Lightning Induced Overvoltages in Mixed 380 kV OHL-Cable-OHL connections

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Abstract—**Transmission of electric energy at high voltage levels is mainly performed by overhead lines. Nowadays, an increasing amount of power grid operators are replacing overhead transmission lines by underground cables. Cable presence in power systems may have consequences for the behavior of the total system, since cables have much larger capacitance than overhead lines. In the Netherlands, a new mixed 380 kV connection is under construction, in which four underground cable sections are embedded between overhead lines. In this paper, the behavior of this mixed line-cable-line configuration is studied during lightning events. The study is performed by using a transient simulation model of this mixed 380 kV system, which is developed in PSCAD.**

Keywords: **Cable, transient model, lightning**

I. INTRODUCTION

The application of underground cable connections in high voltage transmission systems will influence the performance of the power system in several aspects. During fast transient phenomena, like switching actions and lightning discharge currents, fast front surges are generated and this may result in large overvoltages in the system, which can be harmful for power system equipment. A lightning current that hits the overhead line phase conductor causes a fast front surge voltage propagating along the line. At a line-cable junction point, the travelling wave sees a discontinuity caused by a difference in surge impedance between the cable and the line. The surge impedance of an overhead line is about 10 times larger than that of an underground cable [1]. This means that when a travelling voltage wave passes a cable-line junction, the voltage amplitude can be doubled at that point. Furthermore, the propagation velocity in an overhead line is about two times higher than that in a cable. When a cable section is embedded between two relative large overhead line sections, reflections could occur in a short time period. This can result in large overvoltages at cable-line junctions in case of a lightning strike, especially when relative short cable sections are applied [2-5]. Installation of protection equipment, like surge arresters, could be necessary to protect cable terminals against large overvoltages during fast transients. Cable modeling is an important subject when developing an accurate simulation model for transient studies. A lot of fundamental cable modeling work has been published [6-7]. For transient studies, several cable models have been developed over the years. Currently, a widely used cable model for transient studies is the Frequency Dependent Phase model, which is implemented in the PSCAD environment [8]. Model validation is an important topic in cable modeling. The cable models available in PSCAD have been used and verified by field measurements [9].

The work presented in this paper is based on a new 380 kV connection in the Netherlands, which is a mixed line-cable-line configuration with four underground cable sections. The length of the shortest underground cable section in this connection is planned to be 1 km. The goal of this study is to investigate the influence of the applied cable length in this connection on the transient overvoltages during lightning strikes. Furthermore, the effect of surge arresters on overvoltages is observed. A simulation model for the underground cable sections and overhead lines is developed in PSCAD. To achieve this, a model for the surge arrester that represents the non-linear V-I characteristic is applied. The lightning surge current is represented by a 10 kA, 1.2/50 µs wave, generated using the Heidler function [10]. The surge current is injected into the overhead line phase conductor when the mixed line-cable-line connection is operating in steady state. During surge current injection, voltages at the cable-line junctions are observed. To investigate the influence of the surge arresters, the simulations are carried out for the case with and without the presence of the arresters. Furthermore, this simulation is performed for different cable section lengths to investigate whether the overvoltages at the cable terminals could exceed the Basic Impulse Level (BIL) of 1425 kV, specified by the manufacturer.

II. CONSIDERED SYSTEM

The studied 380 kV connection consists of five overhead line sections and four cable sections, configured as a mixed line-cable-line system. A block diagram of this configuration is shown in Figure 1. The transient voltages that appear at the line-cable junctions, indicated by V1 to V10, will be

simulated during lightning events. At location V1, a load with a power factor of 0.95 is connected. At V10, the system is connected to 380 kV supply voltage. In practice, the line ends at V1 and V10 are connected to the transformer substations Beverwijk (BVW) and Bleiswijk (BWK) respectively.
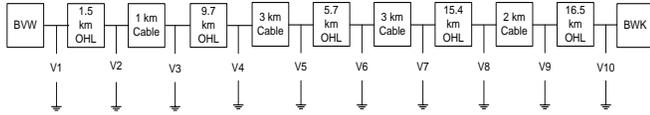
Figure 1. Line-cable-line configuration of the studied system.

This 380 kV configuration consists of two parallel operating three phase circuits and forms a part of the Dutch 380 kV grid. The transmission capacity of the connection is 2600 MVA per circuit. The overhead line sections are carried out with one conductor per phase. In the underground cable sections, there are two cables per phase, in total there are 12 cables in parallel in one underground section. The horizontal spacing between the two cable circuits is 3 meter, while the distance between the cables in one circuit is 0.75 meter. In the practical situation, there is some variety in this distance along the connection. However, in this work, both the depth and the distance are assumed to be constant. The cables are installed in flat arrangement and buried at a depth of 1.25 meter, according to Figure 2.
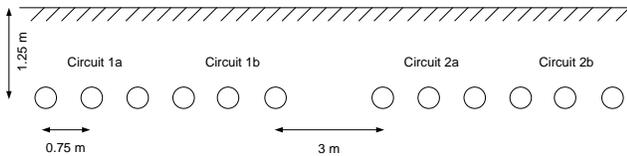
Figure 2. Arrangement of the underground cables.

III. CABLE AND LINE MODELING

The overhead lines consist of aluminum conductors with an overall diameter of 32.4 mm. The modeling work of the overhead line conductors for transient studies is rather straight forward. Underground cable modeling for fast transients is less easy, since the cable consists of different layers. A cross section of the applied 380 kV cable is shown in Figure 3.
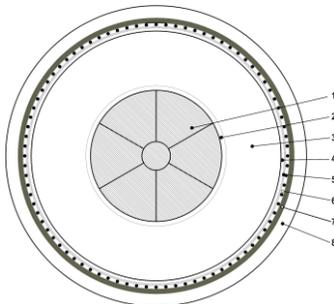
Figure 3. Cross section of the 380 kV cable.

The different cable layers and dimensions are:

1	Copper conductor	(2500 mm^2)
2	Semi-conducting layer	(2.2 mm)
3	XLPE insulation	(26 mm)
4	Semi-conducting layer	(1.5 mm)
5	Bedding (semi-conductor and swelling tape)	
6	Copper screen	(155 mm^2)
7	Lead sheath	(2 mm)
8	PE sheath	(5.1 mm)

To reduce skin and proximity effects, the core conductor of the cable is segmented, as it can be seen in Figure 3. The solid main insulation material is cross linked polyethylene (XLPE), with a semi-conducting material at the inner and the outer side. The screen conductor consists of a copper wire, which is helically applied over the bedding of the swelling tape. A lead sheath forms a radial water barrier and is extruded over the metallic screen. Moreover, the lead sheath acts as an additional cable screen. To protect the cable against mechanical influences, the over sheath consists of high density polyethylene (HDPE).

In this work, the Frequency Dependent Phase Model (FDPM), implemented in PSCAD, is used for both the cable and overhead line [8]. The material and geometric data of cable layers and overhead lines must be entered into the simulation model. In PSCAD, it is not possible to enter explicit data for semi-conducting layers of the cable, which are present between core conductor and the XLPE layer and between the XLPE layer and the screen. To model the effect of the semi-conducting layers, the thickness of the main insulation layer is increased, by assuming a constant capacity between the core conductor and the copper wire screen [9]. The capacity per unit length between the core and the screen is specified by the manufacturer and is equal to:

$$C = \varepsilon_0 \varepsilon_{XLPE} \frac{2\pi}{\ln[r_2 / r_1]} \qquad (1)$$

The given value of this capacitance is about 0.2 μF per km. To take the semi-conducting layers into account, a corrected permittivity must be calculated when the insulation medium is increased by the thickness of the semiconductors layers. This new permittivity is found by:

$$\varepsilon_{corrected} = \varepsilon_{XLPE} \frac{\ln[b / a]}{\ln[r_2 / r_1]} \qquad (2)$$

In equations (1) and (2), ε_{XLPE} is the known relative permittivity of XLPE (2.3), r_1 and r_2 are the inner and outer radius of the insulation layer respectively and a and b are the

outer radius of the core conductor and the inner radius of the screen respectively. In Figure 4, a cross section of the PSCAD cable model is shown for one circuit of six cables. Figure 5 shows the configuration of the overhead line conductors for one circuit. These conductors are placed in a so-called Wintrack tower, which is a new construction for overhead transmission lines to reduce magnetic fields. The dimensions used in the simulation, correspond to the practical situation.
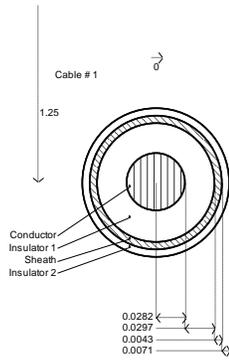
Figure 4. Cross section of the PSCAD cable model of one cable circuit.
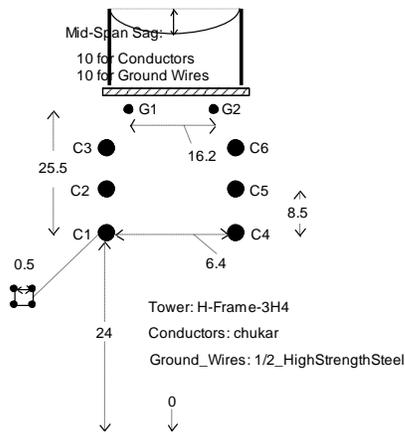
Figure 5. Configuration of the overhead line conductors.

Another important modeling issue is the inductive coupling between the cables. Since the distance between two adjacent cables in one circuit is relatively small, the coupling must be taken into account. When the cable is in service, the screen conductors of the cables are connected to ground. This means that there is no capacitive coupling and only magnetic coupling might influence the performance of the system. In PSCAD, the number of cables that can be modeled as a system is limited to 8. Since the distance between the cable circuits is relatively large, it is decided to ignore the inductive coupling between the two circuits. Therefore, the system is considered by two separate cable systems of 6 cables, operating in parallel at a load of about 1350 MVA per circuit. The way of grounding of the screen conductor of the cable is also important in cable modeling work. The cable screen forms a return path for the charging current. Cross-bonding

of the screen conductor has been applied in underground cable systems to prevent the screen from large overvoltages. In this 380 kV connection, a cable section consists of different minor sections, in which cross-bonding is applied. The conductors used for both the cross-bonding and the grounding are modeled by lumped inductances and the values are taken from [9]. In this paper, the influence of the cross-bonding on the transient voltage responses will not further be investigated. In PSCAD cable simulation model, the ground resistivity is taken as 100 Ohm·m.

At the cable-line junctions, surge arresters will be installed to protect the system against steep overvoltages during fast transient phenomena. The main component of the arrester model is the non-linear resistive element, which is shown in Figure 6. The applied arrester type in the new 380 kV connection is a metal oxide arrester with a rated voltage of 420 kV and a continuous operating voltage of 336 kV. According to the catalog of the manufacturer, the residual voltage for a 1.2/50 surge current with 10 kA amplitude is 1089 kV [11]. The values of the parameters C_a, R_a and L_a of the arrester model are taken from [10], [12]. Applying these values to the arrester model from Figure 6, the calculated residual voltage is 1040 kV. The non-linear v-i characteristic of the applied surge arrestor is shown in Figure 7.

Since the connection shown in Figure 2 is a part of the 380 kV grid, there will be connections to other 380 kV substations in practice. Furthermore, there will be 380/150 kV transformers installed at locations V1 and V10. From the 150 kV side, the energy is further transported to the consumers. To keep the modeling of the system workable, the 380/150 kV transformers are not included in this study. The load at location V1 is represented by a fixed P and Q which represents the nominal steady state operation (1350 MVA at a factor factor of 0.95).
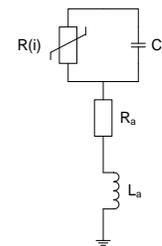
Figure 6. Applied surge arrester model.
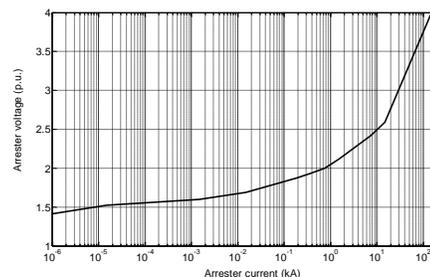
Figure 7. Non-linear v-i characteristic of the applied surge arrester.

IV. Methodology and simulation setup

A lightning surge current is applied to the overhead line phase conductor, when the system is operating in steady state condition. In case of a nominal load condition, the steady state phase current is about 2 kA. The transient voltage responses at the cable-line junctions are simulated when a lightning surge current is injected into the overhead line phase conductor. Current injection is applied to only one phase conductor of one circuit. The lightning discharge current is represented by a 1.2/50 μs surge current with a peak value of 10 kA, as is shown in Figure 8. The string insulators at the high voltage tower are able to withstand voltages up to 1750 kV. When the peak value of the injected surge current would be larger than 10 kA, the resulting voltage between the overhead line and ground could exceed this 1750 kV. In this case, flashover to ground will occur. Moreover, the ground wires placed above the overhead lines protect the system from lightning strikes. When a large lightning discharge approaches the earth surface, there is a large probability that the ground wires will catch this current before the phase conductor is reached.

The peak value of the transient voltage response at the cable-line junction also depends on the instant of surge current injection. To simulate the worst case scenario, the current is injected when the steady state sinusoidal voltage has reached the peak value. In this situation, the peak is reached at 0.019 s. This peak voltage value is 310 kV when the operating phase-to-ground voltage is 220 kV. Furthermore, the location of current injection will also have influence on the peak value of the transient voltage responses. When the lightning current hits the line far away from the line-cable junction, the steepness and amplitude of the propagating voltage surge may be significantly reduced before it reaches the cable. Therefore, the surge current is injected close to the line-cable junction at location V3 (see Figure 1) to simulate a worst case scenario. The simulation time step is set to 0.1 μs, which is sufficiently small in case of the 1.2/50 μs surge current. The simulation is applied for four different lengths of the shortest cable section between the locations V2 and V3. For each cable length, the effect of the surge arrester on the transient voltages will be investigated.
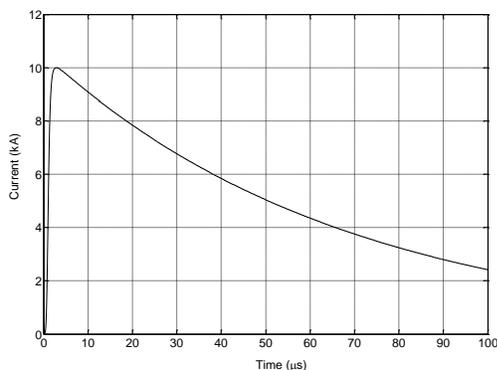
Figure 8. Surge current that is applied to OHL phase conductor.

V. Simulation results

In the first simulation, the cable section between V2 and V3 is 1 km long and the 10 kA surge current is injected into the 9.7 km overhead line section, close to V3. The voltage responses at the instant of current injection for the locations V1 to V5, are shown in Figure 9 for a time period of 500 μs after the current injection at 0.019 s. The upper graph shows the voltages when there are no surge arresters installed. The lower graph shows the voltages for the situation with arresters. It can be observed from this figure that the largest peak voltage occurs at V2 and V3 and is about 760 kV. This is considerably larger than the voltage at locations V4 and V5, which are about 460 kV and 525 kV respectively. The cable section is embedded between two overhead lines. When the injected current hits the line close to V2, a travelling wave will propagate along the cable to V3. At this location, the voltage will almost double in amplitude because of the large surge impedance of the line. The reflected wave will travel back and reflection occurs at V2. Because the travel time of the short cable is small, repeated reflections takes place in a short time period. This results in large voltage peak values at the cable terminals of the short cable section. At the locations V6 to V10, the peak voltages are expected to be significantly lower since the cable lengths of the sections are larger than 1 km. Moreover, these locations are far away from the point of strike. These voltages are therefore not shown in the figures. The same simulation is performed when there are surge arresters installed at all line-cable junctions. The results are shown in Figure 9.
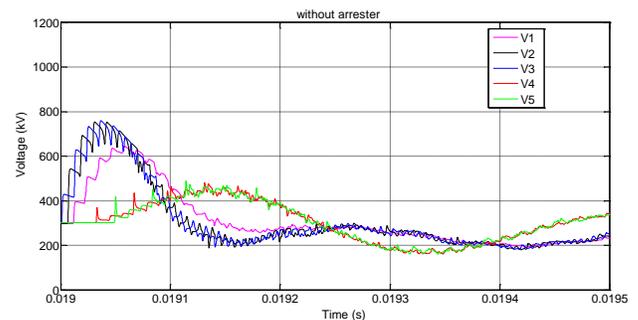
Figure 9a. Voltage responses without arresters for 1 km cable.
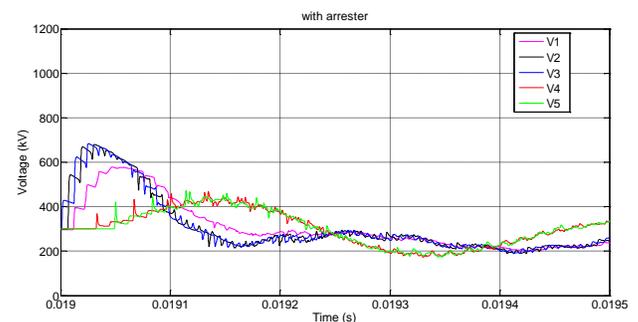
Figure 9b. Voltage responses with arresters for 1 km cable.

To investigate the impact of the cable length on the transient voltage responses, the simulation is repeated for the situation when the length of the cable section between V2 and V3 section is reduced. Simulations are performed for cable lengths of 0.75 km, 0.5 km and 0.3 km. The results for the voltages at V1 to V5 are shown in the Figures 10 to 12 respectively. In each figure, the upper graphs show the results without arresters while the results with arresters are shown in the lower graphs.
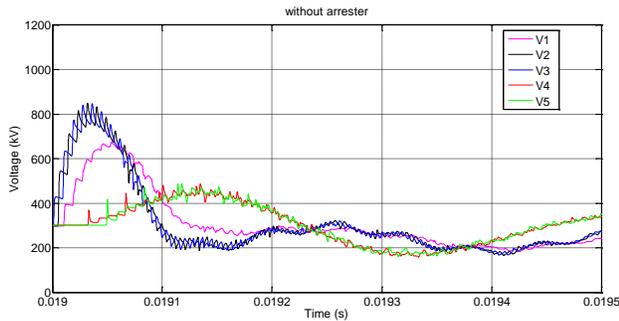
Figure 10a. Voltage responses without arresters for 0.75 km cable.
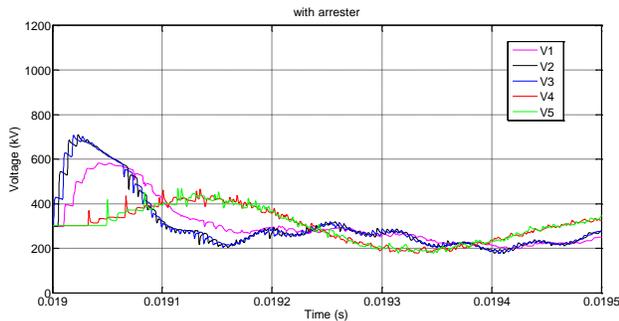
Figure 10b. Voltage responses with arresters for 0.75 km cable.
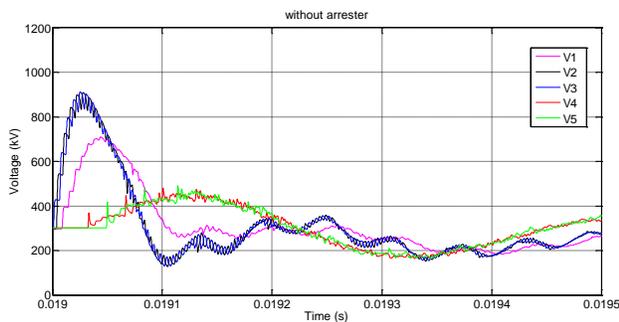
Figure 11a. Voltage responses without arresters for 0.5 km cable.
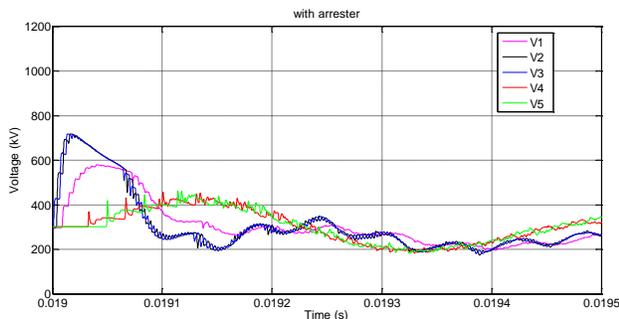
Figure 11b. Voltage responses with arresters for 0.5 km cable.
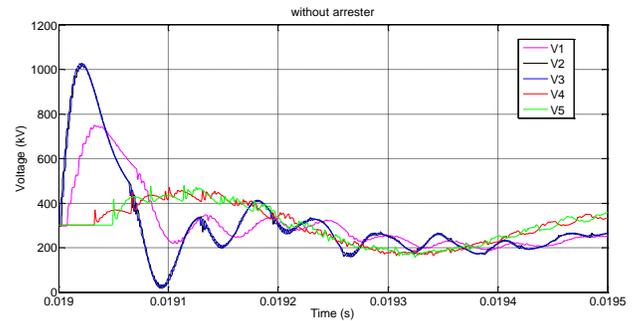
Figure 12a. Voltage responses without arresters for 0.3 km cable.
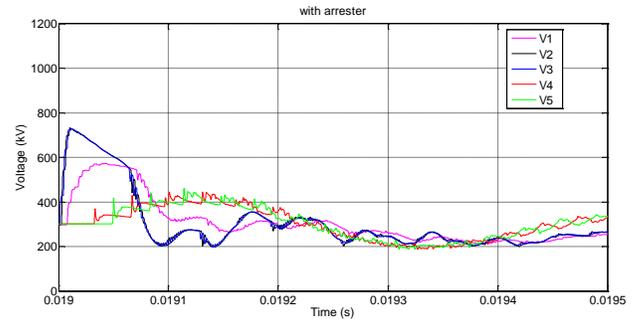
Figure 12b. Voltage responses with arresters for 0.3 km cable.

From the simulation results, it can be seen that the peak values of the voltages at V2 and V3 increases when the cable length decreases. This is the result of repeated reflections in a short time period. The shorter the cable, the more reflections will occur, resulting in large peak voltages at the terminals. The largest peak value observed is 1025 kV, when the cable length is 0.3 km and there are no surge arresters. When the surge arrester operates, the voltage has almost always a similar shape, as it can be observed from the lower graphs of the figures. Furthermore, the influence of the surge arresters depends on the cable length. In case of a cable length of 1 km or 0.75 km, the arresters have almost no influence on the peak voltage. For shorter cable length, more reduction in the peak voltage values is observed. The largest reduction in peak value is achieved in case of 0.3 km cable between V2 and V3. In this situation, the surge arresters cause a reduction in the peak value of about 29%. Based on these results, it can be expected that the reduction in peak voltage would be larger when the cable length is further reduced. This situation is not considered here since very short cable lengths will not be applied in such a practical 380 kV configuration. In table 1, the peak values of the voltages V1 to V5 observed from the figures are shown, for the four different cable lengths of the section between V2 and V3. Moreover, the peak values are shown for the situation with and without surge arresters. The reduction in peak voltage caused by the arresters is indicated by ΔV.

Cable length (km)	Arresters installed	Peak value of voltage (kV)				
		V1	V2	V3	V4	V5
1	No	645	760	760	490	490
	Yes	580	685	685	480	480
	ΔV	**10%**	**10%**	**10%**	**2%**	**2%**
0.75	No	670	850	850	515	515
	Yes	580	710	710	490	490
	ΔV	**13%**	**16%**	**16%**	**5%**	**5%**
0.5	No	710	910	910	515	515
	Yes	580	720	720	470	470
	ΔV	**18%**	**21%**	**21%**	**9%**	**9%**
0.3	No	750	1025	1025	480	480
	Yes	580	730	730	458	468
	ΔV	**23%**	**29%**	**29%**	**4.5%**	**2.5%**

Table 1. Overview of peak voltage values for different cable lengths.

VI. CONCLUSION

In this work, simulations were performed on a new planned 380 kV connection in the Netherlands, which consists of several overhead line and underground cable sections. The goal was to investigate if the voltages at the cable-line junctions would exceed the Basic Insulation Level (BIL) of 1425 kV during lightning strikes in the overhead line phase conductor. A cable and line model was developed in PSCAD to perform accurate simulations under lightning conditions. Several simulations were performed and the impact of the cable length on the transient voltages at different locations along the connection was investigated. The worst case scenario was considered, with respect to the peak value of the injected surge current and the location of injection. The largest peak voltage appeared at the terminals of the shortest cable section. A significant reduction of the transient overvoltage can be achieved by installation of surge arresters. The length of the shortest cable section in this project is planned to be 1 km. Applying this cable length, the 1425 kV was not exceeded. At the terminals of the 1 km cable section, the largest peak voltage value found was 760 kV. Even when the cable length between V2 and V3 would be reduced to 0.3 km, the peak voltages will not exceed the BIL under the given circumstances without protection equipment. Theoretically, it is possible that several lightning strikes will hit the overhead line phase conductor simultaneously at different locations. In such a case, the voltage peaks at the observed locations might be higher and will even exceed the BIL. However, the probability that this occurs in practice, is rather small.

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