An EMTP – RV Based Analysis of the Line Surge Arrester Energy Duty Due to Lightning Discharges

S. Grebovic, S. Pack, S. Sadovic

Abstract—**This paper describes modelling procedure for calculating energy stresses of transmission line surge arresters. A 110 kV shielded transmission line is modelled using ElectroMagnetic Transient Program – Restructured Version (EMTP – RV). Some parts of transmission line such as transmission line towers and stations on both ends of line are modelled thanks to EMTP – RV possibility of grouping electrical elements into subcircuits. Also it was possible to create subcircuit consists of number of other subcircuit. This possibility was very important for dividing transmission line into number of sections that consists of number of towers. Arrester current and voltage, energy duty, insulator voltage and voltage on tower top due to bipolar lightning are calculated and presented.**

Keywords: **Bipolar Lightning Stroke, Line Surge Arrester, Energy duty, EMTP – RV, Transmission line, Modelling, Simulation.**

I. Introduction

THERE are several methods used for the improvement of lightning performance of the existing transmission lines, such as: tower footing resistance reduction, increase of line insulation level, installation of additional ground wires, etc. Line surge arresters (LSA) are mainly used for line lightning performance improvement. LSA may fail in service if it is not correctly selected. In the selection of the line surge arrester for the line lightning performance improvement it is very important to determine arrester energy duty [1]. Energy stresses of transmission line surge arresters (LSA) are commonly analyzed due to unipolar flashes that transport to ground charge of one polarity. Also, it is very important to analyze energy stresses on transmission line surge arresters due to bipolar flashes that can cause serious problems in electrical power systems. Modelling is of great importance in power system transient analysis. Modelling can be used to describe system, to analyze the behavior of a system under conditions that can occur in nature. The main goal is to achieve precise simulation with all required modelling data and within minimal computer timings. So, this paper presents modelling of complete transmission line with large number input and output data.

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II. Modelling Procedure

Transmission line is modelled into several parts: towers, insulators, phase conductors, shield wire, line surge arresters and tower footing resistance. Lightning stroke is modelled as a current source (so called 'I – point by point source'). The studied 110 kV transmission line is 42 km long, span or line length between two towers is considered as a mean value of 300 meters. It is taken that line has a different footing resistance along the line route, so tower footing resistance value is varied. Soil resistivity is 1200 Ωm. In the case when tower is equipped with one LSA it is installed on bottom phase. For installation configuration with two LSA, LSA are installed on bottom and middle phase [2].

A. Tower model

Transmission line tower model, used in simulation is presented in Figure 1.

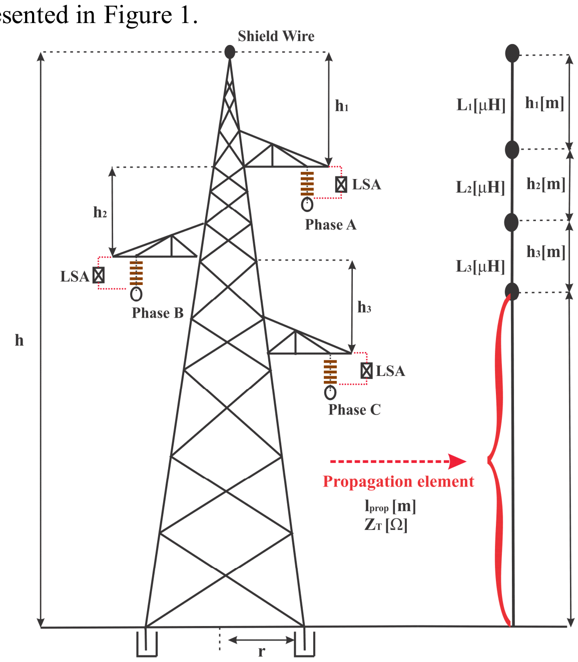

Fig. 1. Tower representation.

Each tower is divided in four parts. First part is section of the tower from bottom crossarm to the ground and it is represented as the propagation element, which is defined by the surge impedance and the propagation length. In EMTP – RV software this part is modelled as constant parameter (CP) and line model (1 – phase version). Second part is sections between tower top and top crossarm. Third and fourth part are sections between crossarms. Sections on the tower top (between tower top and top crossarm and between crossarms) are modelled as inductance branches. On this way it was possible to calculate transient on tower top. Tower surge impedance is calculated according tower shape theory. Branch inductance is determined according to the section length, tower surge impedance and propagation velocity. Wave propagation speed on the tower was taken to be equal to the velocity of light [1].

Figure 2 shows described tower model in EMTP – RV with insulators and pins that enable electrical connection with other elements. On this way it is possible to connect line surge arresters in parallel to the phase conductor insulators and model tower footing resistance.

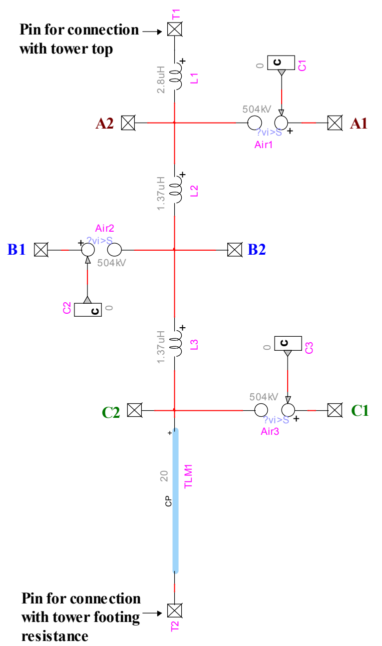

Fig. 2. Tower model in EMTP – RV.

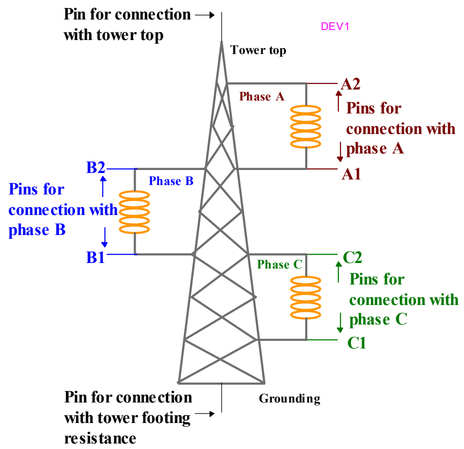

Fig. 3. EMTP – RV symbol for tower subcircuit.

All elements shown on Figure 2 are grouped in subcircuit. This subcircuit is illustrated on Figure 3 and can be use many times for modelling complete transmission line.

B. *Line insulation flashover model*

Insulators are modeled as Air Gap elements. It operates based on equal area flashover model. Flashover occurs when the following integral becomes greater or equal to D [3,4]:

$$\int_{t_0}^{t} \left(\left| v_{gap}(t) \right| - V_0 \right)^K dt \geq D \qquad (1)$$

where:

v_{gap} – voltage across insulator string

V_0 – reference voltage

K=1

D=0,2045d

d – length of gap (m)

t – time to flashover (µs).

CFO – critical flashover voltage can be represented by equation (2) [4].

$$V_0 = 0,9CFO = 0,9\left(400 + \frac{710}{t^{0,75}}\right)d \qquad (2)$$

C. *Line surge arrester*

Used arrester has the following characteristics [2]:

Rated voltage:	108 (kV_{rms})
MCOV:	86 (kV)
IEC class:	II
Nominal discharge current	10 (kA)

The non – linear behavior of line surge arrester is represented by the U – I characteristic [2,3].

D. *Lightning current model*

Bipolar lightning flashes transport to ground both negative and positive charges [5, 6]. A possible explanation of observed bipolar lightning currents is given by Narita et al. They suggested that, in a bipolar discharge, currents of both polarities follow the same channel to ground [7]. There are basically three types of bipolar lightning discharges, although some events may belong to more than one category [6, 8].

Lightning current (bipolar) shown on Figure 4 was measure on Corsica. The negative charge transfer is determined by integrating the absolute value of the current over the negative current component duration. The positive charge transfer is determined by integrating the current over the positive current component duration. The trapezoidal rule is used for integration. The total transfer is summary of the negative and positive charge transfers. The negative part has peak current of -52,86 kA and positive part has peak current of +26,3 kA, with total charge transfers being -3,3025 As and +1,2414 As, respectively.

Lightning stroke is modelled as a current source (so called 'I – point by point source') because it is possible to import measured data point by point. The current shapes and values can be changed in order to study different lightning stroke currents.

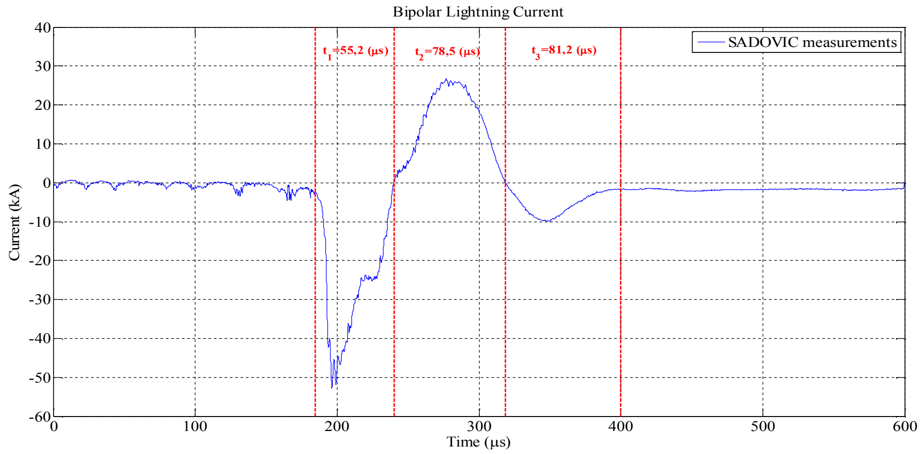

Fig. 4. Bipolar Lightning Current.

E. Transmission line sections

Shield wires and phase conductors are subdivided into number of segments. Each segment is presented with constant parameter (CP) line model (multiphase).

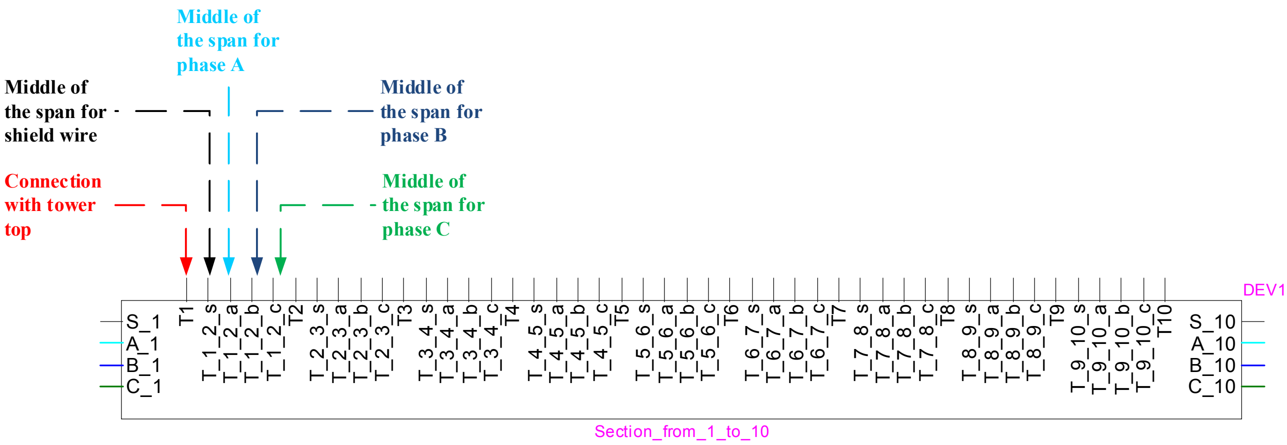

Fig. 5. EMTP – RV section of 110 kV transmission line.

Each span of 300 m is divided in two segments to enable connection between current source and middle of the span for shield wire and phase conductors.

Certain number of tower subcircuiet elements, spans, line surge arresters, grounding footing resistances and corresponding pins (for connection with other elements) are grouped into subcircuit element that presents transmission line section. Example for section that consists of 10 towers is given on Figure 5. It is possible to model sections with 50 or more towers. In this paper some sections are consists of 50 towers and some of them are consists of 10 towers. Stations are modelled on both ends of 110 kV transmission line.

On Figure 5 is illustrated the main idea for EMTP – RV modelling in this work. The idea was grouping subcircuits inside other subcircuits with possible connections between all elements in model. On both ends of section shown on Figure 5 are pin connections for shield wire and phase conductors. This means that is possible to make connection between two or more section subcircuit elements to get complete transmission line. On the top of section subcircuit element shown on Figure 5 are pins for lightning current source connection with tower top and middle of the span. The position of the lightning stroke is varied from hitting the shield wire or the phase conductor in the middle of the span or directly at tower top. Waveform shapes that can be observed in this simulation are: currents for all line surge arresters, energy duties for all line surge arresters, flashover currents and voltages for all insulators and tower footing resistance voltage and current.

III. CPU Timers

To the author's best knowledge, it is first time that complete transmission line is created and solved in EMTP – RV for purposes of transient analyses. CPU time is the amount of time for which a central processing unit (CPU) was used for processing instructions of a computer program. Amount of input and output data is large, so it is important to show CPU timers. Simulation time was 600 (μs). Time – step was 50 (ns). Simulation statistics are: total number of network nodes 1742, size of the main system equations 2175, total number of solution points in time-domain 15441, total number of iterations 47972 and number of iterations per time-point 3,11. The CPU timings are presented in Table 1. CPU timings are based on a Quad – core i7 processor (logical processors: 8 and 2,2 GHz) with 8 GB of RAM. There are no parallel computation in this simulation.

TABLE I
CPU TIMINGS (S)

CPU timers (s)	
Prepare data	0,23438
Read data	0,01562
Time-domain A matrix formulation	0,0
Time-domain B vector updating	1,23438
Time-domain Ax=B solution	22,29688
Solution of control systems	0,15625
Time-domain history updating	2,20312
Time-domain solution	26,68750
Total	27,18750

IV. Simulation Results and Discussion

In this section are given simulation results in the case when lightning source is bipolar lightning current from Figure 4.

Three cases are considered. The first case is that lightning hitting tower top and on tower is installed one line surge arrester and tower footing resistance is 35 Ω.

On Figures 6 and 7 are presented respectively current and voltage for arrester installed on bottom phase.

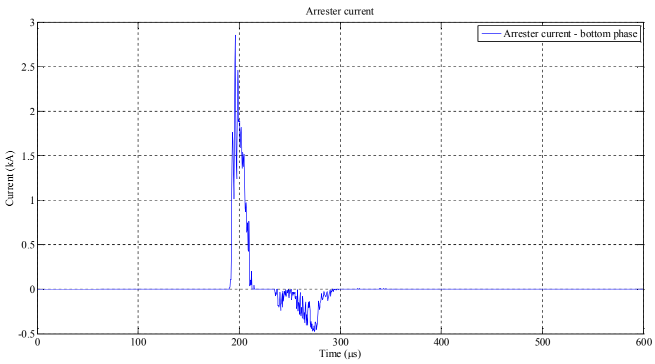

Fig. 6. Current through arrester – case 1.

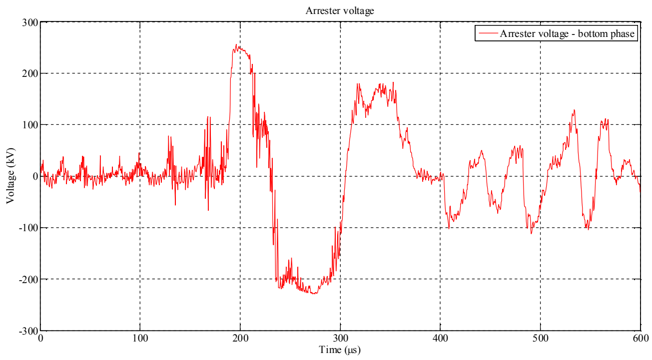

Fig. 7. Arrester voltage – case 1.

On Figure 8 is shown energy duty for arrester installed on bottom phase. Voltage waves across insulators are presented on Figure 9. Coupling between the shield wire and the phase conductor induces a voltage on the phase conductor. Voltages on the tower top and at the bottom phase are shown on figure 10.

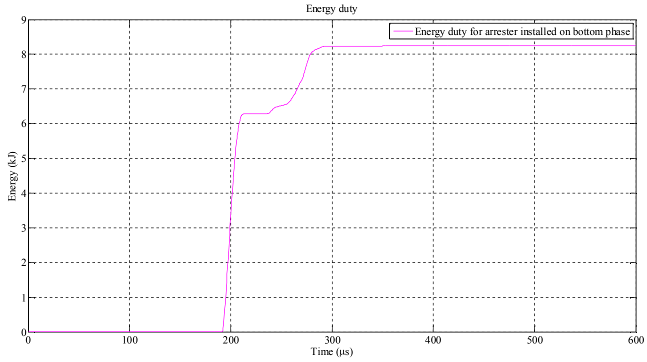

Fig. 8. Energy duty for arrester – case 1.

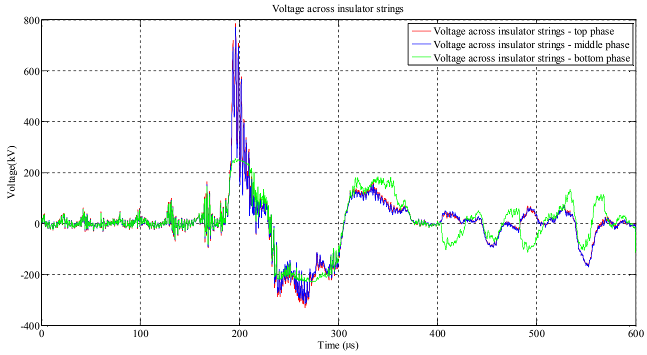

Fig. 9. Insulator voltages – case 1.

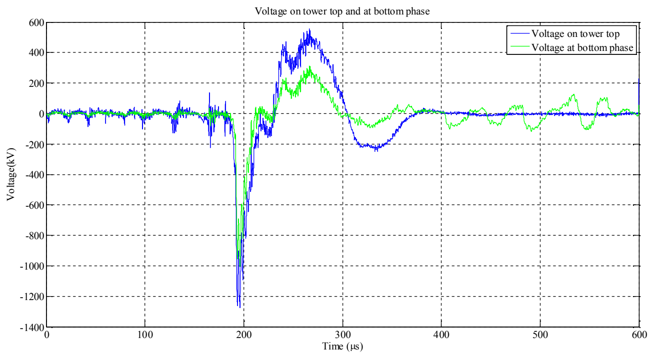

Fig. 10. Voltages on the tower top and at the bottom phase – case 1.

Second case is that lightning hitting tower top and on tower are installed two line surge arrester and tower footing resistance is 50 Ω. On Figures 11 and 12 are presented respectively currents and voltages for arresters installed on bottom and middle phase.

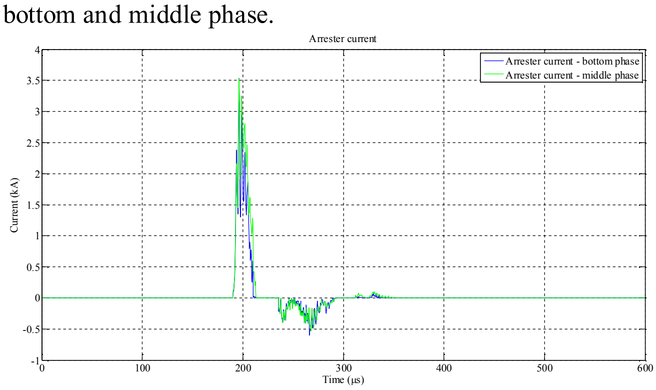

Fig. 11. Currents through arresters – case 2.

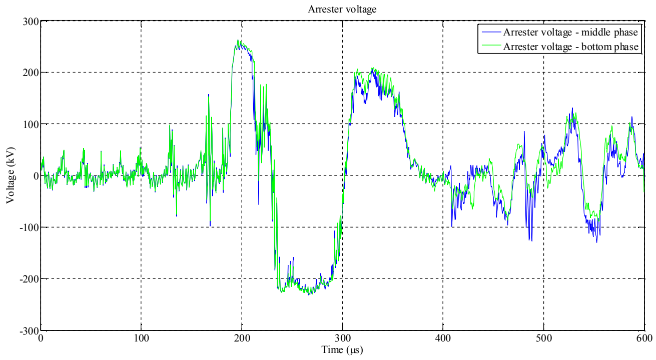

Fig. 12. Voltages on arresters – case 2.

On Figure 13 is shown energy duty for arresters installed on bottom and middle phase. Voltage waves across insulators are presented on Figure 14. Voltages on the tower top and at the bottom phase are shown on figure 15.

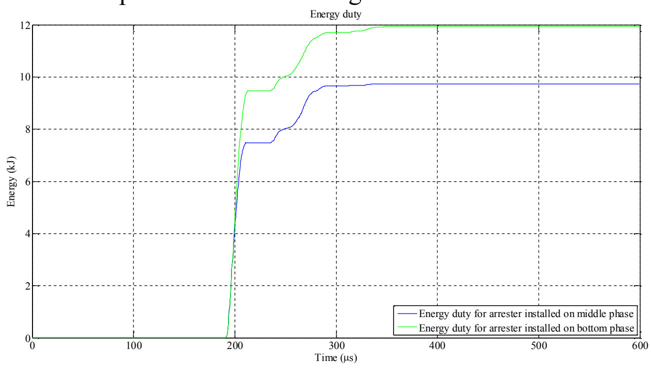

Fig. 13. Energy duties for arresters – case 2.

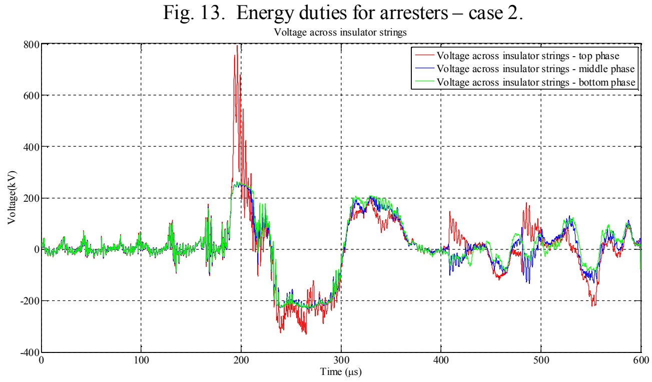

Fig. 14. Insulator voltages – case 2.

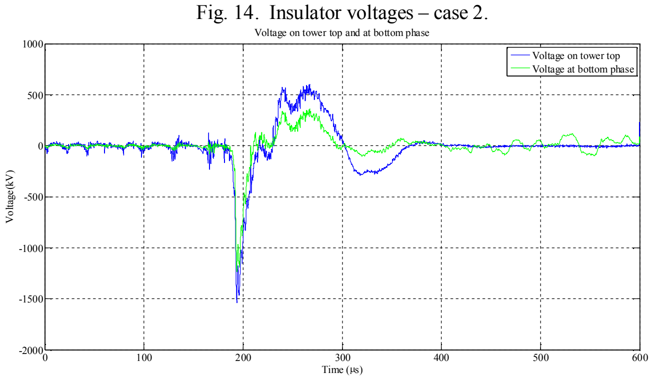

Fig. 15. Voltages on the tower top and at the bottom phase – case 2.

Third case is that lightning hitting tower top and on tower are installed three line surge arrester and tower footing resistance is 60 Ω. On Figures 16 and 17 are presented respectively currents and voltages for arresters installed on bottom, middle and top phase.

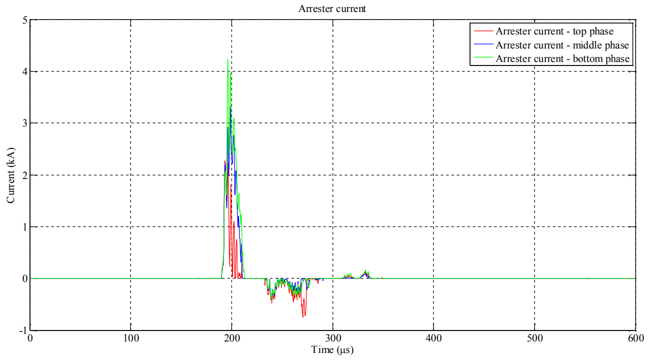

Fig. 16. Currents through arresters – case 3.

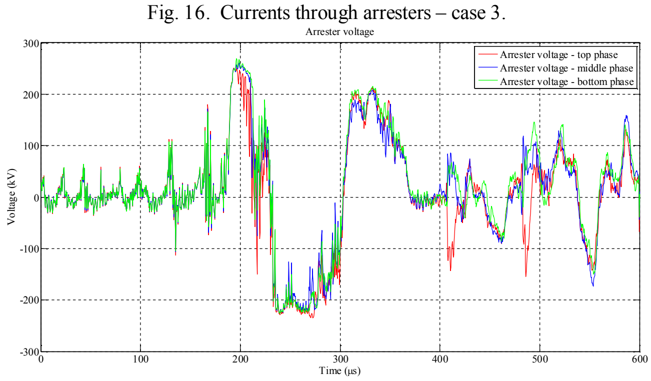

Fig. 17. Voltages on arresters – case 3.

On Figure 18 is shown energy duty for arresters installed on bottom, middle and top phase. Voltage waves across insulators are presented on Figure 19. Voltages on the tower top and at the bottom phase are shown on figure 20.

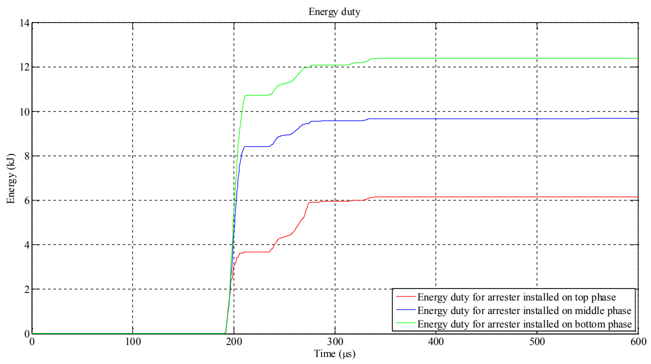

Fig. 18. Energy duties for arresters – case 3.

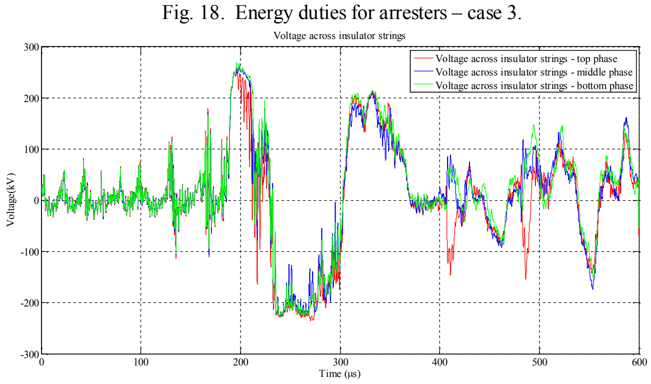

Fig. 19. Insulator voltages – case 3.

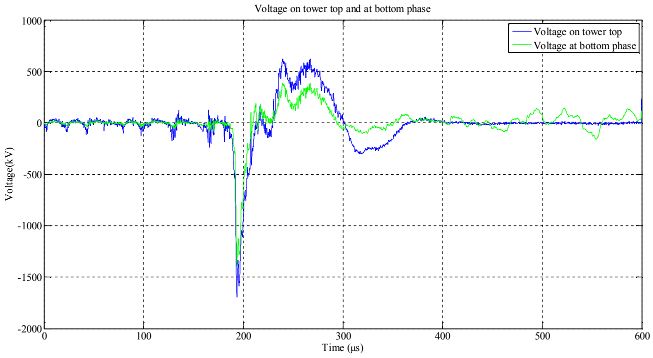

Fig. 20. Voltages on the tower top and at the bottom phase – case 3.

In Table 2 are presented LSA current and voltage peaks and energies for all three cases.

TABLE II
LSA DATA

CASE	Phase	U (kV)	I (kA)	W (kJ)
1 LSA	Bottom	256,27	2,86	8,24
	Middle	-	-	-
	Top	-	-	-
2 LSA	Bottom	263,15	3,52	11,93
	Middle	263,27	3,54	9,73
	Top	-	-	-
3 LSA	Bottom	269,28	4,23	12,38
	Middle	261,18	3,32	9,68
	Top	250,67	2,28	6,15

In table 3 are shown peak values of insulator voltages.

TABLE III
INSULATOR VOLTAGES

CASE	Phase	U_i (kV)
1 LSA	Bottom	256,35
	Middle (no LSA)	771,38
	Top (no LSA)	786,59
2 LSA	Bottom	263,15
	Middle	263,53
	Top (no LSA)	793,29
3 LSA	Bottom	269,49
	Middle	261,63
	Top	251,37

From presented arrester current shapes it is possible to see that the arrester current peaks are not so high as peak of injected lightning stroke. The arrester voltage shape for all cases is similar but with different peak values. It depends of LSA position (is it installed on bottom, middle or top phase) and tower footing resistance. From energy duties consideration we can see that arrester energy rise up as bipolar lightning current arriving at arrester. The corresponding energy duties are not so high. Reasons for that are short durations of arrester currents and fact that considering transmission line is shielded. Insulator voltages are high, especially for phases without LSA installed (for example 771,38 kV). Line critical flashover voltage for 110 kV is 550 kV.

V. CONCLUSIONS

This paper presents powerful and effective EMTP – RV modelling. Grouping of elements into subcircuits and creating subcircuits inside other subcircuits is very useful for modelling large systems. It has been shown that is possible to model complete transmission line and provide plenty of output data. Despite of fact that there is a plenty of input and output data CPU time is not long. Line surge arrester energy duty depends of arrester current shape. So, a knowledge of the occurrence and characteristics of bipolar lightning is needed for the selection of the arrester class (arrester block size) as well as for designing adequate lightning protection schemes for various objects and systems.

VI. REFERENCES

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