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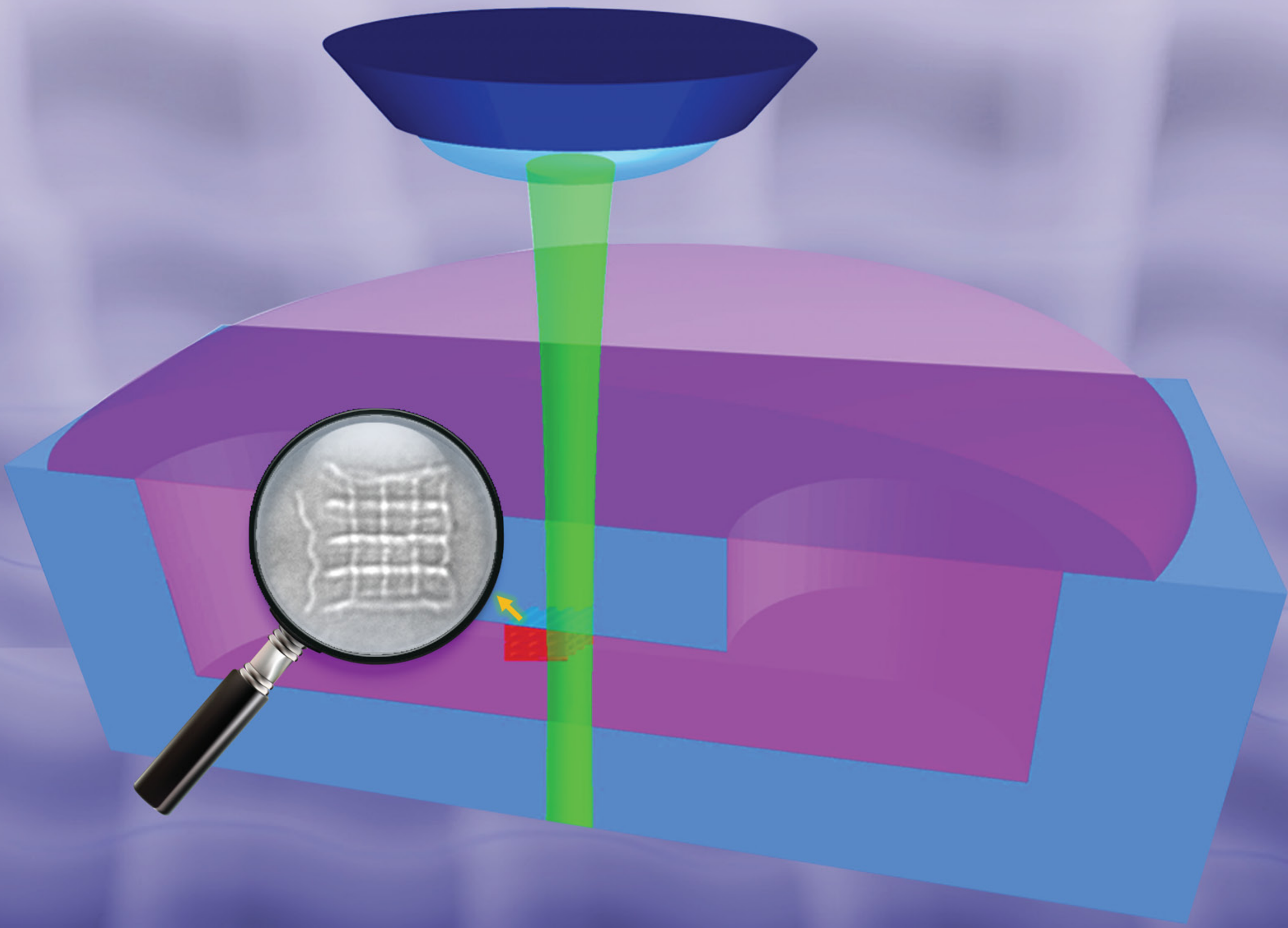

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Article

A Heuristic Method for the Reduction of the Outage Rate of High-Voltage Substations Due to Atmospheric Overvoltages

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Abstract: The adequate protection against lightning surges and the limitation of the expected annual failure rate of high-voltage substations are critical issues, in an effort to secure the safety of the equipment and the personnel. Various factors affect the lightning performance of the substations, determining the developed lightning surges and the expected outage rate, i.e., the grounding resistance, the length of the underground cable between the connected overhead transmission line and the power transformer, and the installation position of the arresters. In the current work, a heuristic method is developed to adjust different parameters of high-voltage substations that upgrade their lightning performance. The proposed methodology can be useful to the studies of substations' designers and engineers, contributing effectively in the reduction or/and elimination of lightning failures.

Keywords: substations; lightning; arresters; grounding resistance

1. Introduction

The lightning performance of high-voltage substations is primarily concerned with the distribution and transmission network operators, since lightning surges contribute to the dielectric stress and the ageing of the insulation. This can lead to failures of the various components of the substations, may result in interruption of the power supply, and are related to dangerous repercussions for the safety of the equipment as well as the personnel [1]. Thus, for the above reasons as well as for reliability issues, it is becoming an increasingly common requirement the improvement of the lightning performance of high-voltage substations and the reduction of the lightning failure rate.

The design of the lightning protection system of high-voltage substations intends to limit the expected outages of substantial equipment of the substations due to lightning overvoltages. It is worth noting that in the case of gas-insulted substations, the severity of the potential consequences due to a lightning overvoltage is more intense, compared to air-insulated substations, considering the repair or/and replacement cost [2]. The combination of an external lightning protection system with surge arresters at the entrance of the substation is the common practice for the reduction of the lightning faults [3–5]. However, various factors influence the protection level and the effectiveness that the applied protective measures provide such as the lightning hit position, the length of the underground cables for the connection of the incoming transmission line and the transformer, the number and the placement of the surge arresters, the grounding resistance. These are parameters that determine the range of the arising surges and have a great impact on the lightning performance of the substations. In [6] the lightning performance of an air-insulated substation that connects a hydro power plant with network is presented, considering different overvoltage protection schemes. The influence of various parameters (i.e., surge front times, soil resistivity, distance of the cable that connects the transformer and the busbar) on the lightning performance of a combined overhead line/cable connected gas-insulated substation is examined in [7], since the role of the earth grid is revealed in [8]. Moreover, the adequate number and the appropriate placement of a surge arrester is also crucial in attempts to upgrade the lightning performance of the power substations [9–12].

In the current work, a method is developed for the design of high-voltage substations intending to improve their lighting performance. A heuristic method is used in order to adjust the critical factors of high-voltage substations that determine their lightning performance, in an effort to reduce the substation's outage rate. The developed method provides the most efficient configuration for the proper planning and developing of high voltage/medium voltage substations, considering the tower footing resistance (TFR), the length of the underground cable that connects the line with the transformer, and the installation position of the arresters, in order to keep the lightning outage rate below a defined threshold. The developed method can be proved useful to power utilities, in order to design or upgrade high-voltage substations and reduce the expected annual lightning failure rate.

2. Protection of High-Voltage Substations against Lightning Surges

Despite the fact that power systems operate mainly in the steady state, they have to withstand and handle overvoltage and overcurrent stresses generated during transient conditions. It is worth noting that the dimensioning of the equipment is dictated by the expected magnitude and the duration of the arising surges. Consequently, the efficient design of a power network in order to transfer and deliver electric power of high quality and reliability, requires a thorough understanding of its transient behavior [1,13]. The installation of an external lightning protection system, according to the electrogeometrical model [3–5,14], is the most common method to protect the substation against direct lightning hits. Accepting the efficiency of the installed external lighting protection system, atmospheric overvoltages that impinge on the connected high voltage line comprise the main reason of insulation faults, degrading the normal operation of the system. The severity of the developed surges in substations is determined by the magnitude and the waveform of the surges impinging on the substation from the connected overhead line, considering the travelling wave behavior of the arising surges. In the case that no surge arresters are installed, the amplitude of the impinging surges is the most important factor, since the slope of the surge and the installation position of the arrester have to be considered, in the case that arresters are used for the protection of the system.

A direct lightning strike to the phases of the incoming high voltage line results in the development of two equal travelling waves that propagate in opposite directions; the prospective magnitude of these overvoltages is determined by the peak value of the lightning current and the surge impedance of the phase conductors. The overvoltage wave that arrives at the entrance of the high voltage substation can cause serious damages of the equipment, leading to interruption of the power supply. It is worth noting, that, in the case of a direct lightning hit, the arising overvoltages are not influenced grounding resistance of the towers, so the installation of surge arresters is the most effective protective measure [15]. Modern metal oxide gapless surge arresters are gapless, consisting of ZnO nonlinear resistors. A prerequisite for the efficient operation of the arresters is a grounding system of low earthing resistance to avoid the development of overvoltages higher than the basic insulation level of the system. Added to this, the appropriate placement and the electrical characteristics of the surge arresters and the lightning hit position are crucial parameters that determine the lightning performance of the substation [16–20].

When lightning strikes the tower or the overhead ground wire of a high voltage line, the overvoltage that arises is a function of the peak value and the slope of the lightning current, the TFR and the induction that the metallic tower presents. The arising surge voltages propagate to the high voltage substation and pose a significant threat to the normal operation of the system. If the magnitude of the developed overvoltage becomes greater than the insulation level of the line, a backflashover occurred; the risk of a backflashover can be limited by reducing the earthing resistance of the tower [21]. Of special interest in respect of insulation assessment and protection are the power transformers, which may be subjected to impulse stresses of high magnitude. To this direction, in order to protect the equipment of the substation, surge arresters are installed at critical positions of the system. Even for overhead lines that are adequately protected by ground wires, the avoidance of backflashover, near the substation, is an issue of priority in an effort to determine the installation position and the number of the demanded surge arresters to accomplish insulation coordination of the substation. As far as the behavior of the metal-oxide gapless surge arresters is concerned, high impulse currents that pass through them may cause thermal instability of the nonlinear resistor, resulting in damage of the arrester that cannot provide protection.

3. Calculation of the Outage Rate

The outage rate of the substation in the case of a lightning hit to a phase, R_{ph} (outages/year), is given as [22]:

$$R_{ph} = R_{P,ph} \cdot [P(I_{cr,SF}) - P(I_{m,SF})] \quad (1)$$

where:

- $R_{P,ph}$, the shielding penetration rate of the connected line within the limit distance,
- $P(I_{cr,SF})$, the probability that corresponds to the current that causes a line insulation flashover at negative polarity,
- $P(I_{m,SF})$, the lightning current probability that corresponds to the maximum shielding current.

The shielding penetration rate (shielding failures/year) is calculated according to procedures presented in [18,23,24]. The currents $I_{cr,SF}$ and $I_{m,SF}$ that correspond to the above probabilities can be extracted from the lightning stroke current probability distribution, concerning the shielding failure range, according to [19,23,25,26]. The probability $P(I)$ of lightning crest current being greater than I is computed as following [23,26]:

$$P(I) = \frac{1}{1 + \left(\frac{I}{31}\right)^{2.6}} \quad (2)$$

The limit distance is calculated according to the procedure presented in Annex F of [22], depending on the lowest considered overvoltage amplitude, the longest travel time between any point in the substation to be protected and the closest arrester, the lightning impulse protective level of the arrester and corona damping effects.

When a lightning hits the overhead ground wire of the connected high voltage line, the outage rate of the substation, R_{gw} (outages/year), is given as [24]:

$$R_{gw} = 0.6 \cdot R_{p,gw} \cdot P(I_{cr.BF}) \quad (3)$$

where

- $R_{p,gw}$, the rate of lightning strokes to the overhead ground wires of the connected transmission line within the limit distance (strikes/year) [22], and
- $P(I_{cr,BF})$, the probability corresponding to the current striking to the overhead ground wires resulting in the overvoltages that exceed the insulation withstand capability of the system [22,25,26].

Considering the above equations, the total substation outage rate, R (outages/year) is given as:

$$R = R_{ph} + R_{gw} \tag{4}$$

4. System Under Examination

Figure 1 depicts the configuration of a 150/20 kV substation. The length of the overhead transmission line is regarded equal to 15 km and the span between the metallic towers is 300 m. In addition, the resistance of the substation grounding system is regarded constant, equal to 1 Ω. Furthermore, a safety factor of 1.15 has been adopted (safety factor = Basic Insulation Level/protective level), according to [22]. Table 1 presents the electrical characteristics of the basic components of the substation under study.

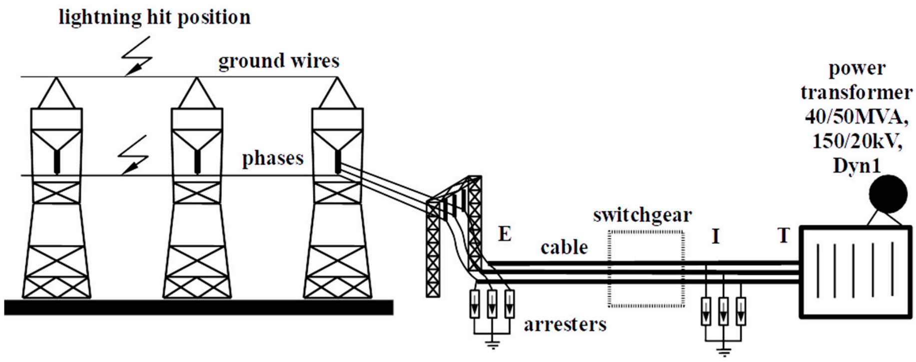

Figure 1. Configuration of the substation under study (E: entrance of the substation, I: intermediate position, T: transformer).

Table 1. Electrical characteristics of the equipment.

Surge Arresters		
U_c		86 kV
U_r		108 kV
U_{res}	5 kA	242 kV
	10 kA	254 kV
	20 kA	280 kV
	40 kA	313 kV
Energy capability		Class 3
Conductors of the Transmission Line		
Type		ACSR
Cross section		636 MCM
Nominal current		795 A
Cable		
Insulation		XLPE
External layer		PVC
Conductor cross-section		800 mm^2
Nominal current		840
BIL		750 kV

The transmission lines and the cable are modeled according to the Bergeron's traveling wave method [27]. Figure 2 depicts the geometry of a typical tower of a 150 kV transmission line. The towers are modeled according to equation [28]:

$$Z_r = 60 \ln\left(\cot\left(\frac{1}{2}\tan^{-1}\left(\frac{r}{h}\right)\right)\right), \tag{5}$$

where

- r, the radius of the tower base (m), and
- h, the height of the tower (m).

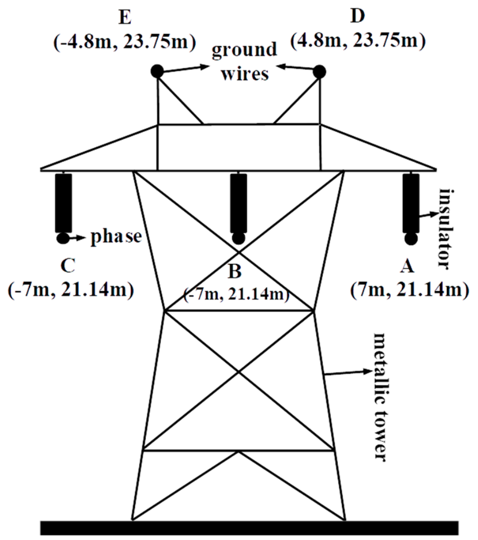

Figure 2. Tower of 150 kV transmission line.

The development of an overvoltage greater than the dielectric strength of the insulators of the line results in a flashover. The flashover strength V_{FO} (in kV) is given as follows [17,29]:

$$V_{FO} = \left(400 + \frac{710}{t^{0.75}}\right) \cdot D \tag{6}$$

where

- D, the length of the insulator string (m), and
- t, the elapsed time after lightning stroke (μs).

Surge arresters are modeled according to the Pinceti-Giannettoni model (Figure 3) [30,31], considering their electrical characteristics for the computation of the parameters of the equivalent circuit.

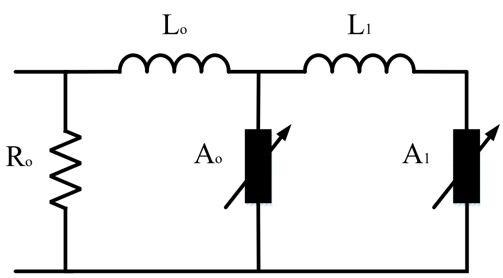

Figure 3. The Pinceti–Giannettoni Model [30,31].

Finally, the grounding resistance is modeled according to the following equations, considering the soil ionization due to lightning current [18]:

$$R(I) = \frac{R_o}{\sqrt{1 + \frac{I}{I_g}}} \tag{7}$$

$$I_g = \frac{1}{2\pi} \cdot \frac{E_o \cdot \rho}{R_o^2} \tag{8}$$

where

- $R(I)$, the grounding resistance,
- R_o, the low current of grounding resistance,
- I_g, the limiting current to initiate sufficient soil ionization, and
- ρ, the soil resistivity.

5. The Impact of Various Factors on the Lightning Performance of High-Voltage Substations

In this section, the impact of various factors on the expected failure rate of the substation depicted in Figure 1 is examined. A lightning flash strikes either a phase (shielding failure) or an overhead ground wire (backflashover) of the incoming transmission line, taking into consideration that the substation is adequately protected against direct lightning strokes. Note, that lightning strikes the second-to-last metallic tower near the substation. The performed sensitivity analysis considers the installation position of the arresters, the length of the underground cable and the TFR.

Table 2 depicts the substation outage rate when a lightning hits a phase conductor of the connected overhead transmission line. It must be noted that the terminal tower is bonded to the grounding system of the substation and that the TFR does not influence the outage rate for a lightning stroke to a phase conductor. The results reveal the upgrade of the lightning performance of the examined substation that metal oxide surge arresters provide and emphasizes the impact of the installation position of the arresters and the length of the cable.

Table 2. R_{ph} in function with the cable length and the installation position of the arresters.

Cable Length (ET)	No Arresters	Distance between Position I and T	
		0 m	20 m
0.2 km	0.04718	0.00042	0.00154
1 km	0.03504	0.00035	0.00107
2 km	0.03126	0.00028	0.00102

Table 3 presents the results obtained considering a lightning stroke to the ground wire of the connected overhead transmission line. The computed outage rate indicate that low TFR values reduce the probability of a backflashover. Moreover, long cables provide high protection against the incoming surges and contribute to the decrease of the expected failure rate. In addition, the installation of surge arresters near the equipment is required for the upgrade of the lightning performance of the substation. Note that for long cables and arresters installed at the high voltage wirings of the power transformer, R_{ph} is almost eliminated.

Table 3. R_{gw} in function with the TFR, the cable length and the installation position of the arresters.

	Cable Length (ET)								
	0.2 km			1 km			2 km		
	Distance between Position I and T								
TFR	No Arresters	0 m	20 m	No Arresters	0 m	20 m	No Arresters	0 m	20 m
1 Ω	0.0054	0.00061	0.00214	0.00411	0.00041	0.00154	0.00915	0.00044	0.00161
5 Ω	0.0165	0.00188	0.00589	0.01653	0.00124	0.00892	0.01647	0.00131	0.00446
10 Ω	0.0250	0.00294	0.09732	0.02204	0.00206	0.01380	0.02196	0.00218	0.00841
20 Ω	0.0429	0.00548	0.01905	0.03847	0.00372	0.02584	0.03836	0.00393	0.01591
30 Ω	0.0586	0.00704	0.02341	0.04398	0.00495	0.03294	0.04285	0.00524	0.01945

Table 4 presents the total substation outage rate.

The extracted outcomes prove the upgrade of the lightning performance of the system, after the installation of surge arresters, revealing, simultaneously, the effect of the TFR (that determines the occurrence or not of backflashover phenomena), the installation position of the arresters and the length of the cable. The installation of the arresters close to the power transformer and the use of long HV XLPE cables reduce the failure rate, even for high values of the TFR values.

Table 4. R in function with the TFR, the cable length and the installation position of the arresters.

	Cable Length (ET)								
	0.2 km			1 km			2 km		
	Distance between Position I and T								
TFR	**No Arresters**	**0 m**	**20 m**	**No Arresters**	**0 m**	**20 m**	**No Arresters**	**0 m**	**20 m**
1 Ω	0.0524	0.00103	0.00368	0.03911	0.00076	0.00308	0.04014	0.00071	0.00264
5 Ω	0.0635	0.00230	0.00743	0.05153	0.00158	0.01047	0.04746	0.00158	0.00548
10 Ω	0.0720	0.00336	0.09886	0.05704	0.00241	0.01534	0.05295	0.00246	0.00944
20 Ω	0.0899	0.00590	0.02059	0.07347	0.00406	0.02738	0.06935	0.00420	0.01693
30 Ω	0.1056	0.00746	0.02495	0.07898	0.00530	0.03448	0.07384	0.00551	0.02047

Table 5 depicts the substation outage rate (R) in the case that the distance between the positions I and T is zero ($IT = 0$ m), assuming that in the majority of the substations (especially for new ones) the arresters are directly connected with the power transformer. Nevertheless, in older substations, arresters implemented away from the equipment to be protected can be met. By regarding R equal to 0.005 as an acceptable value by the power utilities (that corresponds to mean time between failures equal to 200 years), it is obvious, that the compliance with the above limit ($R = 0.005$) is not always attainable, for short cables and high grounding resistances, even if the arresters have been installed near the power transformer.

Table 5. R in function with TFR and the length of the cable for IT = 0 m.

TFR	Cable Length (ET)		
	0.2 km	**1 km**	**2 km**
1 Ω	0.00103	0.00076	0.00071
5 Ω	0.00230	0.00158	0.00158
10 Ω	0.00336	0.00241	0.00246
20 Ω	0.00590	0.00406	0.00420
30 Ω	0.00746	0.00530	0.00551

6. Heuristic Method for the Upgrade of the Lightning Performance of High-Voltage Substation

The analysis presented in the previous sections reveals that the adjustment of the parameters that influence the expected failure rate of the substation, in a technically and financially affordable way, is vital for power utilities, in order to enhance the lightning performance of the substations and increase the reliability of the electrical network. To this direction, an appropriate method is developed to select the arresters' installation position, the cable length and the TFR that ensure that the substation outage rate will not exceed the defined acceptable restriction. Figure 4 illustrates the flow-chart diagram of the proposed methodology. The developed algorithm includes the following steps:

Step 1: data input (number of towers, span length, type of tower, geometrical characteristics of towers, BIL, conductors' cross section of the transmission line, TFR of each tower, cable length, conductors' cross section of the cable, electrical characteristics of power transformer, electrical characteristics of surge arresters, installation position of surge arresters, characteristics of lightning current).

Step 2: calculation of R according to the procedures presented in Section 3.

Step 3: if $R < 0.005$ then end, else go to the Step 4.
Step 4: set IT equal to zero and recalculate R.
Step 5: if $R < 0.005$ then end, else go to the Step 6.
Step 6: Set the grounding resistance of the towers (except from the first tower near the substation) equal to 80% of its initial value and recalculate R.
Step 7: if $R < 0.005$ then end, else go to the Step 8.
Step 8: Set the cable length equal to 200% of its initial value in the case that 300 m $< ET \leq$ 400 m or equal to 165% of its initial value in the case that $400 < ET \leq 600$ or equal to 135% of its initial value in the case that 600 m $< ET \leq$ 1000 m and recalculate R or equal to 117% of its initial value in the case that 1000 m $< ET \leq$ 1500 m and recalculate R or equal to 108% of its initial value in the case that 1500 m $< ET \leq$ 2000 m and recalculate R.
Step 9: Calculation of R, then end.

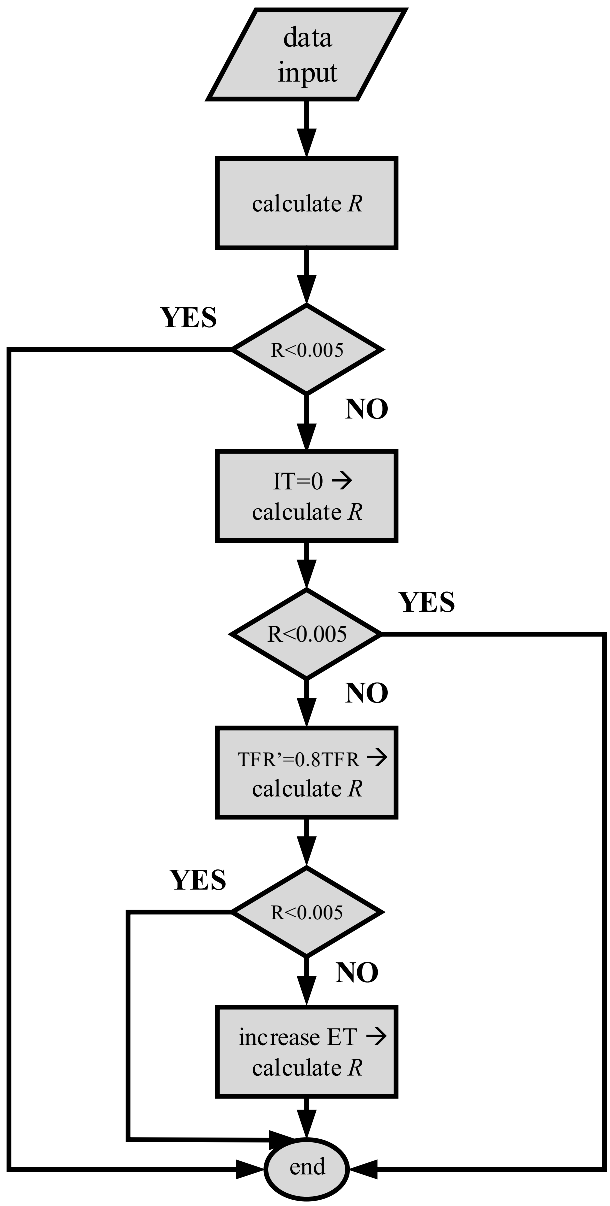

Figure 4. Flow chart diagram of the developed heuristic method.

The proposed first reformative adjustment is the installation of the arresters near the equipment to be protected (IT = 0 m), considering that this modification is effective, technically easy and low-cost. If the compliance of the substation outage rate (R) with the defined limit is not achieved, a reduction of 20% of the TFR is imposed, considering technoeconomical criteria, since further improvement of the grounding resistance can be technically difficult and uneconomical. The increase of the length of the underground cable is the last corrective action to improve the lightning performance of the substation, since the extension of the installed underground cable and the abolishment of tower is a challenging work. The percentage increase for each cable length area is determined considering the topology of common substations, the cost of the cable installation (including the cost of the cable per km, the joints, the labor cost), and the need for reconfiguration of the system. Even if R is greater than 0.005 in Step 9, the procedure is completed, since further reduction of the grounding resistance or increase of the cable length is disadvantageous (in cost–benefit terms).

The presented algorithm is applied for different scenarios; Table 6 presents the calculated results before and after the application of the proposed method, considering four cases.

Table 6. Obtained results before and after the application of the proposed algorithm.

Case		IT (m)	TFR (Ω)	ET (m)	R	Case		IT (m)	TFR (Ω)	ET (m)	R
1	*before*	0	25	1000	0.0052	5	*before*	0	25	2000	0.0057
	after	0	20	1000	0.0040		*after*	0	20	2000	0.0042
2	*before*	45	17	300	0.0310	6	*before*	45	32	500	0.0590
	after	0	13.6	600	0.0044		*after*	0	20.5	675	0.0041
3	*before*	45	25	300	0.0470	7	*before*	15	21	800	0.0140
	after	0	20	600	0.0048		*after*	0	16.8	800	0.0034
4	*before*	0	20	300	0.0055	8	*before*	0	35	400	0.0081
	after	0	16	300	0.0045		*after*	0	20	540	0.0048

The improvement of R definitely proves the effectiveness of the proposed methodology. Figure 5 presents the percentage reduction of the outage rate for each examined case. The application of the proposed algorithm upgrades the lightning performance of the substation and reduces the expected annual number of fault up to 92%. In conclusion, the current work provides a design tool for the protection of brand new or already existing substations that is easy to use and produces adequate reliable results, based on both technical, practical and economic criteria, appropriate to foresee and prevent possible dangers due to atmospheric overvoltages before they arise.

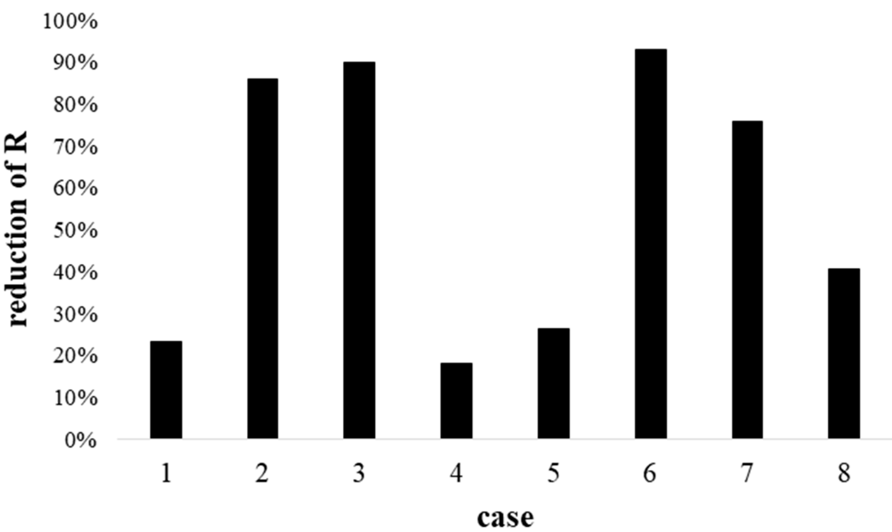

Figure 5. Percentage reduction of substation outage rate (R) for each examined case.

7. Discussion

The presented heuristic method is proven to be advantageous for the effective design of the lightning protection system of high-voltage substations, where the reliability requirements are at a premium. The application of the developed methodology for different scenarios gives efficient results, balancing both technical and financial parameters. In order to assist in the planning of insulation coordination of power systems, the developed methodology provides an easy-to-use procedure for determining appropriate insulation parameters in relation to the electrical characteristics of the equipment. The extracted outcomes improve the lightning performance of the substation, confirming the usefulness of the method, which can prove to be a valuable tool for the studies of electric power system designers. The method proposes, step by step, the most technically convenient and low-cost solutions for the reduction of the outage rate, giving a tool for the appropriate design of new substations or the improvement of the existing substation. The presented results prove the upgrade of the lightning performance of the high-voltage substation, after the implementation of surge arresters at various positions, emphasizing the great importance of the TFR and the length of the high voltage cable. The achievement of low TFR can reduce the probability of a backflashover. Therefore, ensuring the enhancement of the lightning performance of the substation is a desired goal, but not always feasible. In this case, arresters installed close to the equipment to be protected and long high voltage cables contribute to the reduction of the outage rate, even for high TFR.

8. Conclusions

More and more network operators have sharpened their focus on lightning protection of high-voltage substations, facing the challenge of ensuring high power supply reliability and at minimizing the costs for repair/replacement of equipment at the same time. Indeed, lightning issues continue to be an important area for safe development of power systems, since the extent of the lightning faults and the consequences deriving from them can cause serious damages to the equipment of the networks. Considering the above, novel and more efficient design methods are progressing in order to meet higher safety standards and demands. However, utilities need to balance these requirements for adequate protection against lightning with both practical and financial constraints. Each of these goals are not necessarily complimentary, thus utilities need to determine how to address each one. To this direction, a heuristic method is developed in the current work for the reduction of the outage rate of high-voltage substations due to lightning overvoltages, considering the impingement of various factors. The proposed method gives a comprehensive tool to adjust critical parameters of high-voltage substations in an effort to reduce the lightning failures. Insofar as the method seeks to provide attainable configurations of the power substations, practical issues and the cost of the design solutions have to be considered. A distinguishing feature of the proposed method is the consideration of technoeconomical restrictions according to the common practice of the power utilities, extracting reliable and realistic solutions. The developed method is flexible, since users can define the limitations and the way that the parameters change, according to the demands of the utility. The method focuses on identifying the most technically efficient solutions improving the lightning performance of high-voltage substations, without compromising the reliability or jeopardizing the quality of the power supply at a reasonable cost.

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Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Laughton, M.A.; Warne, D.J. *Electrical Engineer's Reference Book*, 16th ed.; Elsevier Science: Great Britain, UK, 2003.

2. Nagarsheth, R.; Singh, S. Study of gas insulated substation and its comparison with air insulated substation. *Electr. Power Energy Syst.* **2014**, *55*, 481–485. [CrossRef]
3. Weck, K.H. Lightning performance of substations. In Proceedings of the CIGRE, SC 33, Rio de Janeiro, Brazil, 12–17 July 1981.
4. Grigsby, L.L. *Electric Power Engineering Handbook*; CRC Press: Boca Raton, FL, USA, 2000.
5. McDonald, J. *Electric Power Substations Engineering*, 3rd ed.; CRC Press: Boca Raton, FL, USA, 2006.
6. Franc, B.; Filipovic-Grcic, B.; Milardic, V. Lightning overvoltage performance of 110 kV air-insulated substation. *Electr. Power Syst. Res.* **2016**, *138*, 78–84. [CrossRef]
7. Kessel, A.; Atlason, V.; Bak, C.L.; Lund, J. Lightning simulation of a combined overhead line/cable connected. In Proceedings of the 29th International Conference on Lightning Protection, Uppsala, Sweden, 23–26 June 2008; paper 6a-6-1.
8. Bak, C.L.; Einarsdottir, K.E.; Andresson, E.; Wiechowski, W. Overvoltage Protection of Large Power Transformers—A Real-Life Study Case. *IEEE Trans. Power Deliv.* **2008**, *23*, 657–666. [CrossRef]
9. Hosseini, S.A.; Mirzaie, M.; Barforoshi, T. Impact of surge arrester number and placement on reliability and lightning overvoltage level in high voltage substations. *Electr. Power Energy Syst.* **2015**, *65*, 146–158. [CrossRef]
10. Lee, H.; Yoon, D.H.; Lee, S.R.; Yang, B.M.; Jang, G. The insulation coordination and surge arrester design for HTS cable system in Icheon substation. *Physica* **2013**, *484*, 223–228. [CrossRef]
11. Trainba, M.; Christodoulou, C.A.; Vita, V.; Ekonomou, L. Lightning overvoltage and protection of power substations. *WSEAS Trans. Power Syst.* **2017**, *12*, 107–114.
12. Christodoulou, C.A.; Vita, V.; Ekonomou, L. Studies for the more effective protection of MV/LV substations against lightning overvoltages. *Int. J. Circuits Electron.* **2017**, *2*, 11–15.
13. Brignone, M.; Delfino, F.; Procopio, R.; Rossi, M.; Rachidi, F. Evaluation of Power System Lightning Performance, Part I: Model and Numerical Solution Using the PSCAD-EMTDC Platform. *IEEE Trans. Electromagn. Compat.* **2017**, *59*, 137–145. [CrossRef]
14. *IEEE Std. 998-1996: IEEE Guide for Direct Lightning Stroke Shielding of Substations*; The Institute of Electrical and Electronics Engineers, Inc.: New York, NY, USA, 1996.
15. Christodoulou, C.A.; Ekonomou, L.; Fotis, G.P.; Gonos, I.F.; Stathopulos, I.A. Assessment of surge arrester failure rate and application studies in Hellenic high voltage transmission lines. *Electr. Power Syst. Res.* **2010**, *80*, 176–183. [CrossRef]
16. Anderson, G.J. *Transmission Line Reference Book—345 kV and Above*, 2nd ed.; Electrical Power Research Institute: Palo Alto, CA, USA, 1982.
17. IEEE Working Group. A Simplified method for estimating lightning performance of transmission lines. *IEEE Trans. Power Appar. Syst.* **1985**, *104*, 919–932.
18. CIGRE Working Group 33.01. *Guide to Procedures for Estimating the Lightning Performance of Transmission Lines*; Technical Bulletin 63; CIGRE: Paris, France, 1991.
19. Hileman, A.R. *The Incoming Surge and Open Breaker Protection, Insulation Coordination for Power Systems*; CRC Press: Boca Raton, FL, USA; Taylor & Francis Group: New York, NY, USA, 1999.
20. Haginomori, E.; Koshiduka, T.; Arai, J.; Ikeda, H. *Power System Transient Analysis, Theory and Practice Using Simulation Programs (ATP-EMTP)*; John Wiley & Sons, Ltd.: Chichester, UK, 2016.
21. Ryan, H.M. *High-Voltage Engineering and Testing*, 3rd ed.; IET Power and Energy Series 66; IET: Stevenage, UK, 2013.
22. International Electrotechnical Commission (IEC). *IEC 60071-2: Insulation Coordination Part 2: Application Guide*; IEC: Geneva, Switzerland, 1996.
23. IEEE Standards Board. *IEEE Std. 1243: IEEE Guide for Improving the Lightning Performance of Transmission Lines*; The Institute of Electrical and Electronics Engineers, Inc.: New York, NY, USA, 1997.
24. Nucci, C.A. A survey on CIGRE and IEEE procedures for the estimation of the lightning performance of overhead transmission and distribution lines. In Proceedings of the X International Symposium on Lightning Protection, Curitiba, Brazil, 9–13 November 2009; pp. 151–165.
25. Imece, A.F.; Durbak, D.W.; Elahi, H. IEEE Task Force: Modeling guidelines for fast front transients. *IEEE Trans. Power Deliv.* **1996**, *11*, 493–506.
26. Anderson, R.B.; Eriksson, A.J. Lightning parameters for engineering application. *Electra* **1980**, *69*, 65–102.

27. Dommel, H. Digital Computer Solution of Electromagnetic Transients in Single and Multiple Networks. *IEEE Trans. Power Appar. Syst.* **1969**, *88*, 388–399. [CrossRef]
28. Darveniza, M.; Popolansky, F.; Whitehead, E.R. Lightning protection of UHV lines. *Electra* **1975**, *41*, 39–69.
29. IEEE Working Group. Estimating lightning performance of transmission lines II—Updates to analytical models. *IEEE Trans. Power Deliv.* **1993**, *8*, 1254–1267.
30. Pinceti, P.; Gianvettoni, M. A simplified model for zinc oxide surge arresters. *IEEE Trans. Power Deliv.* **1999**, *4*, 393–398. [CrossRef]
31. Christodoulou, C.A.; Vita, V.; Ekonomou, L.; Chatzarakis, G.E.; Stathopulos, I.A. Application of Powell's optimization method to surge arrester circuit models' parameters. *Energy* **2010**, *35*, 3375–3380. [CrossRef]