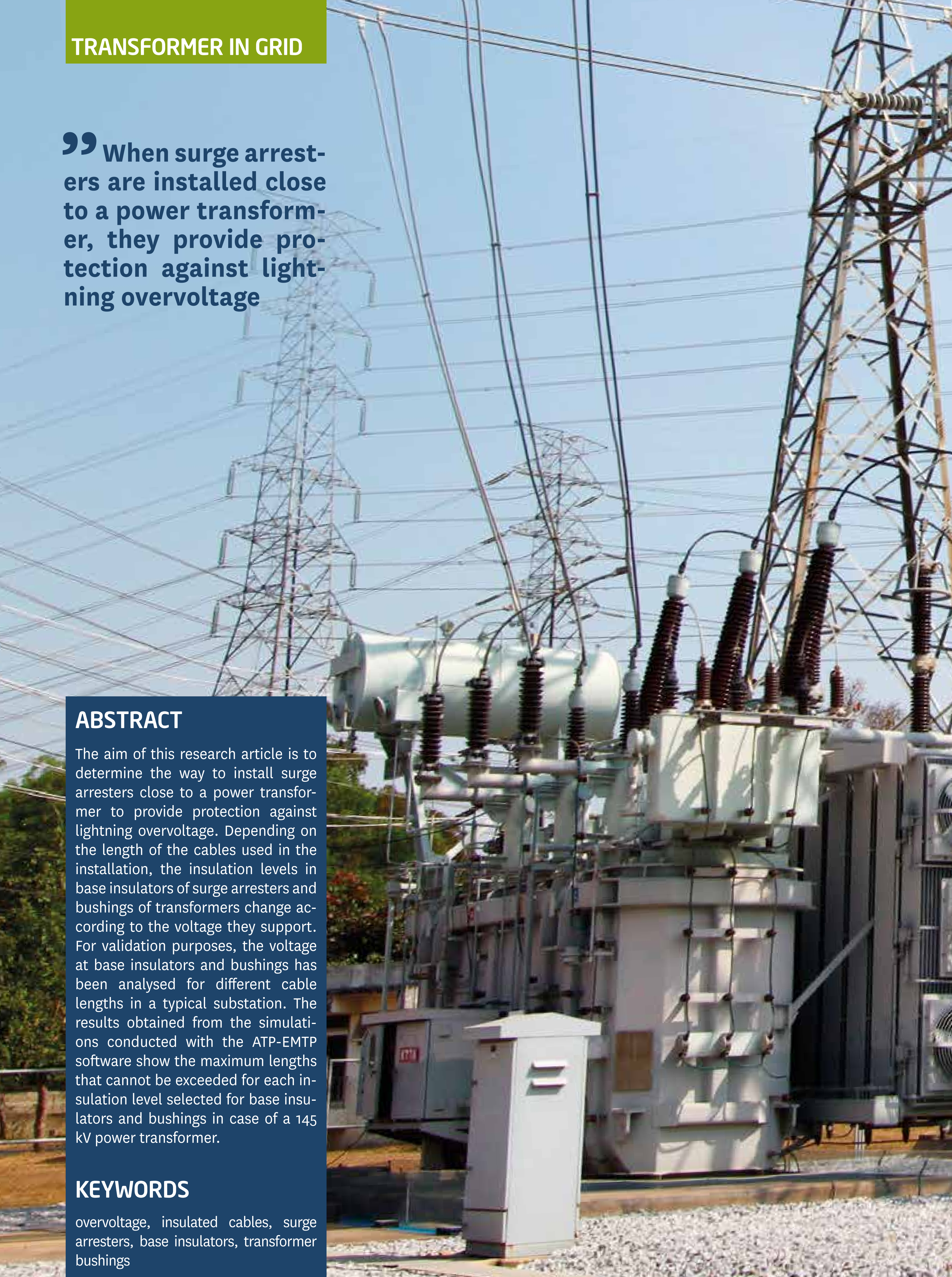

When surge arresters are installed close to a power transformer, they provide protection against lightning overvoltage

ABSTRACT

The aim of this research article is to determine the way to install surge arresters close to a power transformer to provide protection against lightning overvoltage. Depending on the length of the cables used in the installation, the insulation levels in base insulators of surge arresters and bushings of transformers change according to the voltage they support. For validation purposes, the voltage at base insulators and bushings has been analysed for different cable lengths in a typical substation. The results obtained from the simulations conducted with the ATP-EMTP software show the maximum lengths that cannot be exceeded for each insulation level selected for base insulators and bushings in case of a 145 kV power transformer.

KEYWORDS

overvoltage, insulated cables, surge arresters, base insulators, transformer bushings

Jesús BERNAL

Influence of cable lengths on power transformers protection

Selection of the insulated bases in surge arresters

1. INTRODUCTION

The purpose of this article is to investigate overvoltages which appear at the bushing terminals of a Power Transformer (PT) when the transformer is protected by surge arresters (SA) (see Fig. 1), as well as overvoltage appearing in the insulators of the base of surge arresters when an insulated cable provides the connection between the base and the surge counter.

In order to study the cases above, three distances are considered:

- The distance between the PT and the point where the SA is connected: L_1
- The length of the conductor that connects the SA with the line: L_2
- The length of the grounding conductor of the SA (between the base and surge counter): L_3
- The length of the grounding conductor between the surge counter and the earthing system: L_4

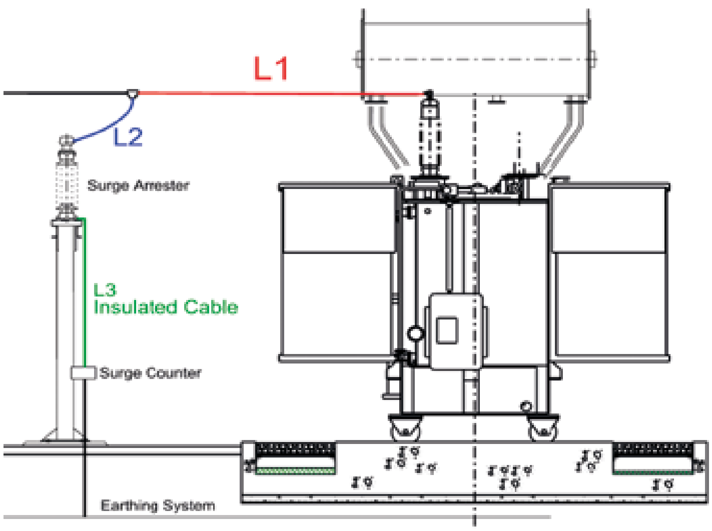

Figure 1. Physical representation of the system under study

In case of an overvoltage, conductors suffer a voltage drop when a high current flows through the surge arrester, affecting the terminal voltage

In case of an overvoltage, each of the conductors in Fig. 1 will suffer a voltage drop when a high current flows through the surge arrester, affecting the terminal voltage. The considered length of the connection between the surge counter and the grounding system is about 1.5 metres. This length (**L_4**) was kept constant because it determines the location of the counter, which has to be within easy reach for the worker conducting the reading.

Fig. 2 illustrates the details of the surge arresters assembly. Depending on the distance between the base of the surge arresters and the surge counter (**L_3**), the base insulators of surge arresters will suffer different overvoltage. Since many manufacturers recommend maximum lengths (**L_3**) for the base insulators that they supply, overvoltage in these insulators has been studied depending on the length **L_3**.

2. SYSTEM MODELLING

This study is based on the use of detailed computational simulations using the Electro-Magnetic Transient Program - Alternative Transient Program (EMTP-ATP). This version of the EMTP (ATP) is a universal program system for digital simulation of transient phenomena, both electromagnetic and electromechanical in nature. Using this digital program, complex networks and control systems of arbitrary structure can be simulated.

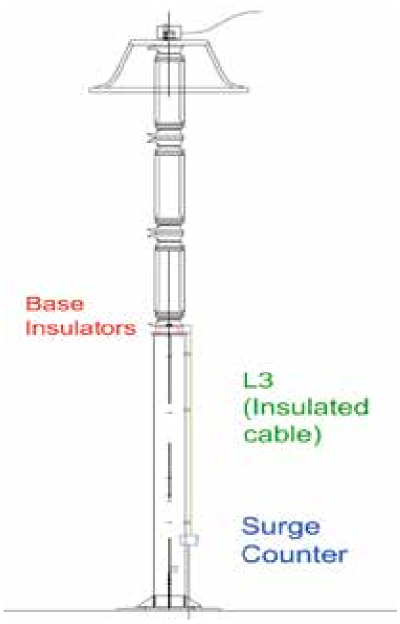

Figure 2. Assembly of surge arresters

Besides the computation of transients, ATP has extensive modelling capabilities and additional important features. Also, the software is regularly updated by the EMTP-ATP user groups [1].

This model has been made in accordance with IEC 600071-4 [2] and the guidelines referenced under [3], [4] and [5]. Being a deterministic study, the worst-case scenarios will be considered here.

2.1 132 kV overhead lines

The power transformer is fed from one OverHead Line (OHL). The typical model considered in this study has the following specifications:

- The impedance of each OHL is 300 Ω
- The velocity of propagation considered is $3{\cdot}10^8$ m/s

There are two sections of the line. The first one is 10 km long (in order to avoid the reflection from the network side), which was used to model a transmission network with overhead lines supported by transmission towers. Towers were not taken into account in the modelling because this would reduce the overvoltage due to back flashover phenomenon (conservative assumption). In this way, there is a smaller possibility for earth leakages in the system, leaving the remaining groundings of the system more affected.

The second section of 1 km in length was used to simulate the distance between the substation and the point at which the lightning strikes. It is clear that the situation would not be improved even if the distance was less than 1 km; however, the flashover nor back flashover phenomenon (conservative scenario) were not included here. A further analysis conducted as part of a sensitivity study could take into account these variables (flashover, corona, distances , etc).

In addition, substations usually have a protection system provided by franklin rods or aerial grounding wires. It is considered that a lightning strike occurring near the substation will hit this equipment, and the literature usually refers to the distance between 600 and 1000 metres. In case a lightning strike hits the nearest gantry, the insulator of the surge arresters is the smallest concern. Please note that this is a deterministic study (not probabilistic), looking for weak points.

2.2 Power transformer 132 / 20 kV

A typical capacitance of the HV winding to ground for 132 kV is 1.5 nF, and is evident from a final transformer test report.

The study of overvoltages which appear at the bushing terminals is based on computational simulations using the EMTP-ATP

Table 1. Typical capacitances for studies of power transformers at High Frequency (HF)

Nominal voltage (kV)	Capacitance (nF)
500	3
187-220-275	2.5
110-155	1.5
66-77	1

A transferred overvoltage between windings has not been studied. The capacitance of the IEC standard is given in the high frequency section. However, a power transformer test report provides test results at power frequency. To get the capacitance at high frequency is a hard work, which requires using a detailed model of the power transformer and applying high frequency hypothesis. Furthermore, the reference [2] proposes values for typical capacitance between HV transformer winding and earth (see Table 1).

2.3 Conductors for setting of the surge arrester

Typically, the surge arrester must be connected as close as possible to the equipment it protects (in this case the power transformer) to ensure its protection. However, the aim of the modelling is to study a range of different cases to establish how different cable lengths affect overvoltages. There are conductors whose length depends on the installation of surge arresters. In this model three different conductors have been taken into account (see Fig. 1 and Fig. 2):

- L_1: The conductor used to simulate the distance at which the surge arrester is connected. Due to the layout requirements, the SA may not be installed near power transformers. This distance will vary from 0 to 40 metres.
- L_2: The conductor needed to connect the surge arrester. Its length may vary from 1 to 3 metres.
- L_3: The conductor that connects the SA with the discharge counter. Its length may vary from 1.5 to 7 metres, depending on the height at which SA is placed. This is an insulated cable in order to ensure the correct reading of the surge counter.
- L_4: The connection of the SA between the surge counter and the grounding system is provided with one conductor of about 1.5 metres.

These connections are modelled by an inductance of 1 µH/m, according to [2].

2.4 Substation grounding system

The considered resistance of the grounding grid was 1 Ω. As the frequency of the overvoltages and overcurrents appearing in conductors is much higher than the power frequency, it was necessary to apply the reference [2]. Due to ionization, earth connections are non-linear resistors, so the R (i) "type 99" model of the ATP-EMTP was used (resistance that depends on the current which flows through it). After the calculations were performed, it was concluded that the value of 1 Ω does not change significantly with the frequency.

2.5 Surge arresters

Surge arresters with a rated voltage of 145 kV have been selected for this study. Table 2 outlines various parameters of these arresters for further use in the EMTP model.

2.6 Lightning strike

In this study, lightning overvoltage wave shapes have been taken into account [2]. According to [2], a lightning strike should be modelled as an ideal current surge. The wave shape is defined in [9] with the parameters illustrated in Fig. 3.

> **A lightning strike was modelled as an ideal current surge of negative polarity and the wave shape of 8/20 µs**

The wave shape of 8/20 µs was selected for the lightning current [2] model, because it is most widely used by manufacturers, utilities and universities. This is a current wave shape (not a typical voltage wave shape of 1.2/50 µs).

The reference [9] suggests that 90 % of the lighting strikes are negative. Therefore, the negative polarity of the lightning strike has been selected for this study.

In terms of the maximum lightning current, overhead lines are equipped with shield wires which prevent a direct lightning strike to the phase. Only a lightning strike with lower peak current values can directly strike the phase conductors. The value considered for this current was 20 kA [3].

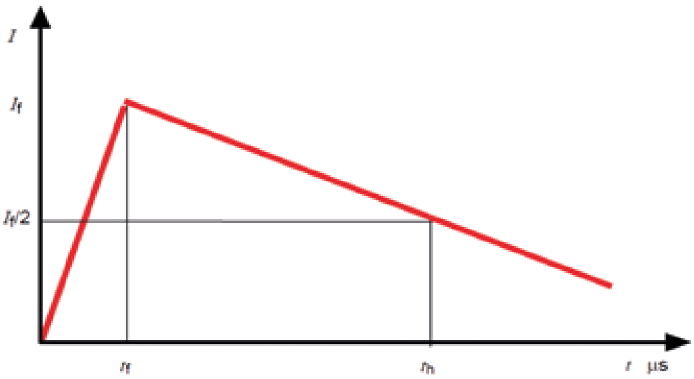

Figure 3. Typical lightning current

Table 2. Surge arrester specifications

U_m (kV)	U_r (kV)	U_c (kV)	Residual voltage at lightning impulse current (8/20 µs)				Residual voltage at switching impulse current (30/60 µs)		
			5 kA	10 kA	20 kA	40 kA	1 kA	2 kA	3 kA
145	144	92	286 kV	328 kV	359 kV	394 kV	281 kV	291 kV	299 kV

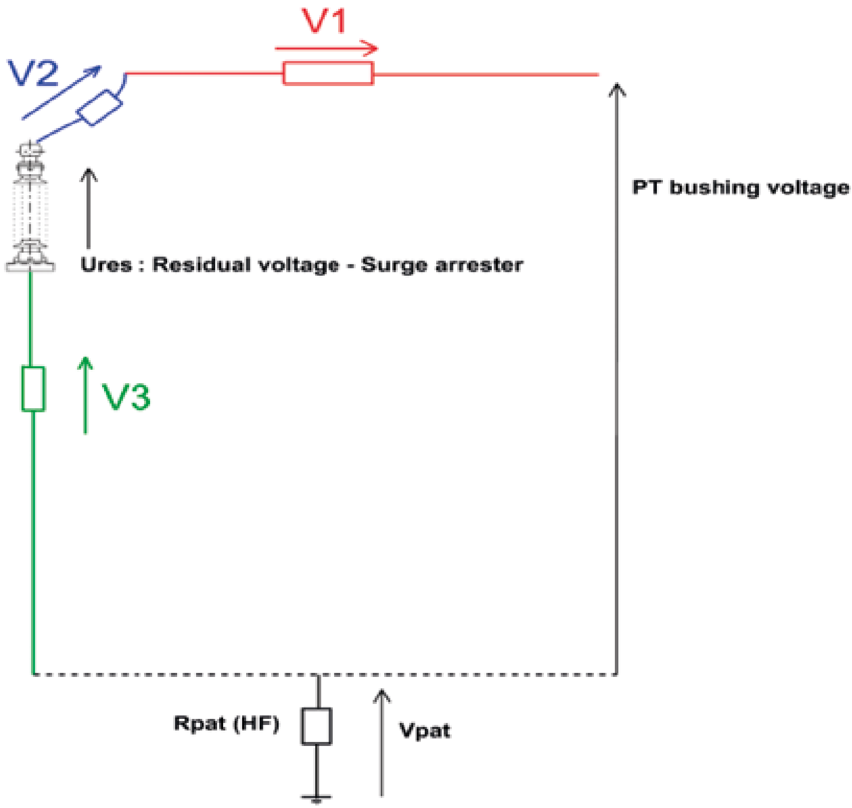

Figure 4. Electrical equivalent model

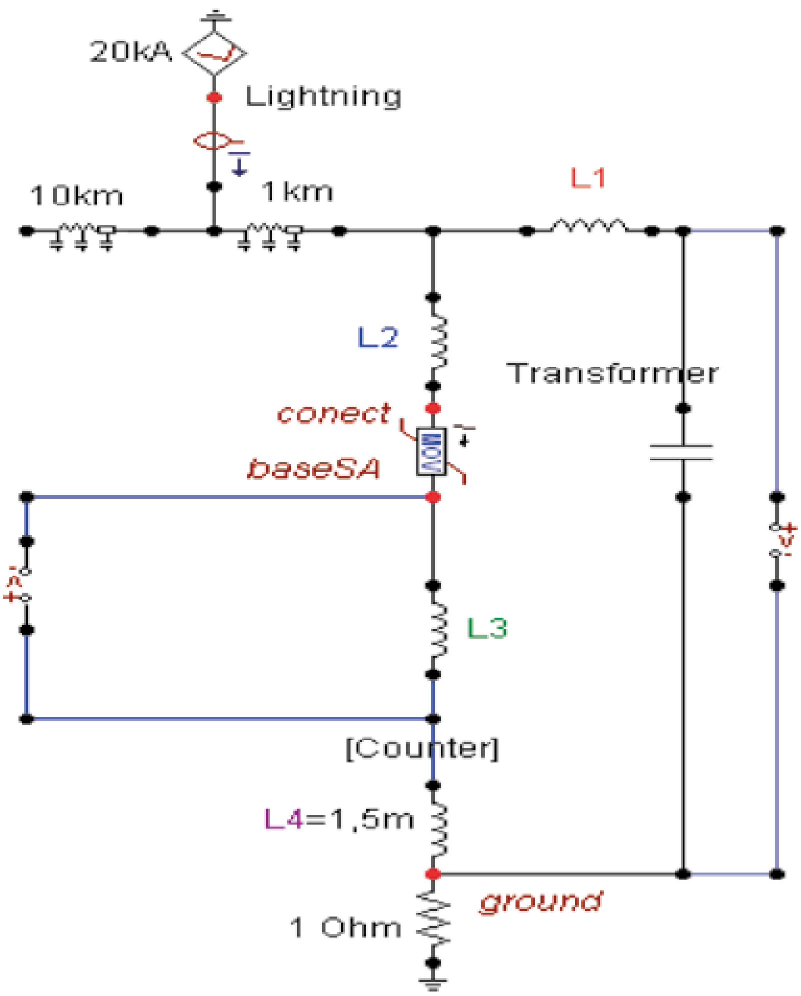

Figure 5. ATPDraw model of the system under study

2.7 Time step and simulation time

The range of time step is 1 to 20 ns according to [3]. The time step selected for this study was 5 ns since this is a common value.

The simulation time ranges from 20 to 50 μs, and is typically at 40 μs [3]. For this study, the maximum simulation time was 2.06 milliseconds. As the lightning strikes at the instant of 2 milliseconds, the recommended simulation time to take the data is 2.04 milliseconds, so that the overvoltage data are maximum values that appear in this range.

2.8 Corona effect

According to IEC TR 60071-4 [2], the corona effect implies a higher capacitance of the wires due to ionization of the air around the wires. The corona effect appears both between phases and between phase and earth. However, since this effect tends to reduce the slope of the incident impulse, to ignore it is to assume a conservative position.

2.9 Complete model

Fig. 4 shows the complete model of the installation under study, representing an approximation of the physical model to an electrical equivalent.

Fig. 5 shows the ATPDraw model used for development of the simulations. Several sensitivity studies have been conducted on this model in order to analyse the impact of different parameters on the overvoltage.

2.10 Initial assumptions

This study demonstrates how a lightning strike causes the change of the overvoltage, as well as how this is affected by the margin of protection of the PT and the base insulators of surge arresters. In order

Several sensitivity studies have been conducted in order to analyse the impact of different parameters on the overvoltage

This study demonstrates how a lightning strike causes a change of the overvoltage, as well as how this is affected by the margin of protection of the power transformer and the base insulators of surge arresters

to carry out the study, sensitivity analysis was performed with L_1, L_2 and L_3 conductor lengths.

The Lightning Impulse Withstand Level (LIWL) considered for the 132 kV PT windings was 550 kV. The LIWL considered for base insulators of surge arresters was between 20 and 25 kV, based on our experience.

3. LIGHTNING OVERVOLTAGES

Some studies are conducted so as to investigate various scenarios. However, all of them share the fact that a lightning strike hitting the overhead line occurs 1 km away from the SA. The goal is to find out how L_1, L_2 and L_3 lengths influence the overvoltage in transformer bushings and in the base insulators of the SA.

3.1 L_1 variation with constant values for L_2 and L_3

The considered values are shown in Table 4.

Table 4. L_1 length variations

L_1	From 0 to 40 metres
L_2	2 metres
L_3	4.5 metres
L_4	1.5 metres

3.1.1 Voltage at power transformer terminals

Fig. 6 illustrates the overvoltage at power transformer terminals. Collection of the voltage data for each length is given in Table 5.

Table 3. Initial basic insulation levels considered

Equipment	Unit	Insulation levels	
		Rated switching impulse withstand voltage	Rated lightning impulse withstand voltage
132 kV transformer	kV_{PEAK}	--	550
132 kV insulators to hold the SA	kV_{PEAK}	--	20 - 25

When the distance L_1 increases, more transients appear in the conductor. As the distance between the SA and the transformer grows, the waves of the voltage travel backwards and forwards through the cable (cable with the length L_1) more frequently, whenever there is a discontinuity.

As stated earlier, the LIWL at power transformer terminals is 550 kV. If the considered Margin of Protection (MP) is 20 %, the maximum overvoltage should be 440 kV. This overvoltage is reached between 25 m and 30 m, as illustrated in Fig. 7.

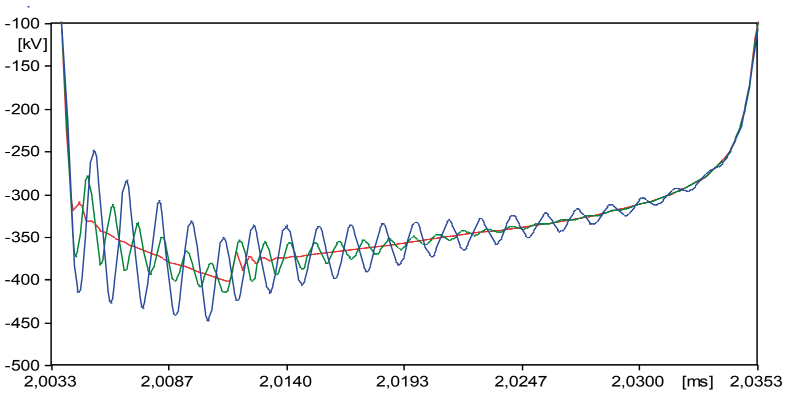

Figure 6. Transients in the voltage at power transformer terminals when L_1 changes

Table 5. Peak values of the voltage at power transformer terminals when L_1 changes

Overvoltage (kV)	Length L_1 (m)
- 401	0
- 413	15
- 446	30

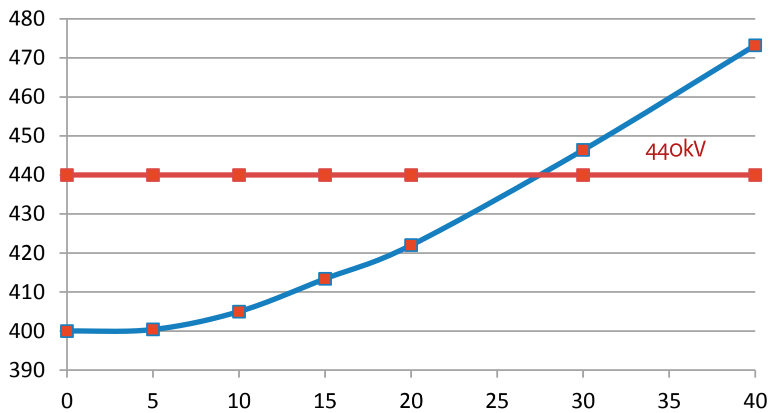

Figure 7. Voltage at power transformer terminals when L_1 changes

> **The base insulators of the surge arrester suffer more from transients when the distance between the surge arrester and the transformer is bigger**

3.1.2 Voltage at the base insulators

Fig. 8 shows the overvoltage at the base insulators of surge arresters. The maximum overvoltage values for each L_1 length is given in Table 6.

The base insulators of the SA suffer more from transients when the distance is bigger, as evident from the voltage waves in Fig. 8.

The considered LIWL of the base insulators was between 20 kV and 25 kV.

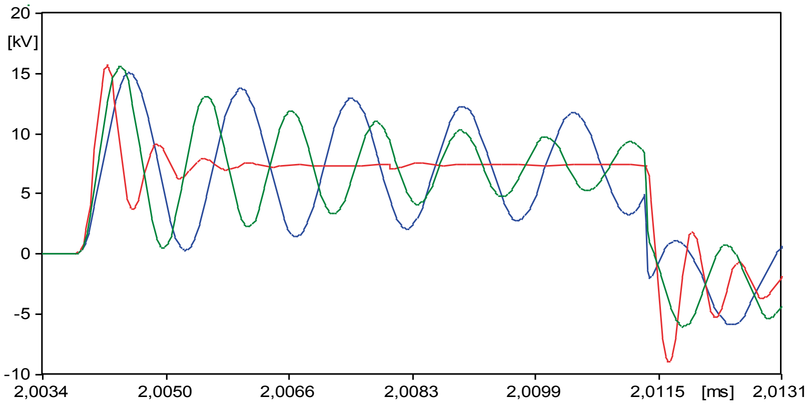

Figure 8. Transients in the voltage at the base insulators when L_1 changes

Table 6. Peak voltage values at the base insulators when L_1 changes

Overvoltage (kV)	Length L_1 (m)
15.65	0
15.6	15
15.04	30

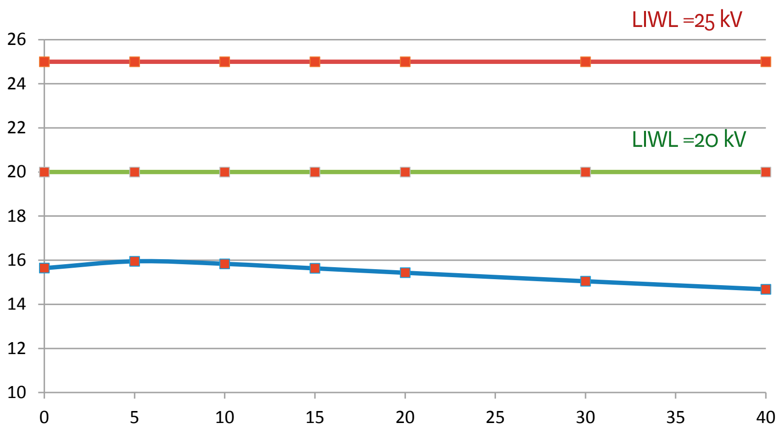

Figure 9. Voltage at the base insulators of surge arresters when L_1 changes

The length L_1 has a greater impact on the transformer terminals than base insulators. When the conductor L_1 increases by 20 metres, the voltage at the terminals rises by 40 kV, whereas the voltage in base insulators decreases by 1 kV. In other words, terminals are able to withstand the voltage higher by 2 kV per metre of the conductor, whereas base insulators are able to withstand the voltage lower only by 0.05 kV.

3.2 L_2 variation with constant values for L_1 and L_3

The considered values are shown in Table 7.

Table 7. L_2 length variations

L_1	3 metres
L_2	From 1 to 3 metres
L_3	4.5 metres
L_4	1.5 metres

3.2.1 Voltage at power transformer terminals

Fig.10 illustrates the terminal overvoltage in three cases. The voltage data for each length is given in Table 8.

Table 8. Peak voltage values at power transformer terminals when L_2 changes

Overvoltage (kV)	Length L_2 (m)
- 399.3	1
-401.5	2
-404	3

> **The length between the surge arrester and the transformer has a greater impact on the transformer terminals than on the base insulators**

Typically, the length of the distance between the connection of the S_A and the power transformer is always as short as possible in order to reduce the terminal overvoltage. However, Fig. 11 shows that there is no significant variation in the voltage with the change in the length of the conductor that connects the SA with the line if L_1 is constant.

The reason for this small variation can be explained as follows. As illustrated in Fig. 7, the overvoltage that appears when L_1 is longer than 5 metres is remarkable. Taking into account that L_2 is 2 m in length, this gives the total distance of 7 m. So, the overvoltage changes considerably when the total distance exceeds 7 m. The total length of the distance between the S_A and the PT for this simulation was the sum of L_1 (equalling to 3 metres) and L_2 (which takes the value of 1, 2 or 3 metres). So, in this section, the distance was increased from 4 to 6 m, which is in the range of values where the voltage does not vary much (Fig. 7). The length to consider when installing a surge arrester is the total distance: $L_1 + L_2$.

3.2.2 Voltage at the base insulators

Fig. 12 illustrates the overvoltage at the base insulators in three cases. The voltage data for each length is presented in Table 9.

Although the voltage increases with the increase of L_2, this is nothing in comparison to the way the voltage changes with the change in L_1. The consequence of altering L_1 is much more evident than that occurring with the change in L_2.

Fig. 13 illustrates the overvoltage at the base insulators of surge arresters.

Although the voltage increases with the increase of distance L_2, this is nothing in comparison to the way the voltage changes with the change in distance L_1

There is no significant variation in the voltage with the change in the length of the conductor that connects the surge arrester with the line if the distance between the surge arrester and the transformer is constant

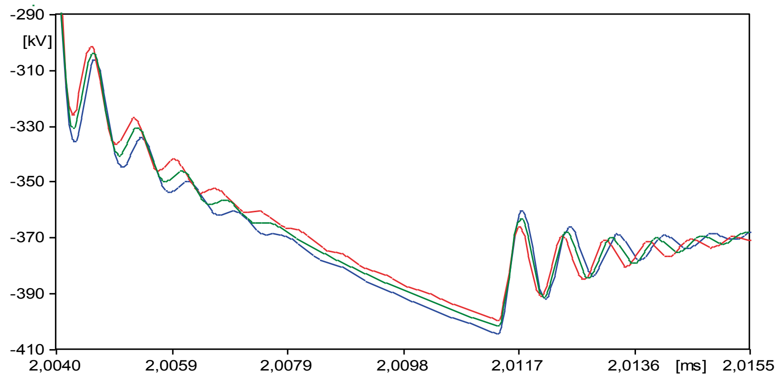

Figure 10. Transients in the voltage in terminals of power transformers when L_2 changes

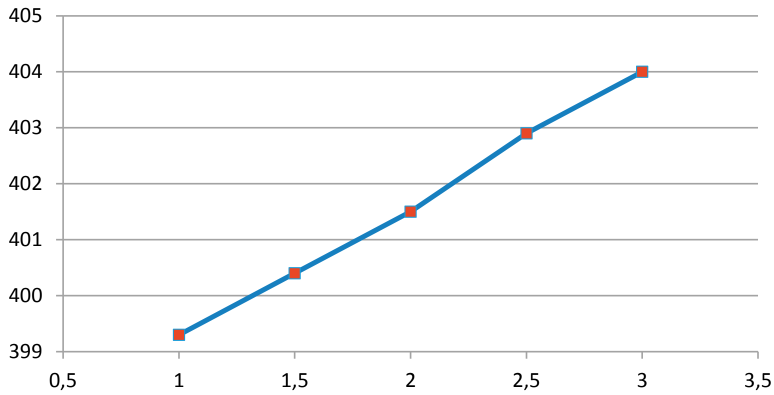

Figure 11. Voltage at power transformer terminals when L_2 changes

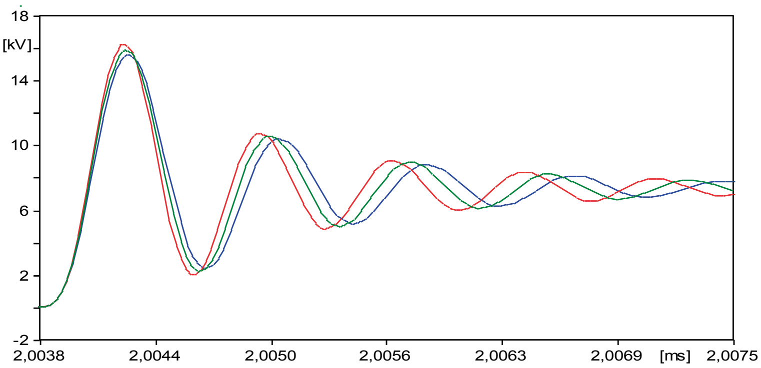

Figure 12. Transients in the voltage at the base insulators when L_2 changes

Table 9. Peak voltage values in the base insulators when L_2 changes

Overvoltage (kV)	Length L_2 (m)
16.26	1
15.9	2
15.6	3

The voltage at transformer terminals grows with an increase in L_2, while the voltage at the base insulators of surge arresters decreases

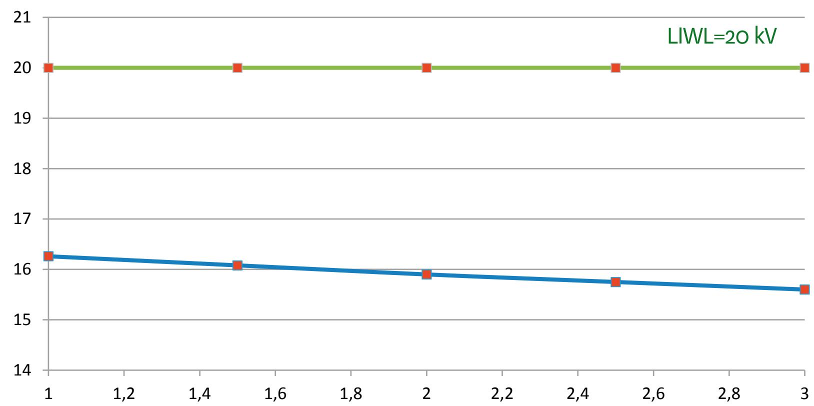

Figure 13. Voltage at the base insulators when L_2 changes

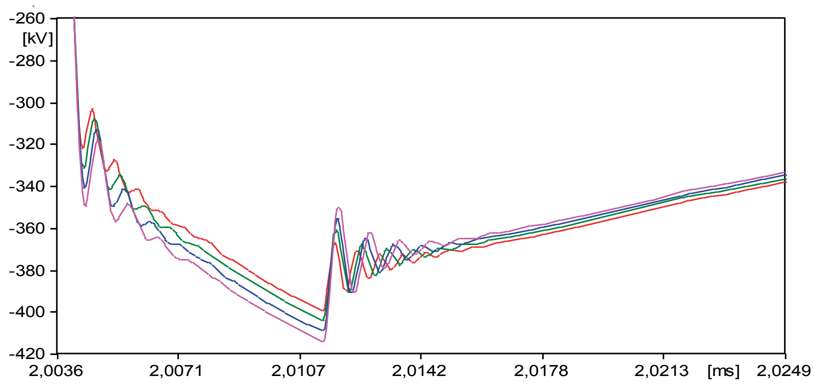

Figure 14. Transients in the voltage at power transformer terminals when L_3 changes

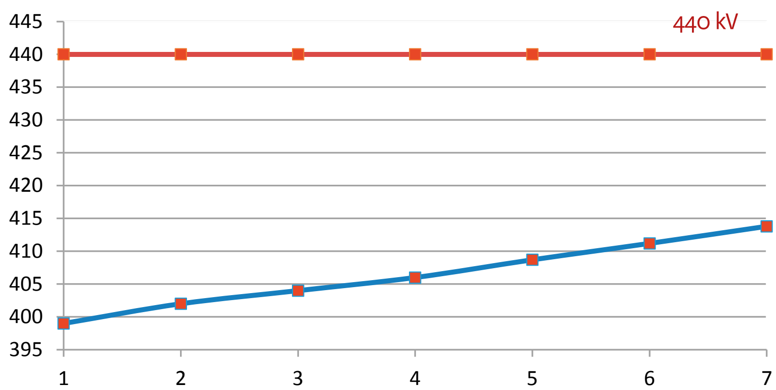

Figure 15. Voltage at power transformer terminals when L_3 changes

Although the voltage at the terminals does not change much, it will be demonstrated that in terms of the base insulators of the surge arresters, L_3 is the most important length

If there is an increase in L_2, the PT terminal voltage grows, while the voltage at the base insulators of SA decreases. However the difference is small.

3.3 L_3 variation with constant values for L_1 and L_2

The considered length values are shown in Table 10.

Table 10. L_3 length variations

L_1	3 metres
L_2	2 metres
L_3	From 1 to 7 metres
L_4	1.5 metres

3.3.1 Voltage at power transformer terminals

Fig. illustrates the terminal overvoltage in three cases. The PT bushings voltage data for each length is presented in Table 11.

Table 11. Peak voltage values at power transformer terminals when L_3 changes

Overvoltage (kV)	Length L_3 (m)
399	1
404	3
408.7	5
413.8	7

Fig.15 illustrates the overvoltage at power transformer terminals.

Although the voltage at the terminals does not change much, it will be demonstrated that in terms of the base insulators of the SA, L_3 is the most important length.

3.3.2 Voltage at the base insulators

Fig.16 illustrates the overvoltage at the base insulators in three cases. The voltage data of for each length is presented in Table 12.

Fig. 17 illustrates the overvoltage at the base insulators.

Table 12. Peak voltage values at the base insulators when L3 changes

Overvoltage (kV)	Length L_3 (m)
5.41	1
15.5	3
24.9	5
33.8	7

The bigger the length L_3, the greater the voltage drop at the terminals and base insulators. Therefore, it is advised to use a short distance for the grounding conductor. L_3 is the conductor which has the strongest impact on the voltage at the base insulators. If L_3 is longer than 5 metres, the base insulators of 25 kV LIWL will not withstand the overvoltage.

If the voltage was higher than the LIWL of insulators, the discharge current measured by the surge counter would be lower than the real one because part of it would pass through the base insulators.

4. RESULTS

The voltage in the bushings of power transformers and the voltage at the base insulators of surge arresters depends on the way the surge arresters are assembled. More specifically, it depends on L_1, L_2 and L_3 lengths.

The sections below explain the influence of each conductor length (L_1, L_2 & L_3) on each parameter (PT protection or insulators of SA protection).

Changing L_1 distance (L_2 and L_3 constants):

- With an increase in length, there is an increase in the overvoltage at PT terminals. According to the hypothesis taken in this study, at more than 25 m in length, the recommended MP is less than 20 %.
- With an increase in length, the voltage at the insulators of the SA decreases, but not significantly. In fact, terminals withstand the voltage higher by 2 kV per meter of the conductor, whereas base insulators withstand the voltage which is only 0.05 kV lower.
- In conclusion, L_1 **must be as short as possible.**

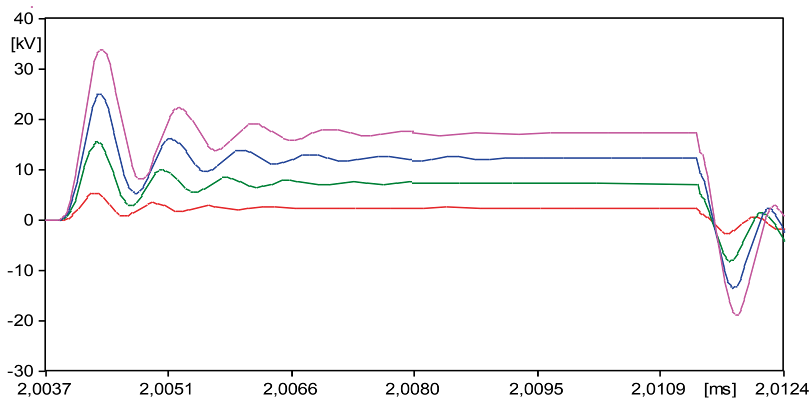

Figure 16. Transients in the voltage at the base insulators when L_3 changes

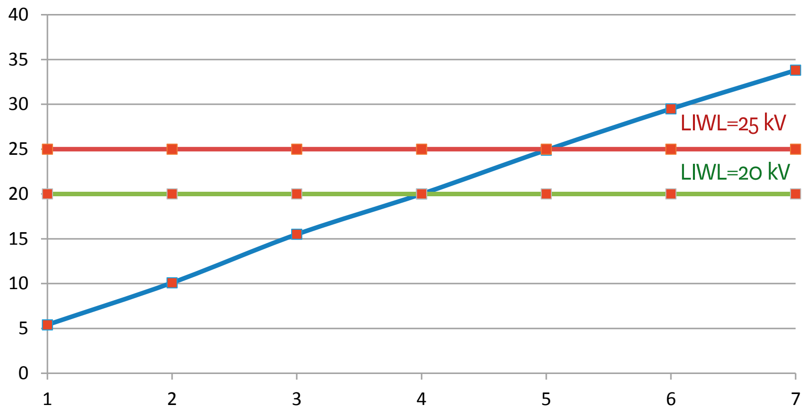

Figure 17. Voltage at the base insulators when L_3 changes

The bigger the length L_3, the greater the voltage drop at the terminals and base insulators; therefore, it is advised to use a short distance for the grounding conductor

A further analysis is required to consider deeper effects of L_3 on the wave shapes, peak values, etc. at the base insulators of surge arresters

Changing L_2 distance (L_1 and L_3 constants):

- With an increase in length, there is an increase in the voltage at PT terminals.
- With an increase in length, the voltage at the insulators of the SA decreases, but not significantly.
- The total length of the distance between the SA and the PT for this simulation is the sum of L_1 and L_2. Changing L_1 or L_2 modifies the total distance between the SA and the PT.
- **The sum of L_1 and L_2 must be as short as possible.**

Changing L_3 distance (L_1 and L_2 constants):

- With an increase in length, there is a slight increase in the voltage at PT terminals.
- With an increase in length, the voltage in the base insulators of the SA increases. In this case, variations in **length L_3 have the strongest impact on the voltage at the insulators. Also, the length has to be selected depending on the LIWL of the base insulators. It is important to highlight that the connection between the base and the surge counter is provided by the insulated cable, so manufacturers of surge arresters can provide assistance in selecting L_3.**

A further analysis is required to consider deeper effects of L_3 on the wave shapes, peak values, etc. at the base insulators of surge arresters.

5. CONCLUSIONS

Bearing in mind that the system commonly requires a 20 % margin protection, Table 13 provides a summary of the conclusions:

Table 13. Influence of the length of conductors on terminals and base insulators

Conductor variations (length or total length)	Impact on the overvoltage at the power transformers bushings	Impact on the overvoltage at the surge arresters base insulators
L_1	High	Negligible
$L_1 + L_2$	High	Negligible
$L_1 + L_2 + L_3$	High	--
L_3	Negligible **(for typical lengths of L_3)**	High

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Jesús Bernal holds a degree in electrical engineering and works with a major Spanish utility (Iberdrola). His work involves electrical studies, modelling and simulating AIS & GIS substations, power transmission lines, off-shore and on-shore wind farms, photovoltaic plants, etc. He has an extensive experience in developing insulation coordination studies and earthing grids design/calculations. In addition, he provides support to other parts of the projects: technical specifications of substation equipment and evaluation of technical offers for procurement procedures, substation design, etc.

A further analysis is required to consider deeper effects of L_3 on the wave shapes, peak values, etc. at the base insulators of surge arresters.

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