# The Influence of Atmospheric Overvoltages on High-Voltage $SF_6$ Substations

***Preliminary Communication***

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***Abstract*** – *Very fast overvoltages are characteristic of high-voltage metal-enclosed SF6 insulated substations. During the transient phenomenon, on the SF6 substation enclosure an undesired, short-lasting induced overvoltage may appear, which cannot be prevented easily. This induced overvoltage is connected to the amplitude, form and duration of an atmospheric overvoltage that enters the substation as a travelling wave, dielectric strength of the SF6 gas and the geometry of the substation and its earthing. The objective of our research is to analyze the appearance of this undesired induced overvoltage on the substation enclosure. The above-mentioned phenomena can be examined by analyzing the results obtained through simulation. Due to the complexity of the equivalent electric model of a high-voltage SF6 substation and the analytic interpretation of the transient phenomenon in such complex substation, it is difficult to precisely analyze the overvoltage on the substation enclosure. The simulation results encourage us to do further research. Computer simulations also allow examination of various influences that affect the observed phenomenon. However, a suitable simulation model is necessary for performing simulations. Literature sources often do not provide a simulation model with simulation program objects. Thus, this paper focuses on the manner of presenting a simulation model with objects in the ATP program.*

***Keywords*** – *atmospheric overvoltage, induced voltage on the SF6 substation enclosure, travelling wave*

## 1. INTRODUCTION

Atmospheric overvoltages are very important for electrical power substations due to their values and speed phenomena. Overvoltages on conductors and earthed substation parts caused by lightning cause malfunctions in the substation, i.e. they disturb correct substation functions. They also affect safety conditions in the substation.

The appearance mechanism, physical grounds of the lightning appearance and lightning current types can be found in [1] and [2]. For the purpose of checking safety precautions in electrical power substations there are usually regulations (norms) that regulate the lightning current waveforms. Details on the mathematic lightning current modeling according to IEC regulations can be found in [1]. Literature sources also provide good coverage of topics related to the influence of the lightning current on electrical power objects. Thus, in [3], a description of possible ways of inducing voltage on electric substations due to a lightning strike may be found. The least convenient case is definitely a direct lightning strike into the electrical power substation conductor. Literature sources [4, 5, 6] provide examples of modeling electrical power substation parts for making simulations related to lightning strike. Modeling high-voltage lines for a lightning strike and numerical results related to the dependence of the line overvoltage value on the lightning current are given in [7]. Literature sources [4, 8, 9] also provide examples of simulations related to safety measures regarding atmospheric overvoltages.

Problems with overvoltages in GIS substations and also with atmospheric overvoltages result from the electrical characteristic of GIS. There are a lot of places where electrical parameter changes occur in GIS. This is firstly related to wave resistance changes in GIS. In such places reflections and strengthening of incidence atmospheric overvoltage surge occur. Literature sources [10, 11, 12] cover the atmospheric overvoltage cases in GIS very well. However, not many papers [13] deal with the influence of atmospheric overvoltages on the potential increase of the transient GIS enclosure. Thus, this paper examines the influence of a lightning strike on the GIS enclosure potential using a simple example of a GIS configuration.

## 2. OCCURRENCE AND SPREADING OF ATMOSPHERIC OVERVOLTAGE INTO GIS

Atmospheric overvoltages enter GIS through connection cables and overhead lines during a lightning strike near or directly into an overhead line. The overvoltage surge (wave) spreads from the place of occurrence to GIS through the line. At the connection point of GIS and external lines reflection occurs and a part of the wave enters GIS (Figure 1).

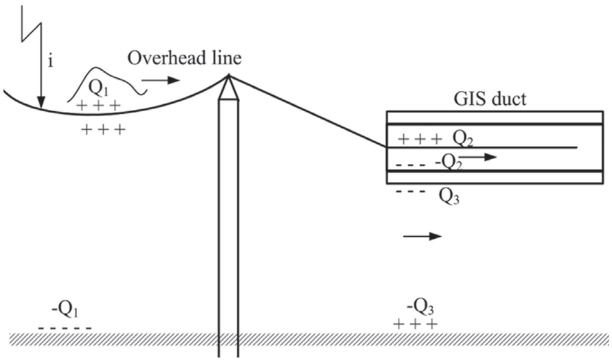


**Fig. 1.** Spreading of atmospheric overvoltage from the overhead line into GISss

A wave spreads along the overhead line with a specific line surge impedance and propagation velocity along the line. At the point where the overhead line is connected to GIS a part of the wave enters GIS. Within GIS, the wave spreads between the busbar and the enclosure, defined by the busbar-to-enclosure surge impedance (Figure 2).

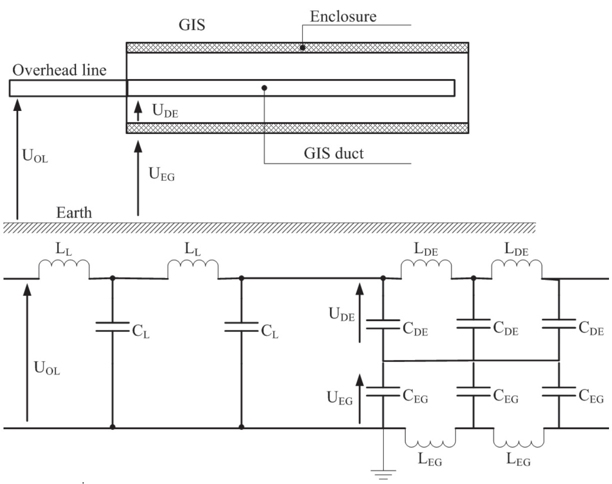


**Fig. 2.** Transfer of an atmospheric overvoltage surge into GIS

In places where surge impedance changes within GIS, additional reflections and possible strengthening of this surge (wave) occurs. Due to the fact that the GIS enclosure earthing is not ideal, the enclosure potential towards the earth increases as the overvoltage surge gets closer. This is a direct result of the earthing impedance increase at high frequencies.

## 3. MODELING LIGHTNING CURRENT AND SOME GIS PARTS

### 3.1. LIGHTNING CURRENT

For modeling the lightning current a standard strike waveform is deployed, which is defined by the amplitude, increase time and decrease time (Figure 3). A lightning current waveform is defined by three parameters: amplitude, wave front time and wave decay time.

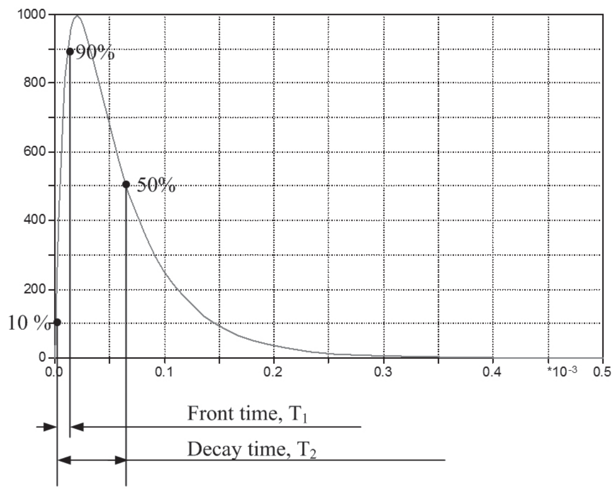


**Fig. 3.** Lightning current waveform model

### 3.2. ENCLOSED BUSBAR, GIS-TO-OVERHEAD LINE TRANSFER AND OVERHEAD LINE

Lightning current injects the charge onto the overhead power distribution line conductor at the point of a lightning strike (Figure 1). This charge induces an opposite charge on the earth's surface. These two charges continue to move to both sides from the point of a lightning strike. Movements of these charges result in current and voltage surges (waves). When a charge reaches the overhead line-to-GIS connection point through a conductor, a part of the charge is transferred to the GIS busbar. At the same time, this charge induces an opposite polarity charge on the busbar enclosure. A part of the induced charge on the busbar enclosure continues to move along the inner side of the enclosure. This part of the enclosure charge is connected to the busbar charge. The other part of the charge induced on the enclosure induces an opposite polarity charge on earth. This charge moves along the external side of the enclosure and together with the charge induced on the earth's surface creates a voltage surge that spreads between the enclosure and the earth.

### 3.3. GROUND LEADS AND STRAPS

There are two ways of modeling ground leads and straps [14, 15]. The first way is modeling with concentrated parameters and the second one is modeling with lines with distributed parameters. For ground lead and earthing modeling, models with distributed parameters are recommended due to high frequencies of phenomena caused by atmospheric overvoltage. The problem related to the ground lead is the fact that it is perpendicular to the earth. Because the ground lead is vertical, the surge impedance of the ground lead constantly changes along its height. According to [13,14], the surge impedance of the ground lead can be defined as:

$$Z_z = 60 \cdot \ln\left(\frac{2 \cdot \sqrt{2} \cdot h}{r}\right) \tag{1}$$

where $h$ and $r$ refer to the average height above the ground of the vertical ground lead and the ground lead radius (earthing strap or round conductor radius), respectively.

### 3.4. SURGE ARRESTER

Surge arrester is modeled with the Branch Nonliner MOV block, available in ATP. This block presents a zinc-oxide surge arrester model. Its resistance depends on the current that passes through it. For the block it is necessary to define the current-voltage characteristics that can be calculated.

## 4. MODELING IN ATPDraw 5.5.

A physical description of phenomena at the overhead line-to-GIS borderline is given in 3.2 and it can be presented in the form of a diagram, as shown in Figure 4.

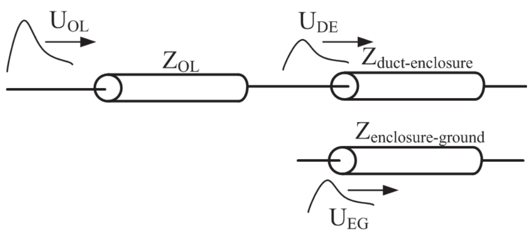


**Fig. 4.** Surge impedances of the overhead line and GIS busbar

Figure 3 shows that busbar and enclosure-to-earth voltages as well as those in-between will be defined by spreading of two surges: busbar-to-enclosure surge and enclosure-to-earth surge.

### 4.1. FREQUENCY, TIME STEP, CALCULATION TIME

Reference [13] states the following expression for the response frequency (in MHz) of the lossless distributed parameter line, whereas the propagation velocity is close to the light velocity:

$$f = \frac{75}{l} \tag{2}$$

where $l$ refers to the bus duct length. Unit resistance and unit inductance significantly depend on the frequency, whereas they are calculated the same as inductive and capacitive resistances. Thus, while modeling, it is important to select the frequency at which line parameters are calculated. Here the calculation frequency is selected according to (2). From (2) the expression for the propagation velocity follows [13] reads:

$$\tau = \frac{1}{4 \cdot f} \tag{3}$$

According to [13], the time step in ATP must be equal to or less than one-half of the shortest transit time. Thus, the time step of the simulation is defined by:

$$\Delta T \leq \frac{\tau_{\min}}{2} \tag{4}$$

According to [13], the duration of the observed transient phenomena is in the range of a few hundred nanoseconds. Here, the selected simulation interval equals 3 ms.

### 4.2. LIGHTNING CURRENT

Lightning current is modeled in ATP with the Source Surge Heidler block. This block is an ideal source. Waveform of the current from this source is performed by entering the following parameters: current factor, wave increase time, strike wave duration and function increase coefficient.

### 4.3. BUSBAR-TO-ENCLOSURE TRANSMISSION LINE MODEL AND ENCLOSURE-TO-EARTH TRANSMISSION LINE MODEL

The enclosed GIS busbar is modeled as a two-phase line with the Lines Distributed Parameter Untransposed block. Modal component values for this block were obtained by means of an ATP calculation. The calculation was performed by entering the geometry and dimensions of the GIS busbar and the enclosure in LCC (Line/Cable Constants) block in ATP. Output results of calculations related to this block are modal wave impedances, propagation velocities, serial impedances and shunt admittances. The overhead line is modeled as a transmission line with distributed parameters by means of the ATP Lines Distributed Parameters block. Parameters of this block were obtained by means of an ATP calculation by entering the overhead line data into the LCC block. An ideal transformer with 1:1 transmission ratio was used for transferring the overvoltage from the overhead line into GIS.

### 4.4. OVERHEAD TRANSMISSION LINE

Overhead line was modeled with the Lines Distributed Parameter block. The block parameters (unit and surge impedance, propagation velocity) were taken from the Bergeron model calculation of the LCC block. The calculation was performed entering the geometry of overhead line conductor into the ATP LCC block.

### 4.5. GROUND LEAD TRANSMISSION LINE

The ground lead was modeled as a lossless line with the surge impedance according to (1). The propagation velocity amounted to 96% of the light velocity (v= 0.96 ·c), as recommended by [13]. This line was connected to the end of the enclosure-to-earth line.

### 4.6. EARTHING TRANSMISSION LINE

Earthing transmission line was modeled with the Line Distributed Parameter block. Parameter values for this block were obtained by means of ATP calculations. The calculation was performed entering the earthing geometry into the ATP LCC block and setting up the Bergeron line model. In this way surge impedance of the line and the propagation velocity on the line are obtained as the calculation result.

### 4.7. ATPDRAW 5.5. DIAGRAM

Based on the facts described in parts 4.2.-4.6., Figure 5 shows an ATP model of a simple GIS case from Figure 2.

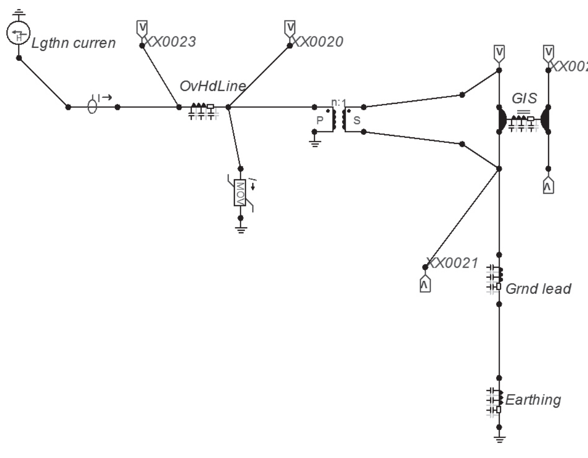


**Fig. 5**. ATP diagram of a simple GIS model

## 5. SIMULATION RESULTS AND RESULTS ANALYSIS

Simulations were performed for the case of a direct lightning strike into a phase conductor of an overhead line, whereas a positive lightning current was given. Some waveforms obtained in the simulation are shown in Figures 5-13. Waveforms in Figures 6-9 are related to the theoretical case of voltage being unlimited by installing a surge arrester. Figures 10-13 show waveforms with an installed surge arrester at the overhead line-to-GIS transfer point. The precondition is the ideally earthed surge arrester with earthing resistance amounting to zero.

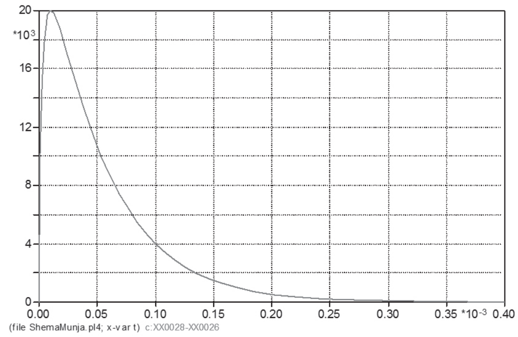


**Fig. 6.** Lightning current model with 20 kA peak

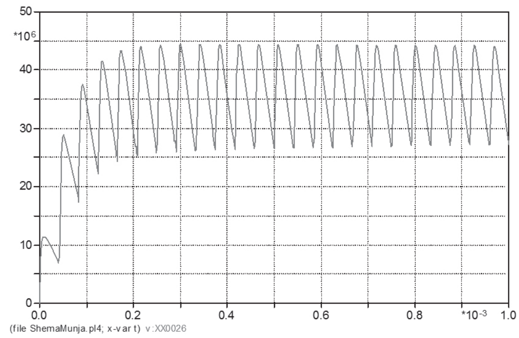


**Fig. 7.** Line overvoltage due to lightning without a surge arrester, line length 5 km

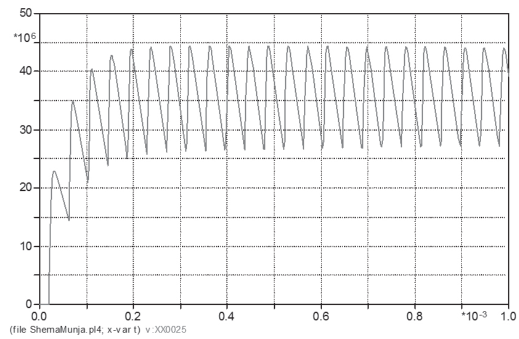


**Fig. 8.** GIS busbar voltage at the overhead line-to-GIS junction point, without a surge arrester

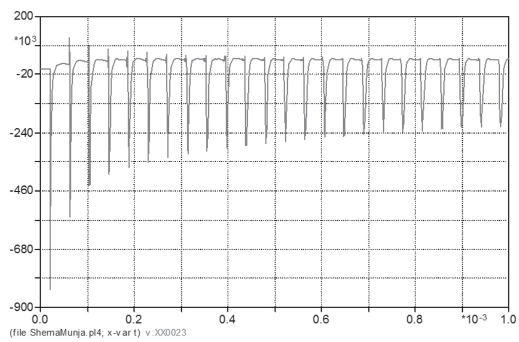


**Fig. 9.** Enclosure-to-earth voltage at the overhead line-to-GIS transfer point, without a surge arrester

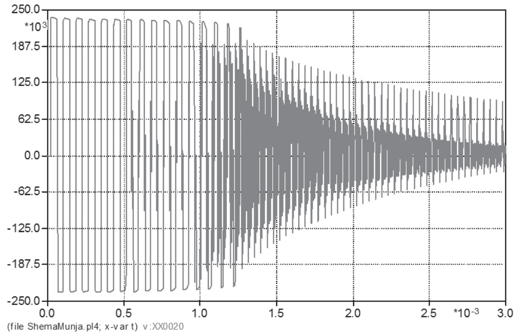


**Fig. 10.** GIS busbar voltage at the overhead line-to-GIS transfer point, with a surge arrester, line length 5 km

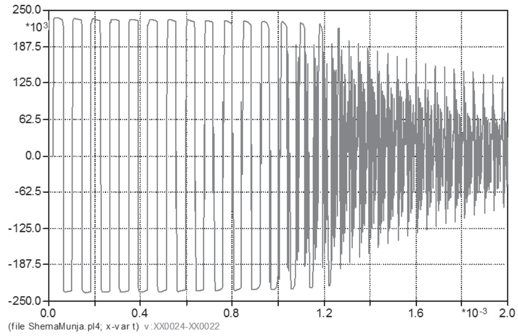


**Fig. 12.** Voltage between the busbar and the enclosure at the overhead line-to-GIS transfer point, line length 5 km, with a surge arrester

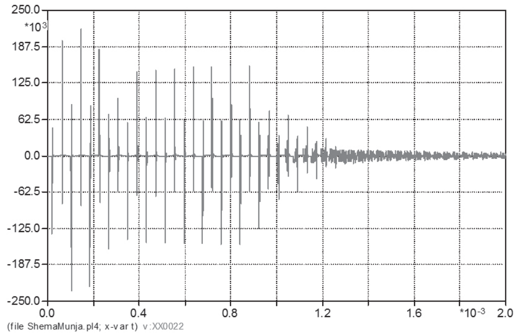


**Fig. 11.** Enclosure-to-earth voltage at the overhead line-to-GIS transfer point, with a surge arrester, line length 5 km

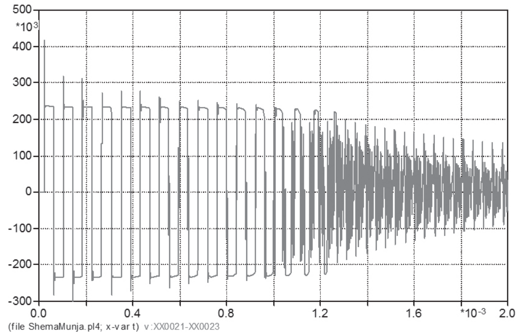


**Fig.13.** Voltage between the busbar and the enclosure at the end of an open busbar, line length 5 km, with a surge arrester

Figures 6-13 were obtained for the basic data provided in Table 1.

**Table 1.** Basic input data for the simulation and results for the transmission line models

| | | | | |
|---|---|---|---|---|
| **Lightning current model (Heidler model)** | | Amplitude (not peak value of surge) | $A$ [A] | 20 000 |
| | | Front duration (time between t=0 and time of function peak) | $T_f$ [s] | $10^{-5}$ |
| | | Stroke duration (time between t=0 and point on the tail where function value is 37% of peak value) | $\tau$[s] | $5\cdot10^{-5}$ |
| **GIS busbar** | | Internal busbar radius | $R_{SU}$ [m] | 0.0383 |
| | | External busbar radius | $R_{SV}$ [m] | 0.051 |
| | | Internal enclosure radius | $R_{OU}$ [m] | 0.1459 |
| | | External enclosure radius | $R_{OV}$ [m] | 0.1535 |
| | | Busbar length | $l_S$ [m] | 10 |
| | | Specific resistance of the busbar | $\rho_S$ [Ωm] | $1.543\cdot10^{-8}$ |
| | | Specific resistance of the enclosure | $\rho_O$ [Ωm] | $2.65\cdot10^{-8}$ |
| | | Height above earth | $H$ [m] | 2 |
| **Overhead line** | | Conductor radius | $R_{NV}$ [m] | 0.01 |
| | | Conductor hight at the top tower | $H_V$ [m] | 15 |
| | | Heights in the middle of the midspan sag | $H_{VM}$ [m] | 10 |
| | | Length | $l_{NV}$ [km] | 5 |
| | | D.C. unit resistance of the conductor | $R_V$ [Ω/km] | 0.2374 |
| **Earth** | | Specific earth resistance | $\rho_Z$ [Ωm] | 100 |
| **Earth line** | | Length | $l_{ZV}$ [m] | 2 |
| | | Strap width | $d_{ZV}$ [m] | 0.04 |
| **Earthing** | | Length | $l_{UZ}$ [m] | 25 |
| | | External diameter | $R_{UZ}$ [m] | 0.04 |
| | | Specific resistance | $\rho_{UZ}$ [Ωm] | $2.65\cdot10^{-8}$ |
| **MODELS OF DISTRIBUTED PARAMETERS TRANSMISSION LINES (calculation results in ATP for the Bergeron line model)** | **Busbar-to-enclosure** | Frequency for parameter calculation | $f_{SO}$ [Hz] | $7.5\cdot10^{6}$ |
| | | Surge impedance | $Z_{SO}$ [Ω] | 63.032 |
| | | Propagation velocity | $v_{SO}$ [m/s] | $2.9975\cdot10^{8}$ |
| | **Enclosure-to-earth** | Surge impedance | $Z_{OZ}$ [Ω] | 207.987 |
| | | Propagation velocity | $v_{OZ}$ [m/s] | $2.8177\cdot10^{8}$ |
| | **Overhead line conductor-to-earth** | Frequency for parameter calculation | $f_{NV}$ [Hz] | 15 000 |
| | | Surge impedance | $Z_{NV}$ [Ω] | 571.48 |
| | | Propagation velocity | $v_{NV}$ [m/s] | $2.4393\cdot10^{8}$ |
| | **Earthing** | Frequency for parameter calculation | $f_{UZ}$ [Hz] | 3·106 |
| | | Surge impedance | $Z_{UZ}$ [Ω] | 15253 |
| | | Propagation velocity | $v_{UZ}$ [m/s] | $1.5848\cdot10^{8}$ |
| | **Ground lead** | Surge impedance | $Z_{UZ}$ [Ω] | 255 |
| | | Propagation velocity | $v_{UZ}$ [m/s] | $3\cdot10^{8}$ |

The following figures show waveforms for examining the influence of how some equivalent circuit elements are modeled. Figures 14 and 15 show the influence of lightning strike closeness. These figures cover the case of lightning striking 10 times closer from the firstly examined case. Figure 16 shows the enclosure voltage with modeling its earthing with concentrated parameters. Figures 17-19 show waveforms for the case of modeling the surge arrester earthing with a distributed parameters line. Figures 20 and 21 show the current through the enclosure that appears due to wave phenomena. Figure 22 shows the influence of lightning current on the enclosure voltage.

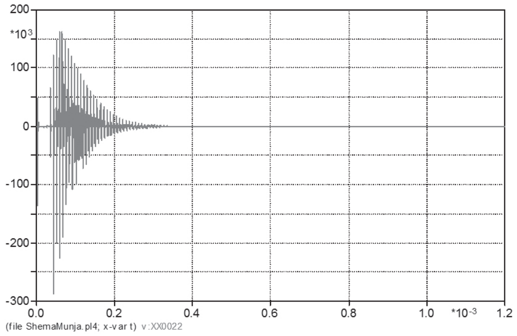


**Fig. 14**. Enclosure-to-earth voltage at the overhead line-to-GIS transfer point, with a surge arrester, line length 0.5 km

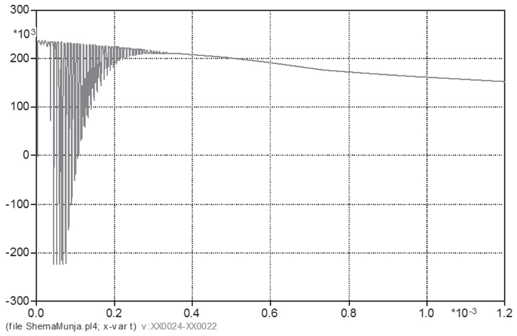


**Fig. 15**. Voltage between the busbar and the enclosure at the overhead line-to-GIS transfer point, line 0.5 km, with a surge arrester

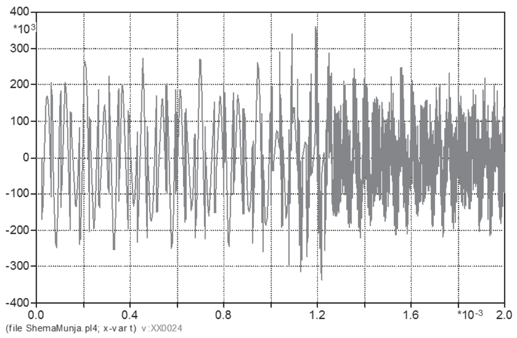


**Fig. 16**. Enclsoure-to-earth voltage at the overhead line-to-GIS transfer point, with a surge arrester, line length 5 km, enclosure earthing with concentrated parameters

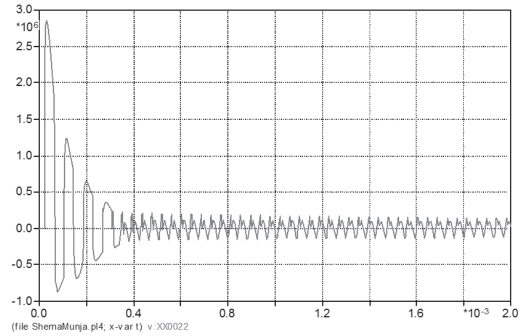


**Fig. 17.** Overhead line voltage at the overhead line-to-GIS transfer point, with a surge arrester, line length 5 km, arrester earthing modeled with distributed parameters

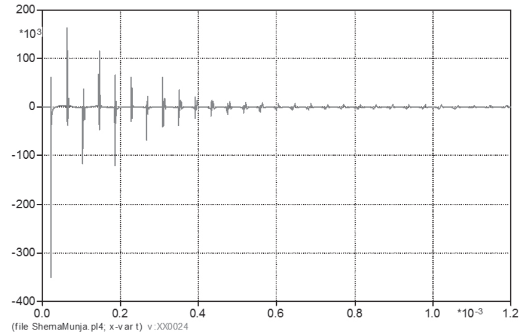


**Fig.18**. Enclosure voltage at the overhead line-to-GIS transfer point, with a surge arrester, line length 5 km, arrester earthing modeled with distributed parameters

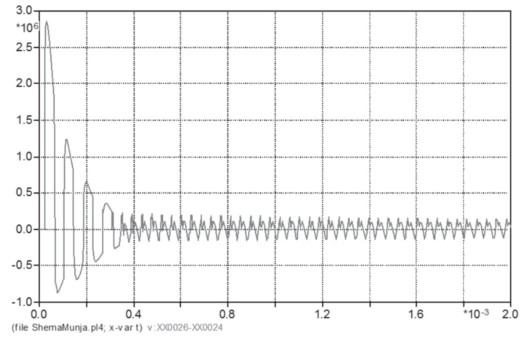


**Fig. 19**. Busbar-to-enclosure voltage at the overhead line-to-GIS transfer point, with a surge arrester, line length 5 km, arrester earthing modeled with distributed parameters

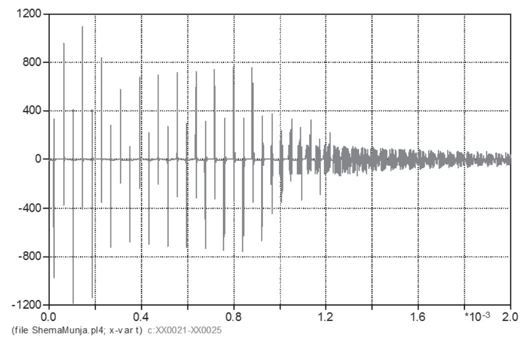


**Fig. 20.** Current through the GIS enclosure, with a surge arrester, line length 5 km, ideal arrester earthing

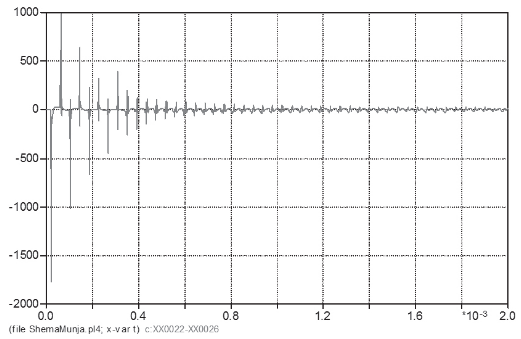


**Fig. 21.** Current through the enclosure, with a surge arrester, line length 5 km, arrester earthing modeled with distributed parameters

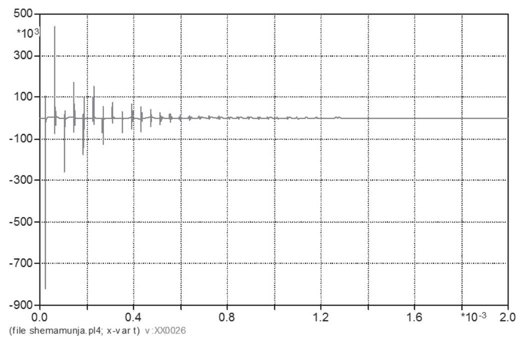


**Fig. 22.** Enclosure voltage at the overhead line-to-GIS transfer point, with a surge arrester, line length 5 km, arrester earthing modeled with distributed parameters, lightning current amplitude amounting to 50 kA.

By analyzing waveforms in Figures 10-12 it is visible that atmospheric overvoltage causes significant overvoltages in GIS. These overvoltages additionally burden the GIS insulation. Also, due to high values, voltages that appear on the GIS enclosure can cause flashovers in air. This can be dangerous to the GIS staff and cause disorders in the control and safety equipment as presented in [15]. Figures 13 shows distinguished enclosure voltage peaks in the case of open busbars (open GIS interrupter, GIS disconnector, busbar end). These peaks result from the voltage surge reflection at the open line end. Figures 14 and 15 show that enclosure voltages are somewhat higher if lightning strikes closer to GIS. However, it is interesting to recognize that voltage oscillations decrease much faster than in the case of lightning striking far away (Figures 11 and 12). By comparing Figures 16 and 11, a significant influence on the simulation results is visible, depending on the way of modeling the GIS enclosure earthing. Figures 17-19 also show more convenient conditions in the case of modeling the surge arrester earthing with a distributed parameters line, which was not expected. Finally, Figures 20-22 show that current impulses with significant values (about 1 kA) may appear through the GIS enclosure. The value of these current strikes does not significantly depend on the way of modeling the surge arrester earthing, but the transient phenomenon duration does.

## 6. CONCLUSION

Due to the existence of the enclosure earthing resistance, enclosure potential in GIS increases in comparison to the earth as atmospheric overvoltage comes closer. Also, due to the waveform of the examined phenomenon, potential difference along the enclosure appears and high-frequency currents pass through the GIS enclosure. This paper focuses on the influence of various ways of modeling some system elements on the simulation results. It can be generally concluded that the way of modeling some elements significantly influences the values of the observed voltage increase in the GIS enclosure. In papers to follow precise ways of modeling certain elements should be explained. As simulation results show, these are high-frequency phenomena. Because of this, modeling actual components, using models available in software and mathematical settings in software significantly influences simulation results. Developing models that in simulations provide results close to the real ones allows a more reliable analysis of observed phenomena. However, even less accurate models can point to the existence of certain phenomena and serve as an encouragement for further research of these phenomena.

## 7. ACKNOWLEDGEMENTS:

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