Lightning overvoltage and protection of power substations

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Abstract: - The protection of power substations against lightning overvoltages is critical for the reliable operation of the electrical network, since atmospheric surges frequently are liable for serious damages of equipment, resulting in power supply interruptions. Studies on the lightning performance of substations are necessary in order to calculate the expected overvoltages and take the appropriate measures. To this direction, in this paper analyses for the lightning overvoltage performance of HV/MV substations are performed, considering various factors, such as the grounding resistance, the installation position of surge arresters and the length of the underground cables. Main novelty of the current work is that the outcomes of the lightning performance study are presented separately for both direct lightning hits and backflashover, while the analyses take under consideration not only the grounding resistance (which is the common practice in similar studies) but also the cable length and the installation position of surge arresters. The obtained results can be useful for engineers and power utilities for the improvement of the lightning performance of already existed substations or for the more effective design of new ones.

Key-Words: - Cable; grounding resistance; lightning performance; substation; surge arresters; transmission line.

1 Introduction

The protection of high-voltage/medium-voltage (HV/MV) substations against atmospheric overvoltages and the improvement of their lightning performance are technical issues of great importance, since they are related to safe, uninterrupted and high quality power supply. HV/MV substations are critical parts of the electrical power system being the border between transmission and distribution system. The basic parts of a typical substation are the power transformers, the incoming overhead transmission lines, the cables, the circuit breakers, the current transformers, the disconnect switches and the ground switches. External overvoltages can cause several damages to a substation, leading to insulation breakdowns, a series of malfunctions, power interruptions and safety issues to the personnel [1-3]. Furthermore, lightning surges may also cause dangerous electromagnetic interference problems to low voltage systems and especially to electronic devices [4, 5]. Hence, the study of the lightning repercussions and the design of an appropriate lighting protection system for substations is a crucial issue, considering the complexity of those installations and their high investment cost.

The adoption of the appropriate protection measures according to the basic guidelines of the International Standard [3] can contribute to the limitation of the developed overvoltages and the reduction of the expected lightning faults. The design of a lightning protection system has to take into consideration the stochastic nature of the external overvoltages phenomena and the various techno economic factors and restrictions of a substation. The position of the lightning hit, the geometrical characteristics of the external lightning protection system, the grounding resistance and the basic insulation level (BIL) are parameters that affect the intensity of the lightning impact. In addition, the installation or not of surge arresters at various positions of the substations has a decisive impact on the magnitude of the developed overvoltages and, consequently, the expected outage rate [6, 7]. The protection of substations against the deleterious effects of lightning may be achieved by using highest insulation levels, taking into account the financial cost, or by installing overhead ground wires in order to intercept the lightning flashes [8-10]. The implementation of metal oxide gapless surge arresters can also contribute to the improvement of the lightning performance of the installation, especially in regions with high soil resistivity [11, 12].

Moreover, the incoming surges from the connected overhead transmission lines have to be considered. Considering that an external lightning protection system (overhead ground wires) combined with the achievement of low values of substation's grounding resistance offer an adequate protection against direct lightning hits, the incoming surges consist the main danger for the insulation of the installation. For this reason, the tower footing resistance has a key role for the lightning performance of the substation.

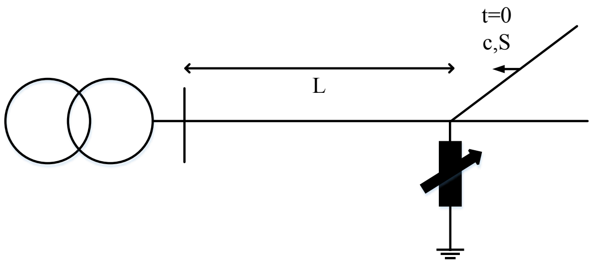
In the current work, overvoltages at different positions of a HV/MV substation are calculated, considering the role of the tower footing grounding, the length of the cable and the installation position of the arresters. The presented analyses concern lightning hits on the phase conductors and on the overhead ground wires of the connected transmission lines, considering that the external lightning protection system (LPS) of the substation protects adequately the substation against direct lightning hits. Compared with other similar studies, the current work reveals the important role of the length of the cable and examines different scenarios for the placement of the arresters. Scope of the current paper is to highlight that the lightning performance of the substations depends on various factors, apart from the grounding resistance.

2 Lightning protection of substations

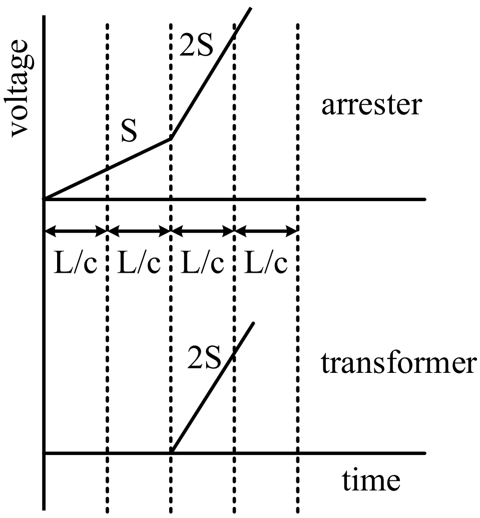
Lightning surges stress the insulation of the equipment and may result in tripping of the protective devices, destruction of critical parts of the substation and a general destabilization of the system. A risk management assessment has to be performed in order to predict the possible dangers and install the appropriate equipment restraining the lightning effects. A four-step procedure is suggested in [1] to intercept the lightning flashes evaluating the importance and the value of the under protection installation, investigating the keraunik level and the exposure of the substation, designing the lightning protection system according to an appropriate method and evaluating the effectiveness and the cost of the lightning protection system (LPS). The most widely used methods for the design of an effective external LPS are the fixed angles method, the empirical curves method and the electrogeometrical model [1, 3].

Furthermore, the lightning performance of a substation can be improved by installing surge arresters at critical positions of the system. The installation position of the arresters plays important role, due to the fact that overvoltages behave as travelling waves. Fig. 1(a) depicts an overvoltage running towards a transformer, assuming a propagation velocity equal to the speed of the light. The arrester presents an ideal behavior, limiting the desired residual voltage. Fig. 1(b) presents the overvoltages at the terminal ends of the arrester and the transformer. It must be mentioned that a voltage wave is totally reflected when reaching an unterminated end of a line. The voltage level at every instant and at every point on the line results from the sum of the different instantaneous values of each individual voltage wave, considering the refractions and reflections due to the changes of the surge impedance. A connected transformer behaves as an unterminated end, since its winding inductivity for fast voltage waveforms presents much higher impedance compared with the impedance of the line. Thus, at the terminated end this value will be doubled. This analysis highlights the importance of the installation position of the arrester, emphasizing the fact that the residual voltage across the arrester terminals may significantly vary from the developed voltage at the entrance of the transformer.

The effective protection offered by an appropriately designed LPS requires also the achievement of low grounding resistance values. A proper substation grounding system provides a path that diverts the fault currents to earth, without exceeding the dielectric withstand of the equipment; simultaneously, grounding system protects personnel against the dangers of electric shock under fault conditions [1, 3]. Basic part of the grounding system is the ground grid, consisted of conductors and rods. In addition, the grounding system includes all of the interconnected grounding facilities in the substation area, including the ground grid, overhead ground wires, neutral conductors, underground cables, etc. [1]. In general, the grounding resistance of HV substations is usually very low (lower than 1Ω) in order to ensure low touch and step potentials inside the substation. However, the tower grounding resistance of the connected overhead transmission lines varies, resulting in the development of dangerous incoming surges.



(a)



(b)

Fig. 1 (a) Power transformer protected by a surge arrester, (b) Developed overvoltages at the terminals of the arrester and the transformer (*S* is the steepness of the lightning surge, *c* is the light velocity, *L* is the distance between the transformer and the arrester)

3 System configuration

Fig. 2 pr esents the topology of the under study substation; a 150 kV single-circuit overhead transmission line is connected with a HV cable, in order to feed the power transformer (150/20 kV, 50 MVA). Each switchgear bay includes in practice the full complement of disconnecting switches (equipment isolation or current flow redirection), ground switches (personnel protection), instrument transformers (voltage and current measurement) and control and protection equipment (substation protection against short-circuit currents). A lightning hits either a phase conductor or an overhead ground wire at position A, considering that the majority of the substation's failures happen due to shielding failures or backflashover on the lines. The developed voltage surge travels through the conductor and the cable to the substation's transformer. The developed overvoltages at the joint position and at the terminals of the transformer are estimated. A sensitivity analysis is performed, considering the installation position of the arresters, the length of the underground cable and the tower footing resistance. The cross-section of the ACSR conductors of the overhead transmission line is 636 MCM. The insulators of the incoming line consist of ten ceramic discs, offering an insulation level of 750 kV. The overhead ground wires are installed in a way to protect the phase conductors against external overvoltages, according to the electrogeometrical model [13]. An overhead transmission line of 15 km is considered with the span between the towers to be equal to 300 m. Table 1 presents the electrical characteristics of the arresters, installed between phase and grounding system at joint between overhead line and underground cable and at the entrance of the power transformer.

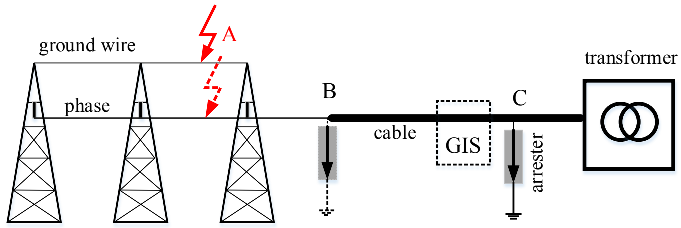


Fig. 2 System configuration

Table 1 Electrical characteristics of surge arresters

Maximum continuous operating voltage		86 kV
Rated voltage		108 kV
Residual voltage	5 kA	242 kV
	10 kA	254 kV
	20 kA	280 kV
	40 kA	313 kV
Energy capability		Class 3

The following sections present the results of the performed studies taking into consideration the installation position of the arresters, the tower footing resistance and the length of the cable.

In details, the distance between the transformer and the arrester is varied between 0 m and 60 m (0, 30, 60 m), the tower footing resistance is varied between 1 Ω and 25 Ω (1, 5, 10, 15, 20, 25 Ω) and the length of the cable is ranged between 300 m and 2000 m (300, 600, 1000, 2000 m). It must be mentioned that the grounding resistance of the substation is considered equal to 1 Ω.

4 Simulation results

4.1 Modelling of the substation's components

The transmission lines and the cable are represented by distributed parameter models, based on the Bergeron's traveling wave method. The towers are modelled according to equation [6]:

$$Z_r = 60 \ln\left(\cot\left(\frac{1}{2} tan^{-1}\left(\frac{r}{h}\right)\right)\right) \qquad (1)$$

where:
r is the tower base radius in m, and
h is the tower height in m.

When the developed overvoltage across the insulators of the line exceeds their dielectric strength, then a flashover is occurred. The flashover strength V_{FO} (kV) is determined by the voltage-time characteristic of the insulator strings, as follows [7, 8]:

$$V_{FO} = \left(400 + \frac{710}{t^{0.75}}\right) \cdot D \qquad (2)$$

where:
D is the insulator string length in m, and
t is the elapsed time after lightning stroke in μs.

For the representation of surge arresters the IEEE model is used [10, 11, 13]. As far as the grounding resistance concerns, it is represented as a lumped resistance. The lightning current is given by a double exponential equation:

$$i(t) = I \cdot (e^{-at} - e^{-\beta t}) \qquad (3)$$

where:
α, *β* are constants, dependent on the lightning current waveshape.

4.2 Overvoltages in case of direct lightning hit

In general, the substations are adequately protected against direct lightning hits, according to the methodologies and the electrogeometrical models, presented in section 2. Consequently, lightning surges that impinge on the overhead transmission lines that are connected with the substations are the main cause of overvoltage stresses of the insulation of the substations' equipment. In case that lightning hits directly the phase conductors of the transmission lines, two travelling waves appear the magnitude of which depends on the lightning peak current and the surge impedance of the conductors. The overvoltage wave will arrive at the entrance of the substation and can result in several serious damages of the components of the substations. It is worth mentioning, that the developed overvoltage is not influenced by the tower footing resistance and the unique protective measure is the installation of surge arresters. Moreover, the position of the lightning hit, the length of the cable, the characteristics of the implemented surge arresters, the position of the installation of the arresters and the grounding resistance of the arresters are critical factors that determine the efficiency of the lightning protection system and affect the lightning performance of the substation. If a surge arrester is installed between phase and earth of a transmission line, part of the lightning current will be diverted to the grounding system (Fig. 3), depending on the achieved grounding resistance. The low values of the grounding resistance ensure that almost the total current will pass through the arrester and the developed overvoltage will not exceed the insulation level of the system.

The current analysis is performed for the configuration of Fig. 2. A lightning of 35 kA hits a phase conductor of a 150 kV overhead transmission line. The developed voltage surge travels through the conductor and the cable to the substation's transformer (150/20 kV). The developed overvoltages at the beginning (position B) and the end (position D) of the cable are estimated, by using appropriate simulation tool.

Figs 3-5 depict the obtained results of the performed sensitivity analysis. The tower footing resistance has no influence on the expected overvoltages. As far as the length of the cable (BD) concerns the obtained results show that longer cables result in the reduction of the developed overvoltages. Furthermore, the installation position of the arresters is of great importance for the appropriate lightning performance of the substation. The increase of the distance between the arrester and the transformer reduces the effectiveness of the installed arresters, in a way that the overvoltage may exceed the BIL, depending on the other parameters, i.e., the magnitude of the surge, the grounding resistance and the length of the cable. Especially, in case of cables with length less than 1000 m the problem is more intense, since the initial surge is higher and a non-appropriately installed arrester will not protect the equipment. For this reason, the protection distance of the arresters has to be taken into consideration during the initial design of the installation and the selection of the characteristics of the arresters.

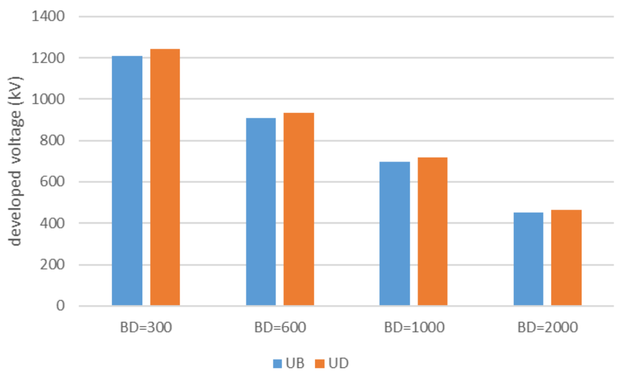


Fig. 3 The developed overvoltages at positions B (U_B) and D (U_D) in function with the length of the cable BD in case of lightning hit on phase conductor of the connected line (no arresters)

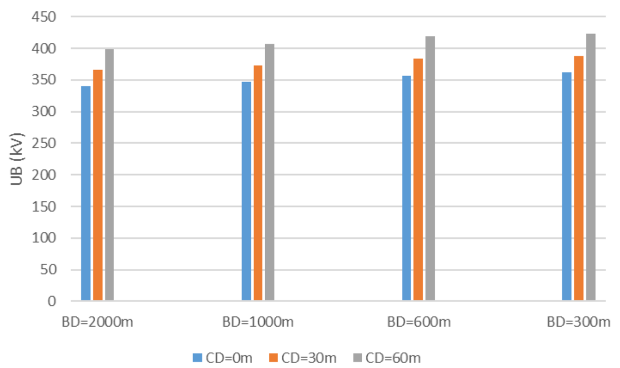


Fig. 4 The developed overvoltage at position B (U_B) in function with the distance CD and the cable length BD in case of a lightning hit on the phase conductor of the connected transmission line

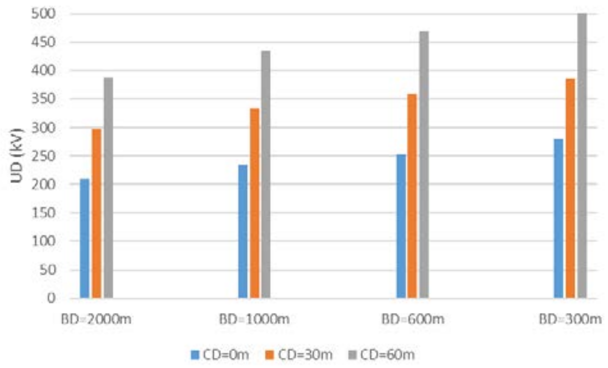


Fig. 5 The developed overvoltages at position D (U_D) in function with the distance CD and the cable length BD in case of a lightning hit on the phase conductor of the connected transmission line

4.3 Overvoltages in case of indirect lightning hit

When a lightning hits the ground wire or the tower of an overhead transmission line, the magnitude of the developed overvoltage depends on the tower footing resistance, the induction of the tower and the rise time of the injected lightning current (Fig. 6). If the overvoltage exceeds the insulation level of the line, a backflashover is occurred. The resulting surge propagates to the connected substation and can lead to serious malfunctions of the system. Backflashover at the connected transmission lines is a common reason of substations' equipment faults and damages.

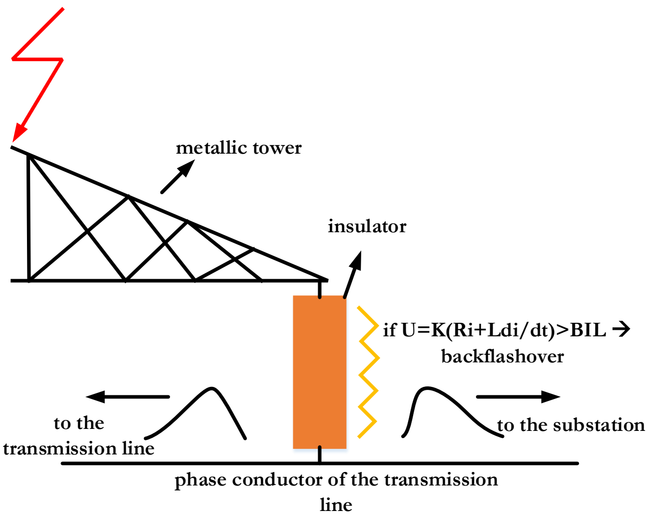


Fig. 6 Lightning hit on the metallic tower of an overhead transmission line

The lightning performance of the system can be improved by installing surge arresters in parallel with the insulators and at the primary side of the transformer (Fig. 7). Surge arresters divert the current of the lightning strike to earth and restrain the voltage at the terminals of the equipment below the BIL. The installation of metal oxide gapless surge arresters is necessary, otherwise the incoming voltage waves will stress the insulation of the equipment, resulting in faults and interruption of the normal operation of the substation.

A lightning of 200 kA hits the grounding wire of a 150 kV overhead transmission line. If the arising voltage exceeds the basic insulation level (750 kV) then a backflashover occurs [14, 15]. The developed voltage surges travel through the conductor and the cable to the substation's transformer (150/20 kV). The developed overvoltages at the beginning (position B) and the end (position D) of the cable are estimated, by using appropriate simulation tool. It is worth mentioning that the selected level of the injected lightning current is extremely higher compared to the considered one in case of direct hit, since according to the applied electrogeometrical model, high currents strike the towers or the overhead ground wires and low currents hit the phase conductors. A lightning current of 200 kA peak may create an overvoltage above the defined limit, influenced by the grounding resistance, the insulators and the implementation (or not) of arresters.

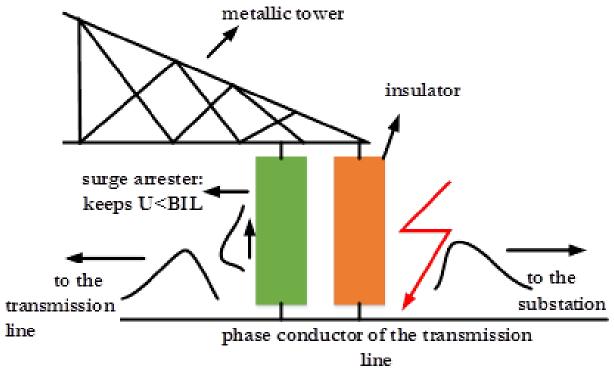


Fig. 7 Overhead transmission line protected by surge arresters

Figs 8-10 depict the calculated voltages in case that appropriate surge arresters have been installed. The achievement of low grounding resistance values is a decisive parameter, in order to ensure the adequate lightning protection of the substation. Surge arresters cannot offer the demanded protection level, if the grounding system is not appropriate. Consequently, the installation of surge arresters cannot always warrant the reduction of the expected overvoltages. The efficiency of the surge arresters is also reinforced by the length of the cable. The calculations show that the estimated overvoltages are strongly dependent on the distance (BD). In addition, the installation position of the arresters is of great importance, regarding the protective distance.

5 Discussion

Based on the obtained results several conclusions are extracted on the behavior of the substation in case that a lightning hits on the phase conductor of the connected overhead transmission line. Thus:

- The developed overvoltages at the end of the cable is greater than those ones at the beginning, due to the reflection phenomena of the traveling waves.

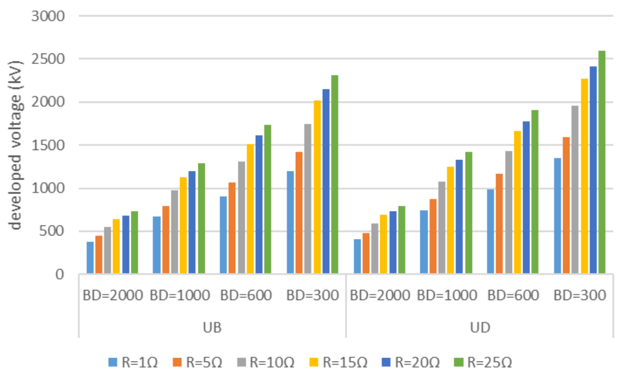


Fig. 8 The developed overvoltages at position B (U_B) and D (U_D) in function with the length of the cable BD and the tower footing resistance (R) (no arresters) in case of a lightning hit on the ground wire of the connected transmission line

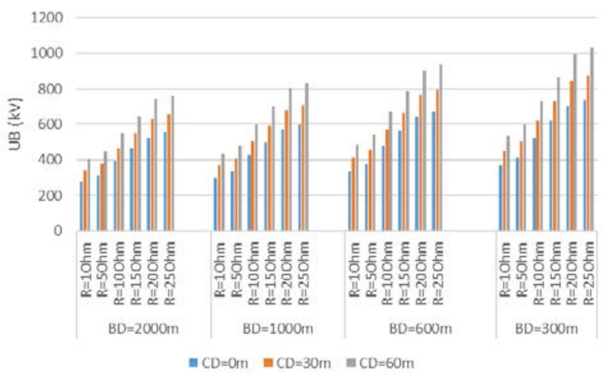


Fig. 9 The developed overvoltages at position B (U_B) in function with the installation position of the arresters CD, the tower footing resistance (R) and the cable length BD in case of a lightning hit on the ground wire of the connected transmission line

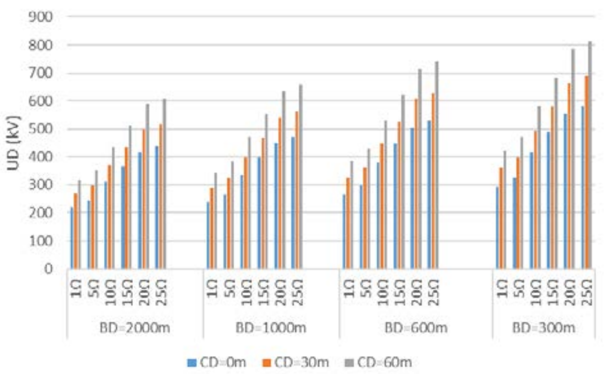


Fig. 10 The developed overvoltages at position D (U_D) in function with the installation position of the arresters CD, the tower footing resistance (R) and the cable length BD in case of a lightning hit on the ground wire of the connected transmission line

- The developed overvoltages are strongly dependent on t he length of the cable. Long cables present a better lightning performance.
- Tower footing resistance has no influence on the expected overvoltages.
- The arresters should be installed near transformer, otherwise the voltage at the equipment to be protected will be considerably higher than the residual voltage at the terminals of the arrester.

The case of a lightning that hits on the tower or the ground wires of the connected transmission line is considered a serious threat for the safety and the normal operation of the substations. The appropriate protection against backflashover phenomena requires the knowledge of the expected surges, in order to design the lightning protection configuration and select the electrical characteristics of the protective means. To this direction, the performed analyses highlight various aspects that the designers should take into account during the initial study of the lightning protection system of the substation, such as:

- Low values of tower footinig resistance always improve the lightning performance of the line; low tower footing resistances do not allow the potential of the tower to exceed the BIL and prevents backflashover.
- Long cable lengths contribute to the reduction of the expected overvoltages. Especially, in case that the tower footing resistance cannot be improved, the increase of the cable length can balance the negative effects of the inadequate grounding system.
- The protective distance of the installed arresters depends on the steepness of the incoming surge and the nominal protection level of the device. The installation of the arresters far away from the equipment to be protected reduces their efficiency, resulting in the development of significant overvoltages higher than the nominal residual voltage of the arresters.

6 Conclusions

The paper presents studies on t he lightning overvoltage performance of HV/MV substations in order to contribute in their more effective lightning protection. In addition to the grounding resistance that previous studies take into consideration, the current work considers also other important factors such as t he installation position of surge arresters and the length of the underground cables. It is proved that both of those factors influence significantly the lightning performance of HV/MV substations. Furthermore both direct lightning hits and backflashover phenomenon are considered in the studies. The obtained results can be very useful to engineers and power utilities for the improvement of the lightning performance of already existed HV/MV substations or for the more effective design of new ones.

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