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Analytical calculations of surges caused by direct lightning strike to underground intrusion detection system

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Abstract. The paper presents an analysis of overvoltages caused by a direct lightning strike in intrusion detection system equipped with underground radiating cable sensors. Waveforms of currents and voltages in the system components are calculated using analytical formulas basing on a transmission-line model in the frequency domain. The time-domain waveforms are computed using the inverse fast Fourier transform (IFFT). Three network configurations of the intrusion detection system are analyzed.

Key words: lightning, transients, overvoltages, analytical modeling, underground cable.

1. Introduction

Lightning is a considerable source of disturbances and damages to electrical and electronic circuits, equipment and systems. Particularly threatened are those systems, which are composed of long outdoor components, due to their exposure to direct lightning strikes and to the lightning electromagnetic fields. Adequate lightning protection system (LPS) shall be used in order to protect electrical and electronic systems against direct strikes [1]. Many works were published on protection of systems affected by the lightning electromagnetic pulse (LEMP), e.g. [2–5].

An intrusion detection system based on long underground radiating cable sensors is the subject of this paper. The intrusion detection networks are used for monitoring perimeters of secured terrains for unwanted activity. Cable systems may be realized as standalone or networked for longer perimeters. Their equivalent lightning collection area [1] can be of the order of square kilometers, so their exposure to lightning action is very likely. Long cable systems spread over large areas are usually not protected by an outer LPS due to unacceptable costs.

The intrusion detection system is composed mainly of electronic controllers, coaxial radiating cable sensors of several hundred meters in length, and cable terminators [6]. The system components are buried in the ground at a depth of 23 cm to 40 cm. Each controller is locally grounded, with the required grounding resistance not exceeding the typical value of 10 W. The system can be realized as standalone, with a single controller and sensor cables usually routed along an open line, or as a network, with many controllers and sensor cables forming an open line or a closed loop. Electrical power can be supplied to each controller by additional wires or through the sensor cables. In the latter case only one or some controllers are directly connected to the power mains. Some representative configurations of the intrusion detection systems are described in Section 3. Low energy is necessary for proper action of the system devices, and relatively small amount of electromagnetic energy is enough to affect their work.

The most dangerous lightning threats for the systems include direct strikes to overhead components and metallic structures, to the earth or to a tree close to the underground cables. A part of the lightning current penetrates the sensor cables. That part of the direct lightning stroke or the lightning-induced current causes overvoltages and leads to interferences or damages. The study of the problem is needed by the designers of underground systems to assess the threat caused by the lightning currents and to choose proper surge protective devices (SPDs) to prevent the electrical breakdown of the system components.

Analysis of the LEMP action on buried cables is relatively difficult. This hazard was analyzed in many publications. Theoretical and experimental study on disturbances induced in buried cables was published in [7, 8]. Results of measurements and modeling of coupling of lightning electromagnetic field to cables in a mine were reported in [9]. Analytical models of transients induced in cables by plane waves were presented in [10–11]. Many theoretical investigations were carried out using numerical methods. Among them, two numerical methods are commonly used: FDTD [12–15] and the method of moments [2–5]. A hybrid algorithm with application of FDTD was presented in [16]. The finite element method was used in [17]. An evaluation of numerical methods can be found e.g. in [18]. An overview of developments in modeling of the LEMP effects on overhead lines and underground cables was carried out in [19].

Models and solutions are usually numerical and their experimental validation needs special equipment [8, 9]. On the other hand, the intrusion detection systems are usually designed and installed by small companies for whom the purchase of advanced commercial computer codes is too expensive. This is why engineers often need possibly simple analytical formulas or low-cost software. The analytical study of the lightning action on cables can be carried out basing on [20, 21]. However,

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most publications in the field consider only single buried cables. The analysis of networked cable systems is rarely met in the literature.

The aim of this paper is to present the use of analytical formulations developed by Vance in [20] for calculations of surges caused by a direct lightning strike to networked buried cables. The presented results are helpful for designing of surge protection for such systems. Studies were carried out after publication of [20], showing limited validity of Vance's formulas [21]. However, the results of the use of Vance's formulas for modeling of direct lightning strikes were proved in [22] to be consistent with outputs of a trusted numerical code.

The present work is a continuation of the research presented in [22–24]. Papers [22, 23] dealt with a model of a single buried cable and its validation, and [24] – with simplified engineering estimation of maximum values of overvoltages caused by lightning in buried systems. In the present paper, calculations of surge waveforms are carried out using analytical formulations in the frequency domain and the IFFT transform to the time domain. Calculations presented here concern systems that are more complex than those analyzed in [22–24], which became possible after overcoming the numerical issues discussed in Section 4.

2. Model of underground cable

The transmission-line model is used for further analysis. Consider a lightning strike to the ground very close to one end of an underground cable of length l (Fig. 1). Controllers C1 and C2 with grounded enclosures are installed at the cable ends. The grounding resistances are equal R_1 and R_2, respectively.

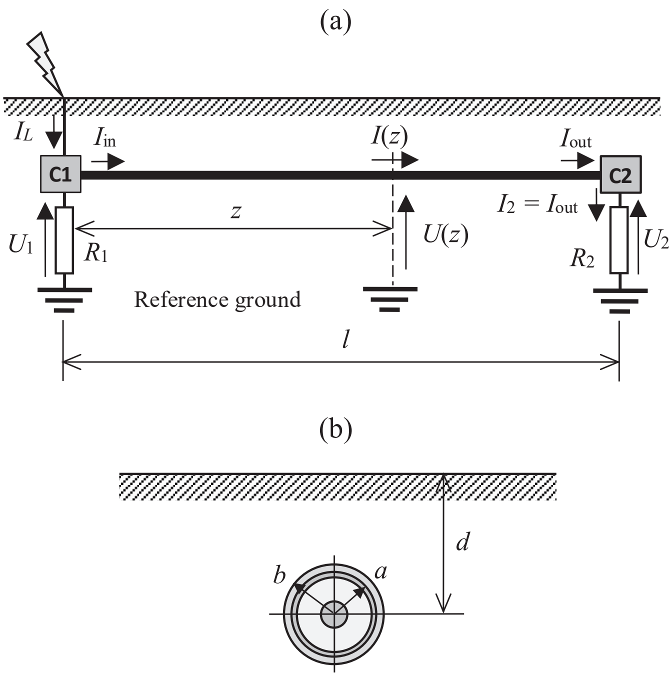

Fig. 1. Single undergound cable (a) and its cross-section (b)

Assume that the system insulation withstands the threat. Part of the lightning current I_L is dissipated to the ground by resistance R_1. Current I_{in} invades the cable outer conductor through a metal enclosure of the input controller C1. The surge current $I(z)$ flows along the cable outer conductor to the enclosure of controller C2 and to its grounding resistance R_2. Symbol $U(z)$ stands for the voltage occurring in the insulating jacket between the cable outer conductor and the reference ground (Fig. 1). Voltage $U(z)$ may be considered as the approximate measure of the threat of electrical breakdown to the components of the system. The contribution of the cable inner conductor is neglected, as in [20].

Dimensions a and b in Fig. 1b are the inner and outer radius of the insulation jacket, respectively. Burying depth d is not considered for the approximate formulas [20]. This approach was validated in [22] for a direct lightning strike.

The propagation factor in the soil is equal to:

$$\gamma_g = \alpha_g + j\beta_g = \sqrt{j\omega\mu_0(\sigma_g + j\omega\varepsilon_0\varepsilon_{rg})}\,, \tag{1}$$

where μ_0 and ε_0 are the vacuum permeability and permittivity, respectively, σ_g – soil conductivity, ε_{rg} – soil relative permittivity.

Current I_{out} and voltage U_2 at the cable output are calculated using the commonly known equations:

$$I_{out} = -\frac{U_1}{Z_0}\sinh\gamma l + I_{in}\cosh\gamma l\,, \tag{2}$$

$$U_2 = I_{out}R_2\,, \tag{3}$$

where Z_0 and γ are the characteristic impedance and the propagation coefficient of the equivalent transmission line, respectively.

Note that the surge analyzed here propagates in the transmission line formed by the cable outer conductor, the cable insulation jacket, and the soil. Hence, Z_0 is not equal to the cable characteristic impedance for a working signal since the working signal is guided between the cable inner and outer conductors.

Characteristic impedance Z_0 and propagation coefficient γ are determined as:

$$Z_0 = \sqrt{Z/Y}\,, \qquad \gamma = \sqrt{ZY}\,, \tag{4}$$

where Z [Ω/m] and Y [S/m] are the impedance and admittance per unit length of the equivalent transmission line, respectively [20].

Impedance Z is the sum of the internal impedance of the soil Z_g, the internal impedance of the cable outer conductor Z_c, and the inductive impedance of the insulating jacket $j\omega L_i$:

$$Z = Z_g + Z_c + j\omega L_i\,, \tag{5}$$

$$Z_g \approx \frac{\omega\mu_0}{8} + j\omega\frac{\mu_0}{2\pi}\ln\frac{\sqrt{2}\,\delta_g}{\Gamma b}\,, \tag{6}$$

$$Z_c \approx \frac{1}{2\pi a T\sigma_c}\,\frac{(1+j)T/\delta_c}{\tanh\left[(1+j)T/\delta_c\right]}\,, \tag{7}$$

$$L_i = \frac{\mu_0}{2\pi}\ln\frac{b}{a}\,, \tag{8}$$

where: $\delta_g = 1/\alpha_g$ – the skin depth in the soil, $\Gamma = 1.78107...$ – the Euler constant, T – the thickness of the cable outer conductor, $\delta_c = \sqrt{2/(\omega\mu_0\sigma_c)}$ – the skin depth in the conductor (copper), σ_c – the metal conductivity.

Admittance Y is composed of the capacitive admittance $j\omega C_i$ of the insulation in series with the unit admittance of the soil Y_g [20]:

$$Y = \frac{j\omega C_i Y_g}{j\omega C_i + Y_g}\,, \tag{9}$$

$$C_i = \frac{2\pi\varepsilon_0\varepsilon_{ri}}{\ln(b/a)}\,, \tag{10}$$

$$Y_g = \gamma_g^2/Z_g\,, \tag{11}$$

where ε_{ri} is the relative permittivity of the insulating jacket.

The input impedance of the equivalent transmission line is given by:

$$Z_{in} = Z_0\frac{R_2 + Z_0\tanh\gamma l}{Z_0 + R_2\tanh\gamma l}\,. \tag{12}$$

The results of calculations in the frequency domain are transformed to the time domain using the Matlab procedure of the Inverse Fast Fourier Transform (IFFT) [25].

The time-domain results are calculated assuming that the lightning current waveform is approximated by the double-exponential impulse of 20 kA, 2/50 μs:

$$I_L(t) = k_I I_m\left[\exp(-\alpha_1 t) - \exp(-\alpha_2 t)\right], \tag{13}$$

where $I_m = 20$ kA, $k_I = 1.07$, $\alpha_1 = 1.5292\times10^4$, $\alpha_2 = 1.1888\times\times10^6$, t – time. These coefficients were introduced in [2]. The assumed waveform has parameters that are close to the average ones met in nature [1, 26–30]. The impulse of 20 kA, 2/50 μs was also used in former Russian literature on lightning protection.

The formula for the lightning current spectrum has the convenient closed form:

$$I_L(j\omega) = k_I I_m\left(\frac{1}{\alpha_1 + j\omega} - \frac{1}{\alpha_2 + j\omega}\right). \tag{14}$$

The plots of the assumed lightning current waveform and the modulus of its frequency spectrum are presented in Fig. 2.

The model of lightning in the form of a lumped current source is used. Hence, the electromagnetic field generated by the lightning channel is not considered. Such assumption may be done for objects located below ground. That may not be done for structures above ground, which are significantly affected by the electromagnetic induction.

3. Configurations of intrusion detection system

A single sensor for intrusion detection is composed of two coaxial cables, up to 400 m in length, called radiating cables: a transmitter and a receiver. These cables run in parallel, at a distance of 1.5 m from one another, and are connected to the same controller. In network configurations, each controller in the system typically handles two pairs of such cables. The terminators of cables associated with one controller are usually directly connected to the terminators of cables belonging to the neighboring controllers [6], so that the galvanic continuity

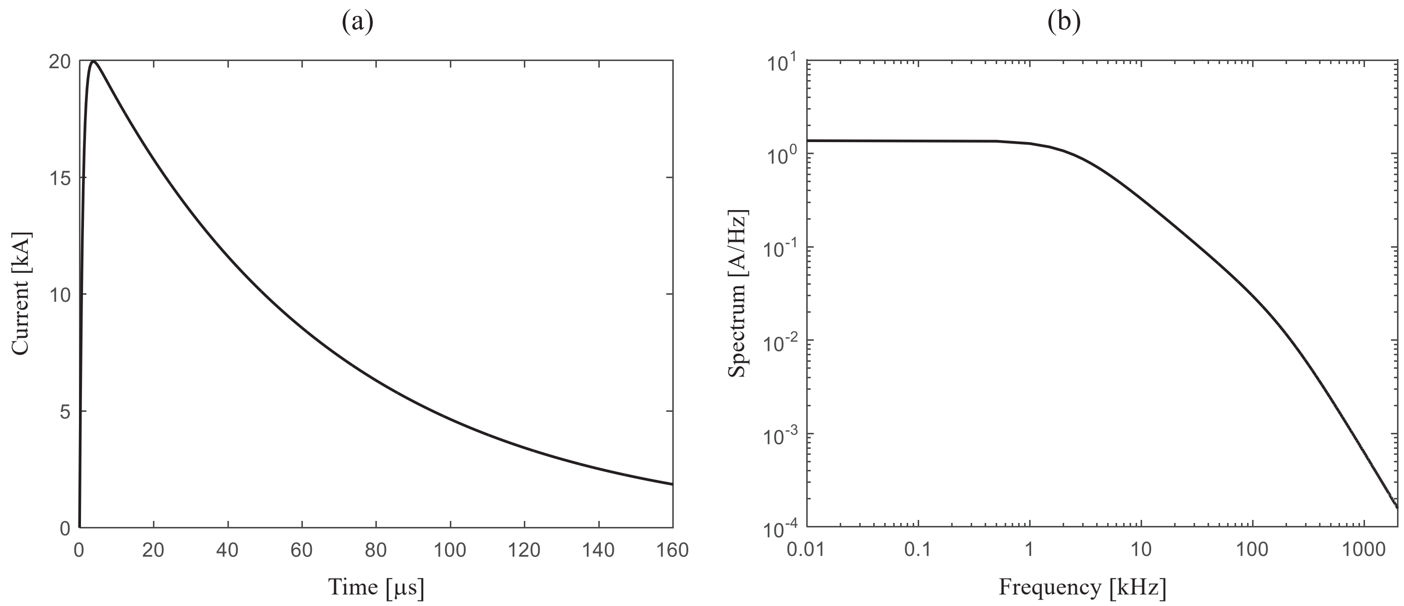

Fig. 2. Waveform of 20 kA, 2/50 μs current impulse (a) and modulus of its spectrum (b)

between the system components is kept. The terminators are isolated from the soil, so the circuit ends shown in Figs. 3a, b are electrically open.

The analysis is focused on the following typical configurations of the system:

- Conf. A: two controllers, each handling one cable sensor forming a straight open line (Fig. 3a).
- Conf. B: three controllers, handling one or two cable sensors forming a straight open line (Fig. 3b).
- Conf. C: six controllers, each handling two cable sensors forming a regular hexagon loop (Fig. 3c).

The parameters of the cables are as follows [6]: $\varepsilon_{ri} = 2.3$, $\sigma_{\mathrm{Cu}} = 58.6{\times}10^6$ S/m, $a = 6.365$ mm, $b = 7.75$ mm, $T = 0.33$ mm, $l = 800$ m. The cables are buried in the soil of typical parameters: $\sigma_g = 0.01$ S/m and $\varepsilon_{rg} = 10.0$. All the grounding resistances $R_1 \ldots R_6$ are equal to 10 Ω, which is consistent with requirements of the IEC standards [1].

Assume that the lightning current reaches the metallic enclosure of controller C1 (Figs. 3a–c).

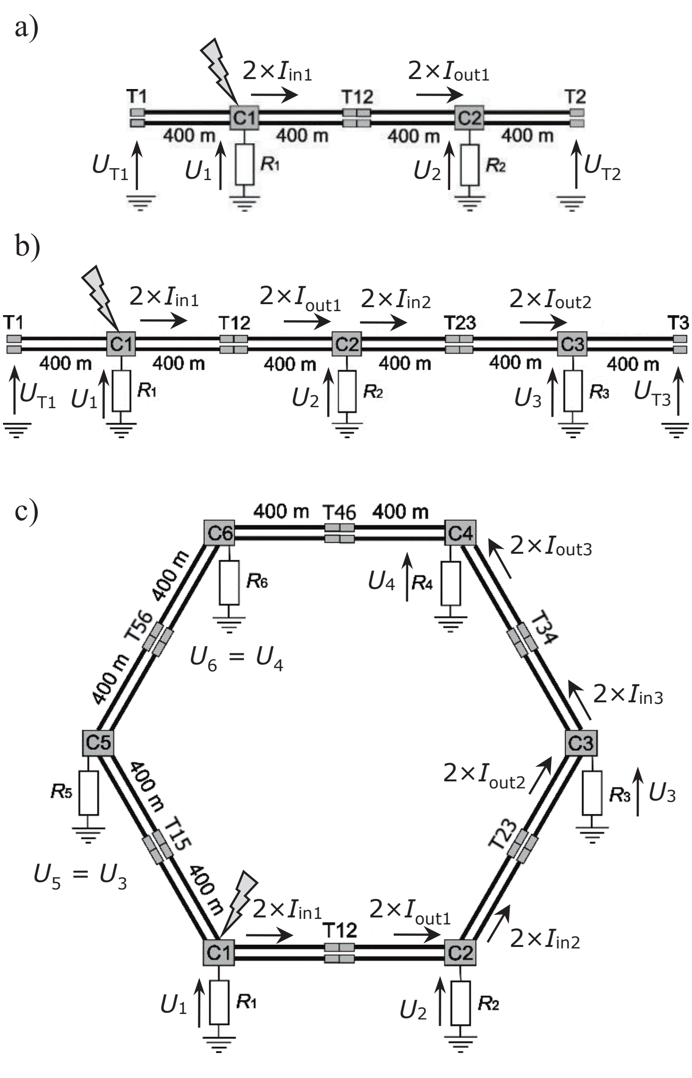

Fig. 3. Configurations of the intrusion detection system: Conf. A (a), Conf. B (b), Conf. C (c). Presented symbols of currents and voltages are used in Figs. 4–9 and in Table 1

The transmission-line model presented in Section 2 in combination with Kirchhoff's laws have been applied for appropriate computer codes written in Matlab [25].

2048 spectrum samples have been computed in the frequency range from 0 Hz to 1023.5 kHz with interval $\Delta f = 0.5$ kHz. That frequency band is sufficient for the analyzed case. However, a wider bandwidth may be needed for analysis of faster changing pulses (e.g. for models of subsequent return strokes [1–4]).

4. Numerical issues

Considerable cumulation of roundoff errors has been encountered during computations of expressions containing hyperbolic functions in the upper part of the analyzed frequency band. The differences of values of exponential functions can be tens of orders of magnitude, which is presented in Fig. 4

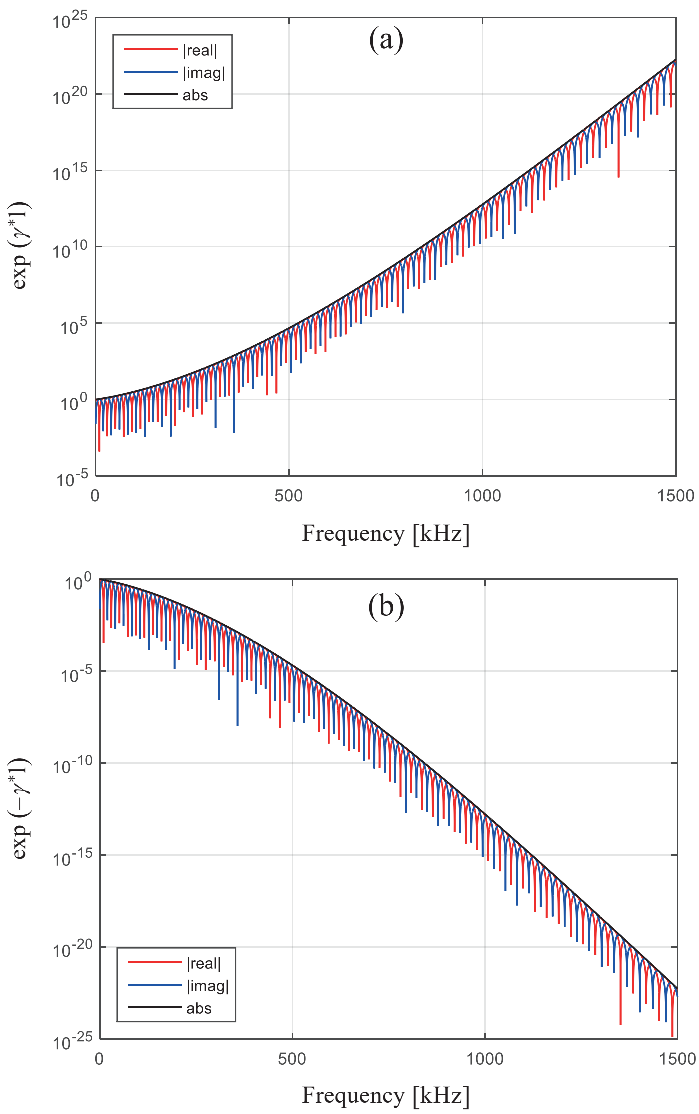

Fig. 4. Plots of real part, imaginary part and modulus of $\exp(\gamma l)$ (a) and $\exp(-\gamma l)$ (b) vs. frequency

showing changes of $\exp(\gamma l)$ and $\exp(-\gamma l)$ in the function of frequency. The double-precision floating-point arithmetic allows storage of only 15–16 digits of mantissa, which explains the problem.

The numerical instability can be additionally affected by the relatively small values of the lightning spectrum modulus at higher frequencies (Fig. 2b).

It is possible to reduce the numerical issues (to move the numerical instability towards higher frequencies) by using (3) instead of the transmission-line formula

$$U_2 = U_1 \cosh \gamma l - I_{in} Z_0 \sinh \gamma l \,. \tag{15}$$

5. Results

The waveforms of calculated currents and voltages are presented in Figs. 5–10. Maximum values of currents and voltages are collected in Table 1.

Table 1
Maximum values of calculated currents and voltages

Quantity	Unit	Conf. A	Conf. B	Conf. C
I_{in1}	kA	2.49	2.49	2.27
I_{out1}	kA	2.97	3.27	2.86
I_{in2}	kA	–	1.22	0.98
I_{out2}	kA	–	1.22	1.14
I_{in3}	kA	–	–	0.32
I_{out3}	kA	–	–	0.33
I_{inOpen1}	kA	2.27	2.27	–
I_{inOpen2}	kA	0.82	0.32	–
U_1	kV	116.4	116.4	109.3
U_2	kV	63.0	47.3	40.9
U_3	kV	–	25.7	16.3
U_4	kV	–	–	13.2
U_{T1}	kV	196.7	196.7	–
U_{T2}	kV	77.3	–	–
U_{T3}	kV	–	31.1	–

Additional symbols $I_{in\text{Open1}}$ and $I_{in\text{Open2}}$ are used that are not shown in Figs. 3a-b for legibility. $I_{in\text{Open1}}$ stands for the input current in the cable on the left that ends with terminator T1. $I_{in\text{Open2}}$ stands for the input current in the cable on the right that ends with terminator T2 (Fig. 3a) or terminator T3 (Fig. 3b).

Effects of reflections from the cable ends are visible as smooth steps of the current and voltage waveforms. The presence of terminators and controllers does not affect the propagation of the surges in the cable insulation jackets.

The calculated maximum values of the surge currents in the outer conductors of the cables are about 15% of the maximum

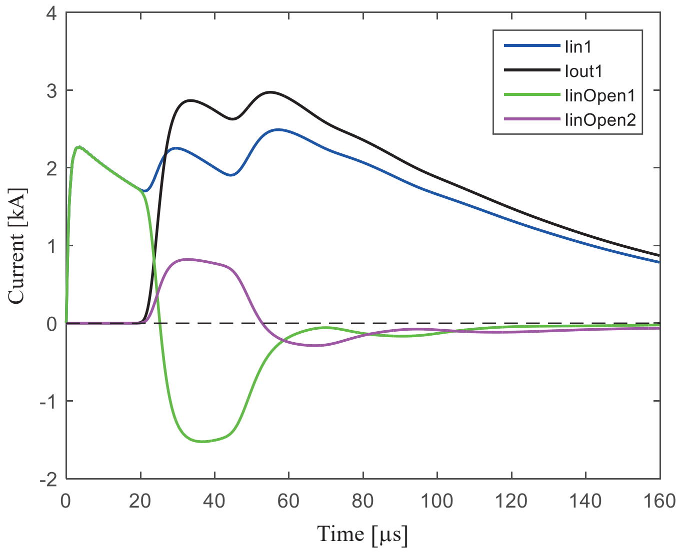

Fig. 5. Surge currents calculated for Configuration A

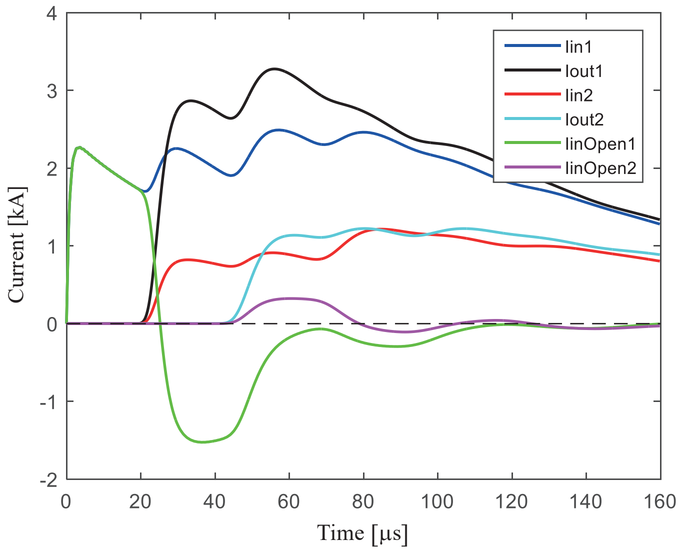

Fig. 6. Surge currents calculated for Configuration B

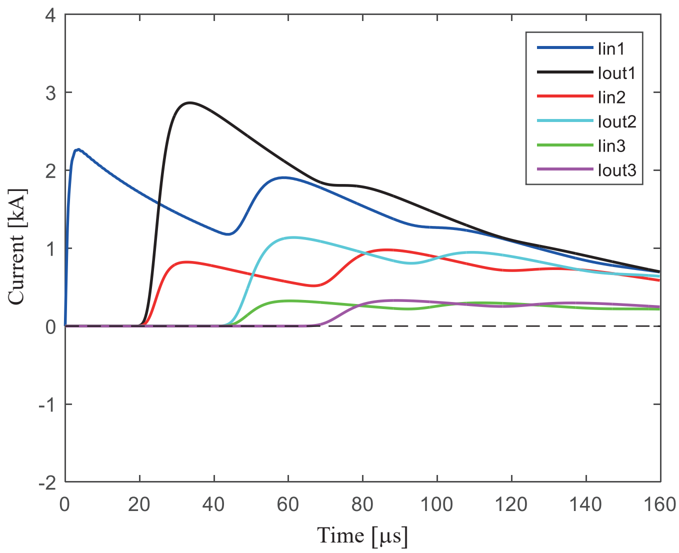

Fig. 7. Surge currents calculated for Configuration C

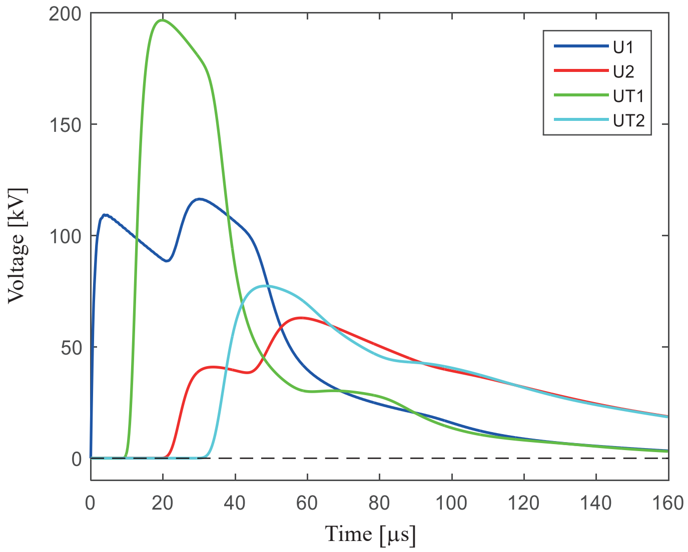

Fig. 8. Surge voltages calculated for Configuration A

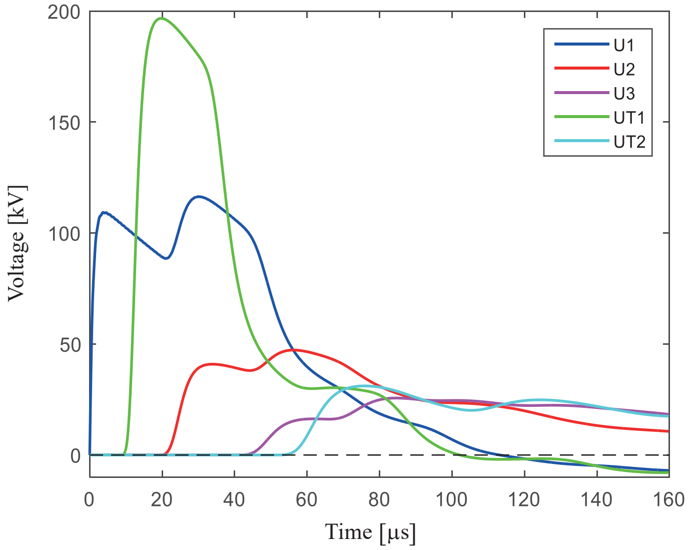

Fig. 9. Surge voltages calculated for Configuration B

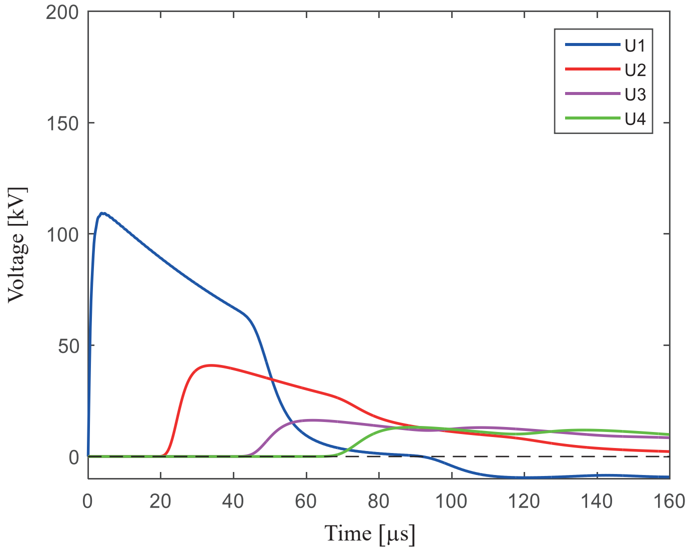

Fig. 10. Surge voltages calculated for Configuration C

value of the lightning current and they may appear after some reflections from the cable ends (Figs. 5, 6, at $t \approx 55$ µs).

The strongest overvoltages related to the lightning current injection need not to be observed at the point of strike, due to the surge reflections from the cable ends. The maximum value of potential of Controller C1 enclosure, which is reached by the lightning current, is about 110 kV. However, the highest voltage of about 200 kV is not at Controller C1 but at Terminator T1 (Figs. 8, 9), which results from the surge wave reflection at the cable open end. On the other hand, the largest current value is reached by current I_{out1} close to Controller C2 (Figs. 5–7).

Reflections from the cable ends cause also changes of polarization of currents and voltages.

Due to the linearity of the analyzed networks, it is possible to estimate the overvoltages caused by the lightning current stronger than that analyzed here (20 kA). For example, if the lightning current is 100 kA, then all currents and voltages should be multiplied by 5. However, new calculations are needed if the model of the lightning current waveform is considerably changed.

The system elements are subject to the threat of electrical breakdown at the equipment interfaces and of surge current thermal effects. Surge protective devices (SPDs) [1] should be installed at both ends of the analyzed cables.

The presented analysis provides much more information on the surge waveforms than the results of the simplified approach published in [24].

6. Conclusion

The presented results of calculations of currents and voltages are caused by the model of lightning surge, which parameters are close to the average ones. The results may be applied for estimation of lightning threat for buried sensor cables used for intrusion detection at large areas. The analyzed system is linear, so the displayed maximum values may be proportionally increased for a higher lightning current.

The highest overvoltages can appear at points which are distant from the point being hit by lightning, due to wave reflections from the system components.

The calculated voltages and currents are large. Many cables cannot withstand such stress, hence SPDs should be installed at both cable ends.

The presented solution is analytical, which can be of value for testing accuracy of numerical codes used for computations of similar problems.

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References

[1] IEC 62305, *Protection Against Lightning*, series of standards, 2010.

[2] K. Aniserowicz, *Analysis of Electromagnetic Compatibility Problems in Extensive Objects under Lightning Threat* (available at http://pbc.biaman.pl/dlibra), BUT, Bialystok 2005 (in Polish).

[3] G. Maslowski, *Analysis and Modeling of Lightning Discharges for Overvoltage Protection*, AGH, Kraków 2010 (in Polish).

[4] T. Maksimowicz and K. Aniserowicz, "Simulation of currents induced in a loop by lightning strike of different waveforms", *Przeglad Elektrotechn.*, 86 (3), 43–44 (2010).

[5] K. Aniserowicz, "Computer analysis of electromagnetic field inside LPS directly stroke by lightning", *7th Internat. Symp. on Electromagn. Compat. and Electromagn. Ecology*, St. Petersburg, Russia, 257–260 (2007).

[6] *Radiating Cables – Technical Data Sheet*, Kabelwerk, EUPEN AG, 2014.

[7] E. Petrache, F. Rachidi, M. Paolone, C.A. Nucci, V.A. Rakov, and M.A. Uman, "Lightning induced disturbances in buried cables – Part I: Theory", *IEEE Trans. on Electromagn. Compat.*, 47 (3), 498–508 (2005).

[8] M. Paolone, E. Petrache, F. Rachidi, C.A. Nucci, V.A. Rakov, M.A. Uman, D. Jordan, K. Rambo, J. Jerauld, M. Nyffeler, and J. Schoene, "Lightning induced disturbances in buried cables – Part II: Experiment and model validation", *IEEE Trans. on Electromagn. Compat.*, 47 (3), 509–520 (2005).

[9] M.B. Higgins, M.E. Morris, M. Caldwell, and C.G. Christodoulou, "Measurement and modeling of the indirect coupling of lightning transients into the Sago mine", *IEEE Trans. on Electromagn. Compat.*, 52 (1), 136–146 (2010).

[10] M. Aguet, M. Ianovici, and C.C. Lin, "Transient electromagnetic field coupling to long shielded cables", *IEEE Trans. on Electromagn. Compat.*, 22 (4), 276–282 (1980).

[11] G.E. Bridges, "Transient plane wave coupling to bare and insulated cables buried in a lossy half-space", *IEEE Trans. on Electromagn. Compat.*, 37 (1), 62–70 (1995).

[12] B. Yang, B.-H. Zhou, B. Chen. J.-B. Wang, and X. Meng, "Numerical study of lightning-induced currents on buried cables and shield wire protection method", *IEEE Trans. on Electromagn. Compat.*, 54 (2), 323–331 (2012).

[13] A. Tatematsu, "A technique for representing coaxial cables for FDTD-based surge simulations", *IEEE Trans. on Electromagn. Compat.*, 57 (3), 488–495 (2015).

[14] M.E.M. Rizk, F. Mahmood, M. Lehtonen, E.A. Badran, and M.H. Abdel-Rahman, "Investigation of lightning electromagnetic fields on underground cables in wind farms", *IEEE Trans. on Electromagn. Compat.*, 58 (1), 143–152 (2016).

[15] H. Tanaka, Y. Baba, and C.F. Barbosa, "Effect of shield wires on the lightning-induced currents on buried cables", *IEEE Trans. on Electromagn. Compat.*, 58 (3), 738–746 (2016).

[16] Z. Ye, X. Xiong, M. Zhang, and C. Liao, "A time-domain hybrid method for coupling problems of long cables excited by electromagnetic pulses", *IEEE Trans. on Electromagn. Compat.*, 58 (6), 1710–1716 (2016).

[17] J. Paknahad, K. Sheshyekani, F. Rachidi, M. Paolone, and A. Mimouni, "Evaluation of lightning-induced currents on cables buried in a lossy dispersive ground", *IEEE Trans. on Electromagn. Compat.*, 56 (6), 1522–1529 (2014).

[18] J.K. Sykulski, "Computational electromagnetics for design optimisation: The state of the art and conjectures for the future", *Bull. Pol. Ac.: Tech.* 57 (2), 123–131 (2009).

[19] M. Ianoz, "Review of new developments in the modeling of lightning electromagnetic effects on overhead lines and buried cables", *IEEE Trans. on Electromagn. Compat.*, 49 (2), 224–236 (2007).

[20] E.F. Vance, *Coupling to Shielded Cables*, Wiley–Interscience, 1978.

[21] F. Rachidi and S. Tkachenko, *Electromagnetic Field Interaction with Transmission Lines*, WIT Press, 2008.

[22] K. Aniserowicz and R. Markowska, "Analytical and numerical calculations of overvoltages in underground cable of intrusion detection system directly hit by lightning", in *Internat. Conf. on Lightning Protection ICLP 2018*, Rzeszów, Poland (2018).

[23] K. Aniserowicz and R. Markowska, "Semi-analytic calculations of overvoltages caused by direct lightning strike in buried coaxial cable", *Przeglad Elektrotechniczny*, 93 (12), 1–5 (2017).

[24] R. Markowska and K. Aniserowicz, "Lightning currents and overvoltages in underground radiating cables of intrusion detection system", *Przeglad Elektrotechniczny*, 94 (2), 34–40 (2018).

[25] *MATLAB Computing Environment*, The MathWorks, Inc., 2018.

[26] V. Cooray (ed.), *The Lightning Flash*, IEE, London 2003.

[27] CIGRE TB 549, *Lightning Parameters for Engineering Applications*, WG C4.407, August, 2013.

[28] M.A. Uman, "Natural lightning", *IEEE Trans. on Industry Applications*, 30 (3), 785–790 (1994).

[29] K Aniserowicz, "Nature of atmospheric discharges", *Telekomunikacja i Techniki Informacyjne*, 1–2, 59–67 (2013).

[30] P. Rózga, "Streamer propagation in a non-uniform electric field under lightning impulse in short gaps insulated with natural ester and mineral oil", *Bull. Pol. Ac.: Tech.* 64 (1), 171–179 (2016).