Ω. The voltage profile is similar with the insulator one with the difference in peak values once insulator breakdown occurs.

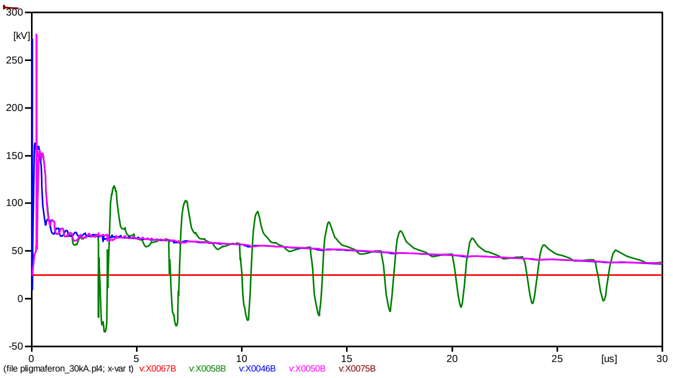

Figure 6. Catenary voltage,I_p=30kA, R_g=70Ω, 1.2/50μs.

In Fig.7 are shown the voltages that are occuring in the insulators in the same points (-8, -1, 0, +1, +8) and for earthing resistance of 70Ω.

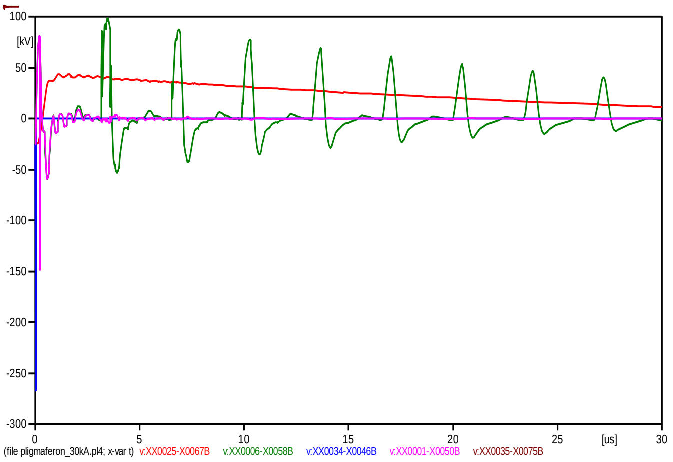

Figure 7. Insulator voltages,I_p=30kA, R_g=70Ω, 1.2/50μs.

The last point that has been simulated is the measured voltages at the top of the poles for earthing resistances of 70Ω as depicted in Fig.8. It is noticed that the voltage of top pole is similar with the rails.

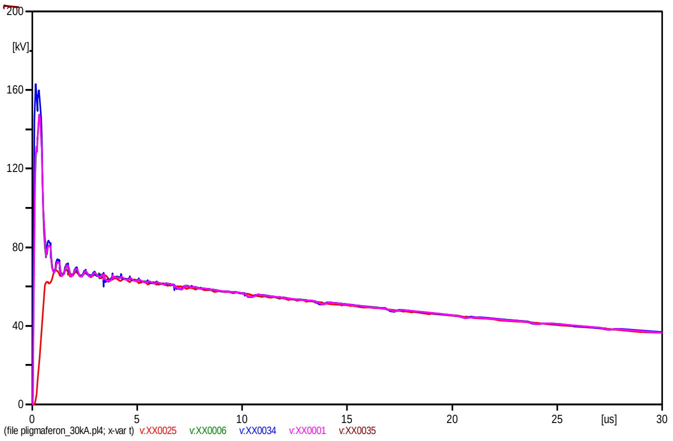

Figure 8. Top pole voltages, I_p=30kA,R_g=70Ω, 1.2/50μs.

The same simulations have been repeated for 100kA lightning peak current and earthing resistance of 10Ω, 70Ω and 245Ω. The simulation results for all cases (pole current, rail voltages, catenary voltages, insulator voltages and top pole voltages) are depicted in the following Table II as peak values. Based on Table II results it is derived that once the earthing resistance and lightning parameters are getting higher more insulator breakdowns occur. The insulator breakdown causes the voltage waveforms of catenary, rails and top poles to be almost similar.

TABLE II. SIMULATION RESULTS FOR 100KA AND R_G=10, 70, 245 Ω

Point	**strike on the catenary wire, 100kA, 1.2/50 µs**														
	Pole current (kA)			**Rail voltage (kV)**			**Catenary voltage (kV)**			**Insulator voltage (kV)**			**Top pole voltage (kV)**		
(Ω)	R_g**=10**	R_g**=70**	R_g**=245**	R_g**=10**	R_g**=70**	R_g**=245**	R_g**=10**	R_g**=70**	R_g**=245**	R_g**=10**	R_g**=70**	R_g**=245**	R_g**=10**	R_g**=70**	R_g**=245**
-8		10		50	230	290	25	30	30	25	200	250		220	300
-7				50	230	290									
-1	1		6	140	480	100	120	480	780	150		250		480	780
0	100	100	90	230	480	780	275	510	800	280		280		510	800
+1	1		6	230	220	780	275	480	780	100	250	250		480	780
+2				140	220	780									
+7				50	250	480									
+8		0	0	50	250	480	175	320	430	130	180	250		220	450

TABLE III. SIMULATION RESULTS FOR 30KA AND R_G=10, 70Ω

Point	**strike on the top of the pole, 30kA, 1.2/50 µs**									
	Pole current (kA)		**Rail voltage (kV)**		**Catenary voltage (kV)**		**Insulator voltage (kV)**		**Top pole voltage (kV)**	
(Ω)	R_g**=10**	R_g**=70**	R_g**=10**	R_g**=70**	R_g**=10**	R_g**=70**	R_g**=10**	R_g**=70**	R_g**=10**	R_g**=70**
-8	0	0	15	70	25	25	10	45	15	70
-7			15	70						
-2										
-1	0	2	45	145	33	50	12	90	45	145
0	30	30	70	160	39	55	33	105	70	160
+1	0	2	45	160	33	50	12	90	45	145
+2				145						
+7			15	75						
+8	0	0	15	75	27	33	10	45	15	70

TABLE IV. SIMULATION RESULTS FOR 100KA AND R_G=10, 70, 245Ω

Point	**strike on the top of the pole, 100kA, 1.2/50 µs**														
	Pole current (kA)			**Rail voltage (kV)**			**Catenary voltage (kV)**			**Insulator voltage (kV)**			**Top pole voltage (kV)**		
(Ω)	R_g**=10**	R_g**=70**	R_g**=245**	R_g**=10**	R_g**=70**	R_g**=245**	R_g**=10**	R_g**=70**	R_g**=245**	R_g**=10**	R_g**=70**	R_g**=245**	R_g**=10**	R_g**=70**	R_g**=245**
-8	0	10	1	50	225	295	25	25	25	26	200	460		225	270
-7				50	225	295									
-2															
-1	0	3	5	150	480	790	50	480	790	110	260	790		480	770
0	100	100	100	225	520	790	68	510	790	170	260	790		520	790
+1	0	3	5	225	480	790	50	480	790	110	260	790		480	770
+2				150	480										
+7				50	225	460									
+8	0	0	1	50	225	460	30	325	460	26	180	460		225	460

B. Results of lightning strike on the top of the pole (1,2/50μs)

The results depicted hereto are for lightning strike 1.2/50μs. Several simulations have been executed for I_p=30kA and 100kA, R_g=70Ω, 10Ω and 245Ω. The results of each simulation type for pole currents, rail voltages, catenary voltages, insulator voltages and top pole voltages are depicted in Table III and IV.

C. Results of lightning strike on the top of the pole (10/350µs)

For the completeness of the discussed topic it was simulated also the performance for slow time parameters of lightning strike, some of them are depicted in the following figures.

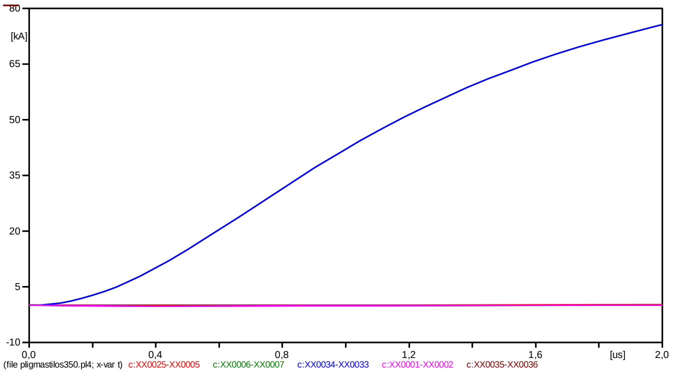

Figure 9. Pole currents for I_p=100kA, R_g=245Ω, 10/350µs.

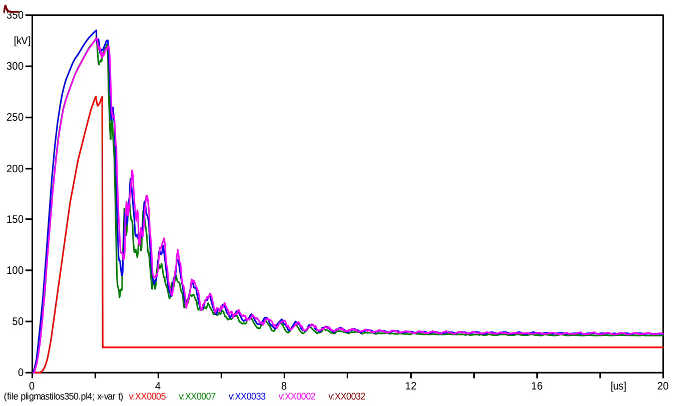

Figure 10. Rail voltages for I_p=100kA, R_g=245Ω, 10/350µs.

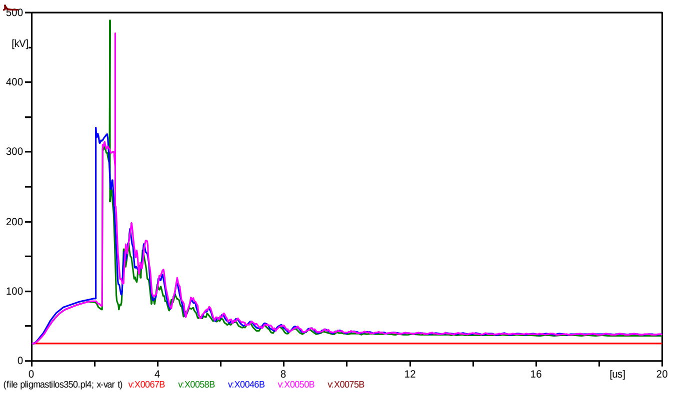

Figure 11. Catenary voltages for I_p=100kA, R_g=245Ω, 10/350µs.

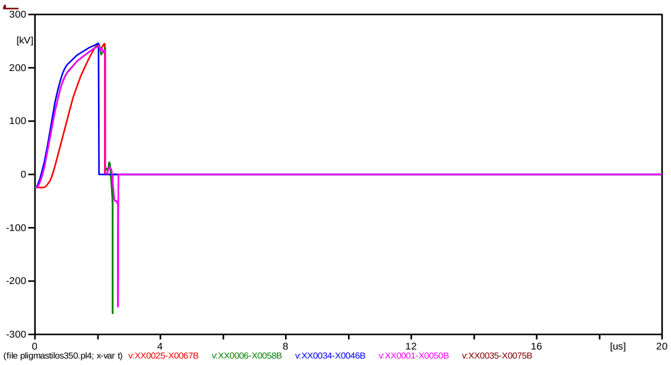

Figure 12. Insulator voltages for I_p=100kA, R_g=245Ω , 10/350µs.

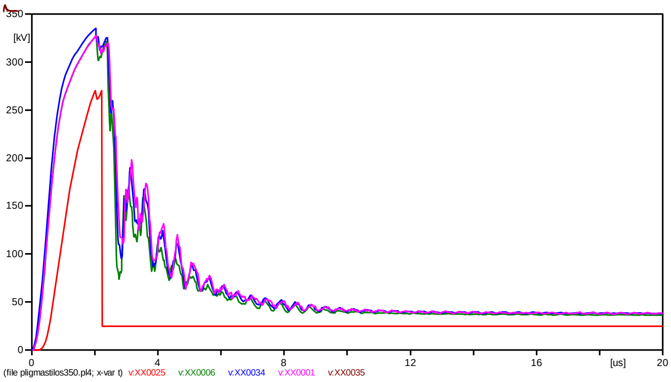

Figure 13. Top pole voltages for I_p=100kA, R_g=245Ω , 10/350µs.

The results depicted hereto are for lightning strike 10/350µs. Several simulations have been executed for I_p=30kA and 100kA, R_g=10Ω, 70Ω and 245Ω. The results of each simulation type for pole currents, rail voltages, catenary voltages, insulator voltages and top pole voltages are depicted in Table V.

TABLE V. SIMULATION RESULTS FOR 100KA AND R_G=10, 70, 245Ω

Point	**strike on the top of the pole, 100kA, 10/350 µs, R_g=245Ω**				
	Pole current (kA)	**Rail voltage (kV)**	**Catenary voltage (kV)**	**Insulator voltage (kV)**	**Top pole voltage (kV)**
-8	0	275	25	250	260
-7		275			
-2					
-1	0	320	480	250	310
0	70	330	330	260	325
+1	0	320	460	250	310
+2		320			
+7		275			
+8	0	275	290	250	280

From the above results it is confirmed that the lower is the earthing resistance of the pole the better is the performance of the system during lightning strikes. More specifically, the currents are minimized quickly and same occurs for the voltages in the rails and the poles while less insulator breakdowns are noticed. The worst performance is noticed for the highest earthing pole resistance since all insulators are getting to breakdown and high voltages occur.

IV. CONCLUSIONS

In the current paper was studied via simulations the effect of earthing resistance on a rail during a lightning strike. From the simulation it was extracted that the currents that are measured in the poles apart from the one that is affected are quite low with maximum value of 10kA. These are getting zero with significant delay apart from the case of I_p=30kA and R_g=10Ω or R_g=70Ω. For 30kA strike and R_g=70Ω the catenary and insulator voltages for the first 504m part have oscillations compared with the ones of the last part. For I_p=100kA and R_g=70Ω or R_g=245Ω deviate only in the peak values. The rail voltage waveform is similar with top poles. In case of insulator voltage breakdown, the voltage waveforms are the same for rail, catenary and top pole are the same. It was noticed also that with the increase of lightning amplitude and earthing resistance most insulators are led to breakdown. In the cases of lightnings with slow time parameters (10/350μs) the voltage peaks are lower than the ones in the fast lightnings but they have longer decay. For the insulators which face breakdown the catenary returns to nominal voltage of 25kV. There are minor differences between strike on the pole or the catenary which are only visible for 30kA and slow time parameters. The reduction of earthing resistance all induced voltages are getting significantly lower, all currents and pole and rail voltages are dissipated fastly, the catenary voltages are getting stable at 25kV with delay while less insulators are getting breakdown. For high amplitude lightnings (100kA) all voltages have high values due to the insulator breakdown before the lightning event gets completed. From the simulation it was derived that the ideal earthing resistance is the one of 10Ω. In case of such earthing resistance insulator breakdown occurs on the pole that is hit by lightning for the case of catenary hit while for hit on the pole no breakdown has been noticed. Taking into account that in real conditions 10Ω resistance cannot achieve easily 70Ω earthing resistance is acceptable. The worst case earthing resistance is the one of 245Ω due to the high voltages occur and also due to the fact that all insulators are led to breakdown.

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