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Lightning induced effects on lossy multiconductor power lines with ground wires and non-linear loads - Part II: simulation results and experimental validation

***Abstract**. Using the procedure and the model analysed in the companion paper part I: model, in this paper simulations are carried out in order to evaluate the overvoltages produced on a multiconductor line. In particular, the shielding effect produced by ground wires and the role of surge arresters are investigated. The model has also been validated using experimental results.*

Streszczenie. Streszczenie.** W artykule zaprezentowano model obliczeń napięć indukowanych podczas nie bezpośredniego wyładowania na wieloprzewodową linię zasilania. Uwzględniono przewód uziemiony podłączony do nieliniowego obciążenia. (**Efekty powodowane wyładowaniem w wieloprzewodowej linii zasilającej z przewodem uziemionym obciążonym nieliniowo – część II-symulacje i eksperymenty)

Keywords: lightning, power transmission lines, surge arresters.
Słowa kluczowe: wyładowania, linia zaislająca.

Introduction

This paper is the companion paper of *Part 1: model*. In Part 1 a model for the calculation of the induced overvoltages produced by indirect lightning on a multiconductor power line was analysed. In particular, the model uses, as channel base current, the Heidler's expression [1] in the frequency domain [2]; as return stroke model the MTLL model [3] (however, the procedure developed allows the use of different return stroke models [4,5]). Then a transmission line model to describe the coupling of an external EM field to a line is presented. In This Part II some case studies areanalysed: numerical simulations of a three-phase line with and without ground wires are carried out to study their shielding effect. Besides, the effects of non-linear terminations (surge arresters) and losses are discussed. Finally, the numerical simulations are compared with experimental results, with reference to a single line. The results can be used to investigate damage and power quality problems induced by lightning to power lines, transformers and other utility equipment [6-11] and also as a term of comparison with other models, for example analytical models, for the calculation of the overvoltages e.g [10,11]

Applications and results

In the following a three-phase line is analysed. The considered geometry is represented in Fig.1. The phase conductors are located at a height of 10 *m*. The radius of the conductors is 9.14 *mm.* The ground wires are located at 3.05 *m* over the phase conductors and their radius is 3.96 *mm.* The line is 1 *km* long. The stroke location is at 50 *m* from the line centre, at the same distance from the two terminations. The adopted channel base current is the one represented in Fig. 2 (see also Part 1). The velocity of the return stroke is $v = 1.9 \cdot 10^8 \ m/s$, the channel height is 7.5 *km***.**

For such a configuration the per unit length inductance matrix of the line $\boldsymbol{L}$ is given by

$$\boldsymbol{L} = \begin{bmatrix} 1.54 & 0.21 & 0.11 & 0.15 & 0.24 \\ 0.21 & 1.54 & 0.21 & 0.24 & 0.24 \\ 0.11 & 0.21 & 1.54 & 0.24 & 0.15 \\ 0.15 & 0.24 & 0.24 & 1.76 & 0.26 \\ 0.24 & 0.24 & 0.15 & 0.26 & 1.76 \end{bmatrix} \mu H/m$$

while the per unit length capacitance matrix of the line $\boldsymbol{C}$ is

$$(1) \quad \boldsymbol{C} = \varepsilon\mu\boldsymbol{L}^{-1}$$

as the dielectric has been considered homogenous. Note that we have assumed $\varepsilon = \varepsilon_0, \ \mu = \mu_0$.

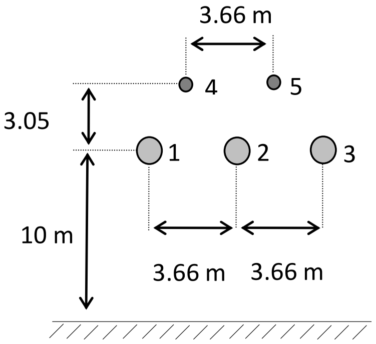

Fig.1. Geometry of the line: 1, 2 and 3 phase conductors, 4 and 5 ground wires

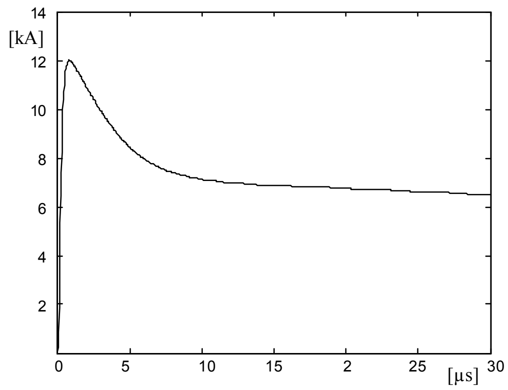

Fig.2. Typical lightning current over 30 μs

Three-phase line without ground wires

In this example we consider the three-phase line in Fig.1 without the two ground wires in place. Firstly we consider each conductor terminated on its characteristic impedance in absence of the others, namely

$$(2) \quad \boldsymbol{R}_0 = \boldsymbol{R_d} = \begin{bmatrix} 461.4 & 0 & 0 \\ 0 & 461.4 & 0 \\ 0 & 0 & 461.4 \end{bmatrix} \Omega$$

Fig.3 shows the overvoltages obtained. We have also analysed the effects of the losses, by putting $\boldsymbol{G} = \boldsymbol{0}$, and $\boldsymbol{R} = diag(125)\ \mu\Omega/m$, however, for such a line (1 *km* long) losses do not introduce significant differences (the percent difference is in the order of 0.001).

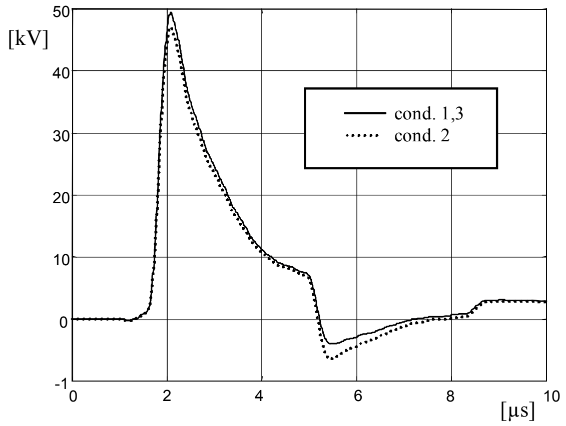

Fig.3. Voltages induced on 3-phase line without the ground wires

Three-phase line without ground wires and with surge arresters

Besides, the line has been analysed when terminated on non-linear loads: each conductor, in this case, is terminated at both ends on a 461.4 Ω resistor R_L in parallel to a Zn-O surge-arrester, inserted to "protect" the load R_L (Fig. 4).

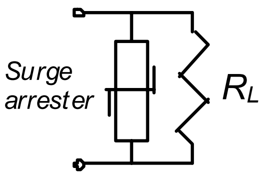

Fig.4 Non-linear load terminating the phase-conductors

The Zn-O surge-arrester has been modelled by $i = k(v/v_{ref})^n$,with $k = 2.5\ kA$, $n = 24$ and $v_{ref} = 40\ kV$ (Fig.5).

The results are plotted in Fig.6. The overvoltage is chopped to the desired level but the mismatch introduced by the non-linear loads produces stronger reflections.

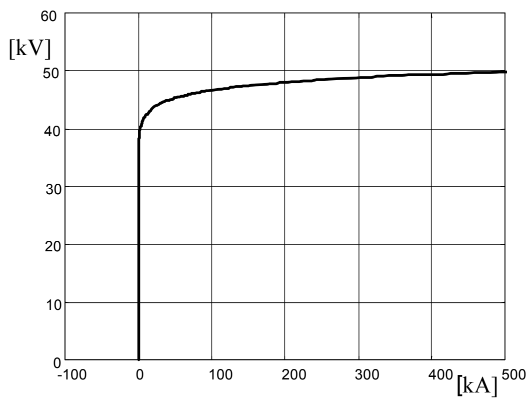

Fig.5 Characteristic of the Zn-O surge arrester

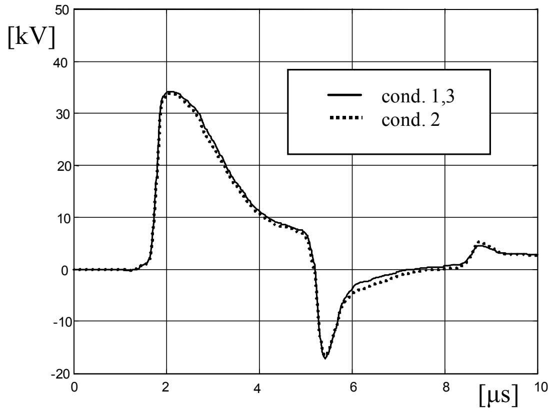

Fig.6. Voltages induced on three-phase line terminated on non-linear loads

Three-phase line with ground wires

Here we consider the overall system shown in Fig.1. Fig.7 shows the induced overvoltages on the phase wires, when these wires are connected to resistors and the two ground wires are grounded at the terminations. By comparing the obtained results with the ones shown in Fig.3, it is evident the significant shielding effect due to the ground wires. Fig.8 shows the current flowing into the ground wire #4. Fig.9 shows the induced voltages when the ground wires are not connected to ground.

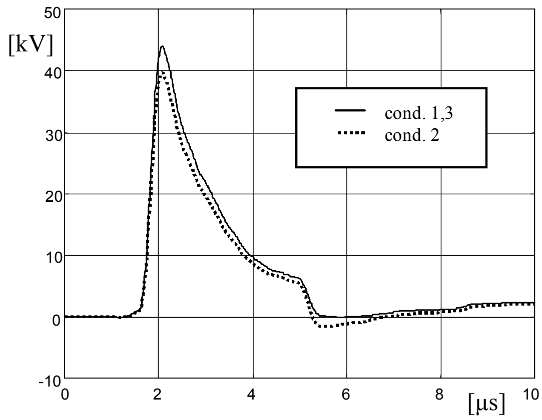

Fig.7. Voltages induced on three-phase line with the ground wires

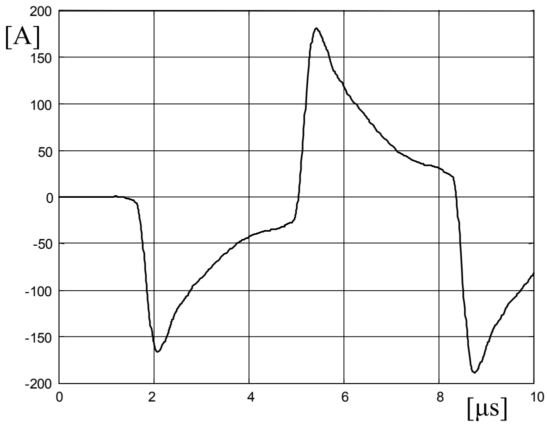

Fig.8. Current flowing into the ground wire #4

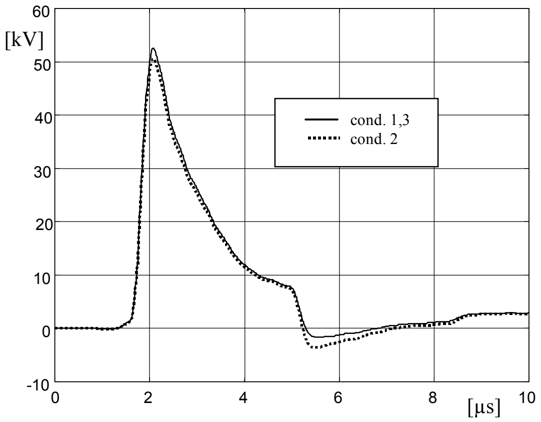

Fig.9. Voltages induced on three-phase line with the ground wires not connected to the ground

By comparing Figg.7 and 9 we note that the shielding is more effective when the ground wires are connected to ground.

Experimental results

In order to validate the model proposed in Part I, an experimental activity has been carried out, by using the Nuclear ElectroMagnetic Pulse (NEMP) facility available at CISAM (Interforce Study Center for Military Applications), Pisa, Italy. The simulator, which is the hugest in Italy, is shown in Fig. 10 and the technical characteristics are given in Table 1. As a preliminary result, we report the measurements relevant to a 10 *m* long single line, composed of a wire 1 *m* above the ground, and terminated on its matching resistors. The line has been excited by a field produced by a guiding structure fed by a Marx generator.

In Fig.11 the incident vertical electric field is shown, with reference to the middle of the line. Fig.12 shows the currents obtained by measurements and by simulation, applying the described model.

Tab. 1. NEMP simulator technical data

Pulse polarity	Positive or negative
Pulse repetition frequency	1 pulse per minute
Electric field	50 ÷ 1000 *kV/m*
Control and computation Software	FEMTO_V3
Tansmission System	Melopee 1000
Acquisition System	6 digital oscilloscopes
Overall Dimensions	96 x 28 x 19 *m*
Testing Volume	15 x 14 x 6 *m*
Standards ref.	AEP-4 ed. 1986 Finable 2.c.10, cap. 5, MIL-STD 461C e 461D

Fig.10. EMP simulator

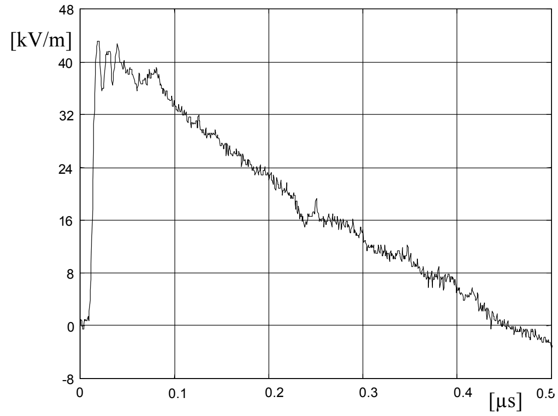

Fig.11. Measured electric field at the middle of the line

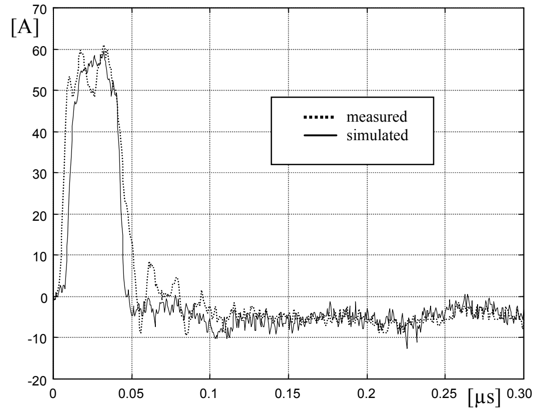

Fig.12. Measured and simulated currents at terminations of the line

As it can be seen, the simulations are in a good agreement with the experimental results: the overall waveshape has been reproduced, and the evaluation of the peak value and the duration of the pulse are very accurate. We have also observed that the reflection could be evaluated more accurately if the inductive effects of the terminal resistors are considered.

Conclusions

The model describing the lightning phenomenon presented by authors in Part I of the paper has been tested by means of an experimental session, as far as a single line. As to the influence of the ground wires, the paper shows that the shielding effect is remarkable, but it is sensitive to the effective connection to ground. The non-linear surge-arresters play a significant role in limiting the induced overvoltages. However, they introduce a mismatch that amplifies the reflections augmenting the duration of the disturbance.

Some perspectives are suggested by this study. The ana-lysis of the most general case of frequency dependent lossy transmission line can be directly carried out, also considering the effect of the finite ground conductivity on the propagation of the lightning field. Besides, in order to gain more insight into the effect of the ground wires, it will be useful to perform a study of a more realistic situation, in which the ground wires are periodically connected to ground along the power line.

We also aim to carry out an experimental session involving a three-phase line in a real geometrical configuration; we also aim at studiyng the effects of lightning channel tortuosity: some preliminary studies by the authors are available in [11,12]

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