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Design and computation of a lightning protection system in an urban 110 kV substation

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Abstract: A lightning protection system (LPS) of an urban 110 kV substation is designed and analysed according to NFPA 780 and IEC 62305-3 standards. The analysis of the LPS is established on the value of risk assessment. The total area of the plant is described by one soil layer with uniform resistivity. This study aims to improve the understanding of an unexpected manner of the grounding system beneath lightning currents by clarifying the basic concepts of the lightning protection level and the new design procedure in this paper was clarified according to NFPA-780 level 1 for a lightning protection system. The program is integrated with the CDEGS software, which provides effective geometrical modeling with object and result visualization. Furthermore, module and automated fast Fourier transform (FFT) is implemented in this study to simulate electromagnetic fields in the time and frequency domains. These current values are compared to the desired protection levels within the standards. The study results show that for the improved protection of the system against lightning, the total power grid must be considered as a source of improvement for studying shielding influence and the protection levels provided inside this substation.

Key words: CDEGS software, fast Fourier transform (FFT), IEC 62305-3, lightning protection system (LPS), NFPA 780 level 1

1. Introduction

A lightning protection system (LPS) is an extremely controversial subject. It is difficult to obtain realistic information on the capacity of the system even if precautions are accurately calculated. Lightning is a natural phenomenon that cannot be controlled by humans, but LPSs are not. Lightning protection provides a path to direct high energy into the soil, which is achieved by a grounding grid under the area to be protected. A lighting strike causes large potential differences in the electrical systems that are distributed one by one in the substation grounding grid. In this study, a 110 kV substation is designed, and the lightning voltage and current, and the LPS protection of the substation during a thunderstorm are calculated. The designed LPS results in the reduced impact of lightning disturbances and improved robustness of the grid substation. The assessment of the LPS is performed using traditional techniques from the literature [1]. Lightning generates significant high voltage in transmission and distribution systems through direct strikes. These considerable voltage anomalies lead to line power failure. Furthermore, modern developments have made it potential to outfit a solution to lightning problems, and also to minimize the total cost of the substation design [2]. These studies and analyses are carried out to provide high protection for this substation. This model proposes a new design of electrical stations and is accomplished by modeling simulation using the CDEGS software as shown in Fig. 1. In some cases, lightning affects the upper part of the substation, which does damage to most of the equipment inside the substation, leading to a complete cessation of all parts of the substation accordingly, insulation error on a transmission line in front of the substation can cause a short circuit with high magnitude [3]. Electrical substations can be abnormal to sundry forms of voltage aberration. During the design step, the engineer should select the risk level for which the substation is designed according to the risk standard, its frequency, affined to the basic insulation level chosen. To reduce the occurrence of such specific risks copper was added to the top of one corner of the substation [4]. In the paper, a new analytical implementation of lightning is presented. The primary circuit arrangement is the same as in [5]. However, the present implementation was extended to include lightning surges on a 110 kV urban substation. To estimate the performance at the beginning of a lightning stroke, the frequency content of the lightning current stroke is used as an approach of the first cycle. The time framework waveform is transferred to the frequency domain by using a rolling sphere method [6]. The LPS is prepared by the keraunic level at the natural status of the substation that is defined as the rate number of thunderstorm days per year and is related to the density of flashes to the ground [7]. When lightning strikes the main generation tower, a moving voltage is generated going back and forth along the tower and this is reflected at the tower footing, which leads to a high voltage at the insulators and intersections. In this case, the insulator will turn into a flash, if the transient voltage exceeds its resistance level [8]. In high-voltage transmission lines, pollution flashover in metallic parts (such as switches and insulators) is one of the biggest obstacles to be solved. Ionization gas is used as a means of realizing the expected problems [9]. When the back flashover diffuses in the transmission lines, leakage current is formed on the conducting layer, which in turn gives a high temperature and humidity to the surface of the insulator. In this case, electric brackets and leaks will appear on the insulator [10]. Most of the previous research that was based on it shows that the excess voltage in the lightning is considered one of the main factors that cause annular flash and damage to the insulators in the transmission lines [11, 12]. The previous studies were taken to effect the grounding resistance by metal-oxide gapless surge arresters and the obtained results indicate the possibility of reducing the effects of lightning according to the mechanism of the lightning rod dependent to some case [13]. The presented results prove the upgrade of the lightning performance of the 110 kV substation and were relied on some of the previous papers [14]. According to a lightning wave, processes that were reached in a negative voltage wave with a steepness of 2 000 kV/μs spread outside of an arrester.

The superimposition reflected from the arrester devices, causes the voltage at the substation to maintain a constant value of 823 kV [15]. The international standard IEC62305–1 Ed. 2 [16] defines three types of lightning impulses relevant to lightning research and engineering applications, these are: the first positive impulse, the first negative impulse and the subsequent impulse. All these current waveshapes are mathematically described by using a special case of the Heidler function with the current steepness factor [17, 18]. In this paper another mathematical function, other than the Heidler function, will model the first and subsequent lightning return strokes according to [19, 20]. A lightning protection system for the evaluation of the exact term for the lightning over a transmission line and substation ground grid is presented, and its mathematical features are thoroughly discussed. Moreover, simulations are performed with the aim of comparing this approach with the approximate formulas and testing their accuracy [21].

This substation was designed according to the yearly average flash density in the region N_g = 10 (f/km square/year) depending on the international map of the lightning frequency strike. In this study, three-dimensional 110 kV ground grid substations are applied, as well as passing simulations in the CDEGS software and the assessment of the lightning effectiveness of the substation are performed. All calculations were conducted and analyzed according to the international standards for the design of 110 kV substations. Moreover, the plan was built on the full frames that provide high protection of the substation. For modeling, the lightning current flowed into the ground.

2. Model and analysis

This paper presents the planning of a grounding grid for a 110 kV urban substation by an MALT model using the CDEGS software. The area of the substation is 58.5 × 36 square meters, and the soil resistivity is uniform. The depth of the layer is 3 m, and the value of the soil resistivity is 2 000 Ωm. The introductory design of a 110 kV substation grounding grid is represented as shown in Fig. 1, dependent to NFPA 780 level 1. When a lightning

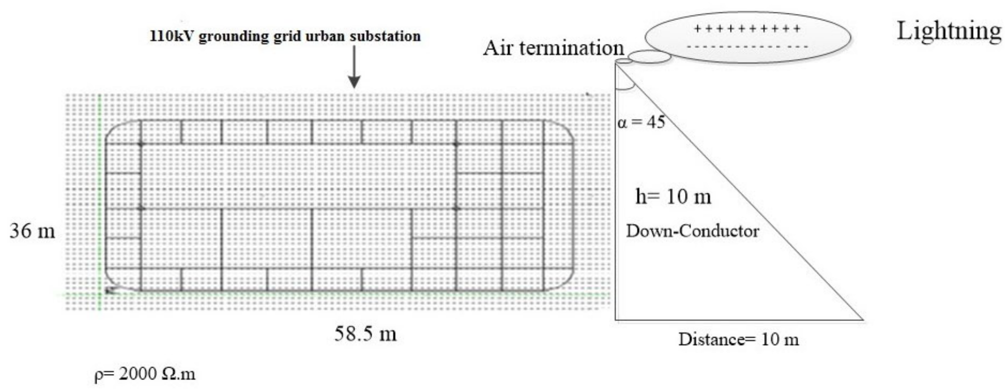


Fig. 1. Lightning in a 110 kV grounding grid urban substation

strikes this substation, a part of the lightning current passes into the soil through the down conductor and its grounding device. However, if the lightning current is high, the insulator would be a flashover, and a part of the lightning current invades this station. Therefore, this model was developed to handle the problems resulting from lightning strikes. We relied on optimal measurements to obtain the preventive parameters like the touch and step voltages. We analyzed the basic rules to get high protection for the substation. We also discussed if the substation needs an LPS. These steps are described in the remaining sections of this paper.

2.1. Lightning protection system

A lightning protection system (LPS) consists ultimately of an air termination system (ATS) that overheads the topmost parts of the model, with down-conductors and an earth-termination system. For the protection standard selection, the IEC standard suggests the assessment of the risk mentioned in [22, 23]. Four lightning protection levels (LPLs) for the assembly was realized to satisfy the desired LPL efficiency class. For each LPL, a set of maximum and minimum lightning current parameters is fixed. Each equipment includes level-dependent and level-independent construction rules. Four classes of LPSs (I, II, III, and IV) are determined as a set of construction rules, based on the identical LPL, we used the risk assessment to determine the class of the LPS. If $N_d \leq N_c$ the system does not need an LPS, and if $N_d > N_c$, otherwise. The risk assessment depends on the parameters shown in Tables 1 and 2. The main risks of lightning are studied extensively using mathematical modeling and simulations. The structure of the substation is designed by the CDEGS software shown in Fig. 1 and all calculations of risk assessment are explained in the following.

Table 1. *C* coefficient specification

Symbol	**Relative structure location**	**Value**
C_1	Isolated structure	1
C_2	Metals	0.5
C_3	High value	2
C_4	Risk of panic	3
C_5	Consequences to the environment	10

Table 2. Model calculation of the LPS parameters

Symbol	**Computation result of the parameters**
A_e	Isolated structure
N_d	Metals
N_c	High value

2.2. Lightning risk assessment

The risk assessment is performed to determine if the substation needs an LPS. For this, the lightning strike frequency (N_d) should be compared to the tolerable risk factors (N_c). The comparison is conducted by the ratio between the acceptable risk and the lightning strike frequency. If the calculated rate is 1.0 or higher, then an LPS is required, and if it is lower than 1.0, then there is no need for an LPS. The application is through the NFPA 780-2008 edition [24]. The lightning strike frequency to the system can be calculated as:

$$N_d = N_g \times C_1 \times A_e \times 0^{-6}. \tag{1}$$

The lightning strike frequency (N_d) consists of the common area of the facility (A_e), its surrounding environment (environmental coefficient C_1), and the lightning flash density (N_g) of the city. The common area of the substation structure can be obtained as:

$$A_e = LW + 6H(L + W) + 9\pi H^2, \tag{2}$$

where L, W and H are the length, width and height of the structure, respectively. At this substation, the surrounding environment of the facility has an integral effect, so the designed external structure is critical to avoid the impact of lightning strikes, and all factors indicate that the high protection of the station leads to full stability of all parts of the substation [25]. The tolerable risk of the facility (N_c) is determined by Eq. (3) and is dependent on the structure coefficient (C_2), contents within the structure (C_3), structure occupancy (C_4), and lightning consequence coefficient structure (C_5).

$$N_c = \frac{C_1 \times 10^{-3}}{C_2 \times C_3 \times C_4 \times C_5}. \tag{3}$$

Eqs. (1), (3) are used to determine the distribution of the lightning current amplitudes that strike the shield wire. The structure is metal, and the coefficients are shown in Table 1, according to NFPA-780. Furthermore, after applying Eqs. (1) and (3) and Table 1, the result of the lightning risk assessment will determine whether an LPS should be installed. From the results in Table 2, we find that an LPS should be fixed because $N_d > N_c$ or the ratio of N_d/N_c is greater than 1. Three LPLs used in this study are based on the standards. All lightning parameters are essential input variables for determining the influence of overvoltage protection. More recent lightning strike measurements were obtained by the SES-shielded CDEGS software.

3. Lightning protection level

There are four classes of lightning protection systems (LPSs) (I to IV), as shown in Table 3. The characteristics of a lightning protection system are determined by the characteristics of the structure to be protected and by the considered lightning protection level. The standard corresponding to LPLs is defined by IEC 62305-3. After that, to determine the protection level class, the efficiency protection (E) is calculated to be 99% according to Eq. (4). A lightning strike is uncontrollable. However, it can be detected, and lightning storms can be tracked [26, 27].

$$E \geq 1 - \frac{N_c}{N_d}. \tag{4}$$

Table 3. Class of lightning level and efficiency in IEC 62305-1 [3]

Class of protection level	LPS efficiency
I	98%
II	95%
III	90%
IV	80%

3.1. Air termination system

An air termination system (ATS) is designed to prevent lightning damage to the substation. It should be designed to avert uncontrolled lightning strikes to the protected structure, as ATSs can consist of rods, spanned wire cables, meshes, conductors in the substation grounding grid.

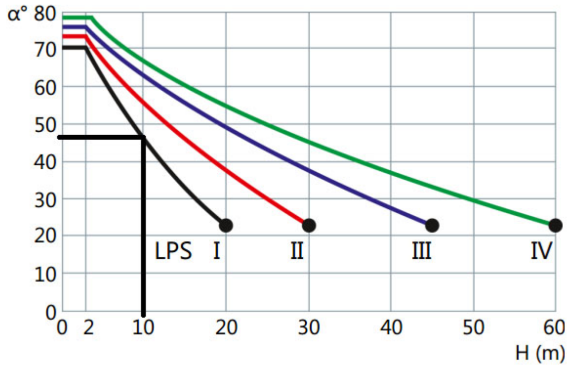
We used air-termination rods according to [28]. When the surface requires some rod air terminal units, we determine the air termination dependence as

$$d = 2\sqrt{2rh - h^2}, \tag{5}$$

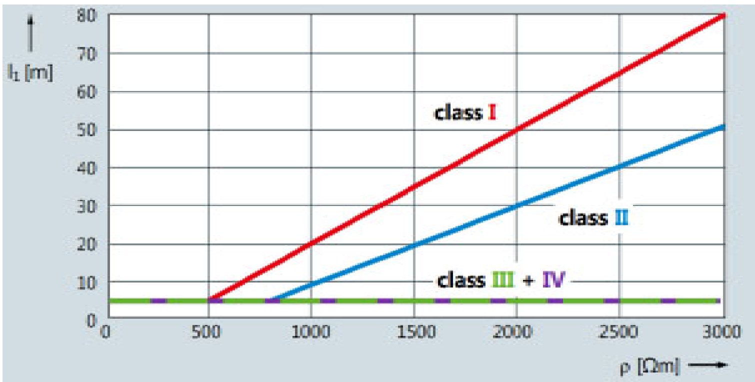
where: d is the distance between two rods (m), r is the radius of the rolling sphere (m), and h is the height of the rods (m). At all events, earth-termination system designs with a considerable area between conductors and the soil buried deeply in the ground lead to lower step-voltages on the surface than those that are less deeply buried or have shorter conductors. In determining the situation of the air-termination system for variable surfaces: the first is the protective angle method for the height difference between two plan surfaces and the second is the rolling sphere method for the height between more surfaces, in the cases of structures with complex global volume. According to the standard DEHN shield, the determined height of the air-termination rods h (m) is presented in Fig. 2(a). The penetration depth of the rolling sphere is governed by the most considerable distance of the air-termination rods from each other [29]. Air-termination rods are used to protect the surface of the substation on the roof against a direct lightning strike. The maximum lightning current depending on the value of the rod is shown in Table 4.

Table 4. Value of the rods and maximum current dependence for level I

Parameter name	Computation result of the parameters	Unit
r	20	m
h	10	m
α	45	°C
Maximum lightning current	200	kA



(a)



(b)

Fig. 2. Model of the LPL [29]: description of the resulting value of the LPS between angle α and h (m) (a); the minimum length of each earth electrode according to the resistivity and the LPS class (b)

3.2. Down-conductor systems

We hope to minimize the damage caused by lightning to this substation. It is necessary to use a down-conductor system for the LPS. Typical values of the distance between down-conductors and the LPS are shown in Table 5. All values are given by IEC 62305-3 [30]. In this system the

Table 5. Values of the down-conductor distances according to the LPS level [29]

Class of the protection level	Typical down-conductor distances (m)
I	10
II	10
III	15
IV	20

down-conductors are placed in one of the corners of the 110 kV substation; they are distributed around the perimeter. The down-conductors are connected directly to the substation. They are installed directly onto the structure because of the temperature increase phenomenon during a lightning strike to the LPS. If the wall is made of an ordinarily inflammable material, the down conductors may be installed directly on or in the wall shown in Fig. 1.

3.3. Earth-termination systems

Earth-termination systems are an essential portion of LPSs. They must be designed to ensure safe lightning current transition into the earth without generating step voltages on the surface of the soil, which would be risky to human beings [31]. The attitude of an earth-termination system under high lightning currents was studied to minimize hazardous overvoltages. This was performed by many authors theoretically both in the frequency and time domains [32, 33]. In an earth-termination system, the length of an earth electrode should be calculated according to the class of an LPS, to determine the soil resistivity layer. For class I, the $\rho = 2\,000$ Ωm and the length of the electrode is 50 m as shown in Fig. 2(b).

4. Peak lightning current

Lightning currents that can pass through a direct lightning strike can be simulated with the wave current of a waveform of 10/350 µs in IEC 62305-3. For class I, the peak value current is 200 kA, symmetric to the first short stroke LPS [34]. The lightning wave current can be jointly explained by the attached double exponential function in Eq. (6) and Fig. 3. Also the Heidler function is used. This can be seen in Eq. (7) [35].

$$i(t) = \frac{I}{\eta} e^{-\alpha t}\, e^{-\beta t}, \tag{6}$$

$$i_h(t) = \frac{I}{\eta} \frac{\left(\frac{t}{\tau_1}\right)^{n_h}}{1 + \left(\frac{t}{\tau_1}\right)^{n_h}} e - \frac{t}{\tau_2}, \tag{7}$$

where: I is the peak current (A), η is the correction factor, t is the time variable, α and β are the time constants, τ_1 is the rise time constant, τ_2 is the decay time constant, n_h is the Heidler steepness factor. In this paper, to calculate the lightning surge, we used the parameter of double exponential function representation of the lightning surge and subsequent current pulse wave as one of the most widely used surge models for the lightning surge propagation in the transmission line and grounding system shown in Table 6, and the Heidler approximation parameter is described in Table 7, based on Fig. 4. The field methods are mostly more accurate than circuit or substation approximation, but they take into account all electromagnetic phenomena. The calculation is carried out for conductive structures with single earth electrodes in the earth with 2 000 Ωm. The surge current distribution in the vertical and horizontal elements of the LPS is calculated during a lightning strike to the corner of the substation.

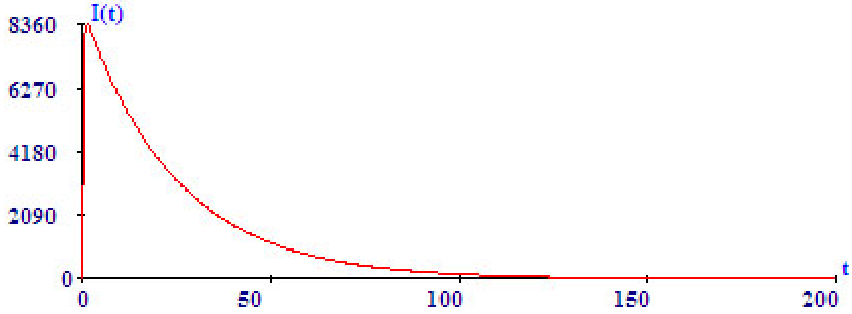


Fig. 3. Graph describing the double exponential-type function in the form of a 10/350 µs lightning waveform using FFTSES-CDEGS software

Fig. 4. Graph describing the Heidler function in the form of a 10/350 µs lightning waveform using FFTSES-CDEGS software

Table 6. Parameters for Eq. (6)

Parameter	**10/350 µs waveform**
I	8.3 kA
η	0.5
α	53 798.93
B	499 449.6

In this study, the effect of high lightning current density that lead the grounding performance was not taken into account, which is a path adopted by many researchers [36–39]. In high lightning strike currents, the electromagnetic field in the earth electrodes is probably larger than the electric power of the soil, resulting in breakdown. This mostly improves the grounding grid performance, essentially in lower resistivity soil. There is no unanimity on the natural formularization that takes into account the impact of this combination and patchy process as they are forced by the necessary implied simplifications and presumption [40, 41].

Table 7. Parameters used in Eq. (7)

Parameter	Heidler	Approximation
I	11.9 kA	
η	0.93	0.93
τ_1 (µs)	19	–
T_2 (µs)	485	485
n_h	10	–

5. Computation results

The computation step is mostly based on the use of the well-known SES shield to design the substation according to the lightning specification, striking distance, and ground flash density. The probability for a stroke current smaller than 12.52 kA is 15.571%. Additionally, the likelihood that there will be one failure per year is 1 per 0.0033%. All substation characteristics, critical and intermediate values, are computed by the CDEGS software, as shown in Table 8 and Table 9 and Fig. 5. From the result of the risk assessment using the CDEGS software, the summation area of a direct blow to the structure (58.5 × 36 square meters) is 2.229 m and the overhead lines from direct strikes are 34.05 m. The CDEGS software first uses the fast Fourier transform to draw the field lightning surge, as utilized in references [42, 43]. The modern methods conducted in this paper to choose the appropriate solutions to represent the substation ground grid were built on the basis of protecting the upper part of the earth station in accordance with the paragraph 4.

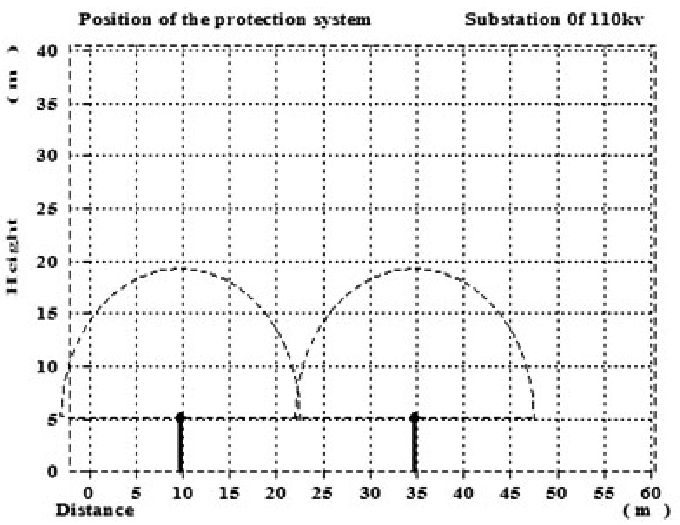


Fig. 5. Risk assessment for lightning protection in the 110 kV substation

Table 8. Substation characteristics using the SES shield

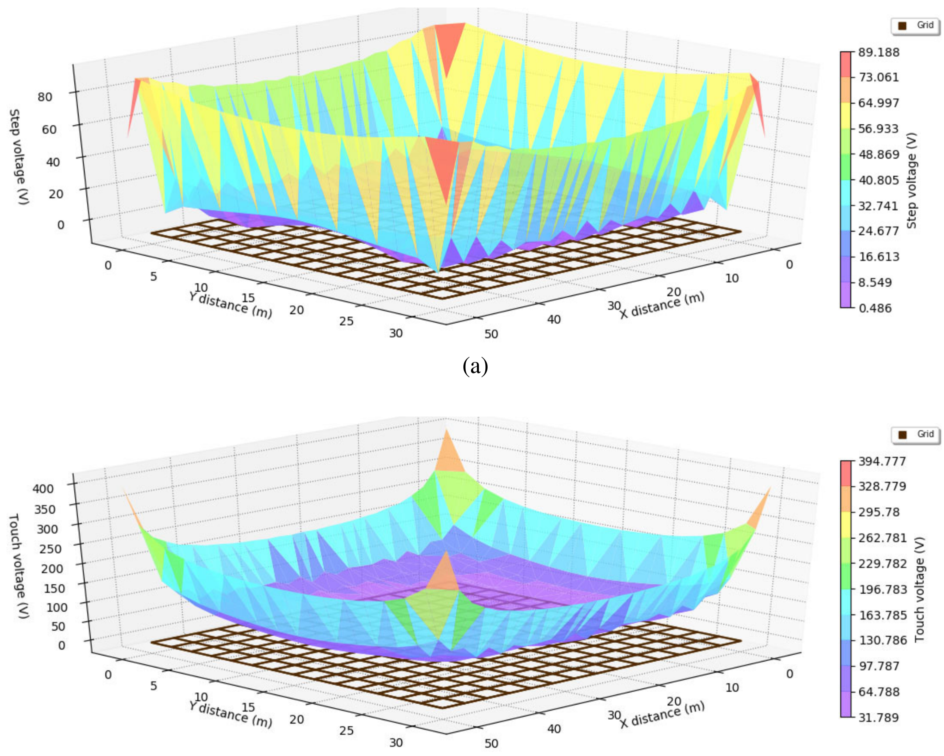
Parameter	Value	Unit
Voltage phase	110	kV
Basic impulse	1 850	kV
Mid-span height	26	m
Outer diameter of the conductor	25.4	m
Bundle spacing	0.460	m

Table 9. Intermediate and critical values used in the SES-CDEGS software

Parameter	Value	Unit
Withstand insulator voltage V_C	1 850	kV
Equivalent bundle radius R_0	0.204	m
Surge impedance Zw	499.4	kΩ
Critical current I_c	12.57	kA
Critical distance S_c	41.3	m
Height of the protection system H_g	58.5	m
Lightning surge per year	30594	1 per-years

Finally, step and touch voltages in the 110 kV substation present risk to anybody in the substation owing to a lightning stroke. Thus, they were studied and represented based on the basic values in the design to avert all risks arising from lightning, as shown in Fig. 6(a). After the procedure of arrangement the system in the CDEGS software and studying the influence of lightning on the 110 kV substations, the system was stable, predicated on the values described in the system shown in Table 9. The most amount of the current was estimated based on the impedance values that the substation needs to proceed to repair the faults. In the pass-through process, previous studies indicate the potential of changing the current depending on the grounding potential rise. In this study, we tried to find reasonable solutions to resolve the problems resulting from the selection suitable values of the soil resistance and the characteristic of the soil. All the forms in this paper signalize confirmed solutions to help their implementation. By far, the maximum cost-effective control of the assessment of high-transmission lines under a lightning is the optimization of the shielding angle and the decrease of the grounding resistance. Furthermore, for the 110 kV substation, the standard was updated using the CDEGS software to improve the spacing rods.

Based on the results represented in this paper and according to all international standards for the protection of high-voltage substations, it was concluded that the effects of lightning can be reduced using LPSs. In addition, Fig. 6(b) shows the summary of the study in terms of the optimal representation of the calculation of step and touch voltages in the protection of the human elements and equipment as well as all various types of 110 kV substations. This study indicates



(a)

(b)

Fig. 6. Status design for 110 kV using SES-CDEGS software: 3D-step voltage (a); 3D-touch voltage (b)

Table 10. Intermediate and critical values used in the SES-CDEGS software

Status	**Maximum value (V)**	**Computed value (V)**	**110 kV grounding grid status**
Potential rise	5 000	498.3626	Acceptable
Touch voltage	1 005.2	252.8969	Acceptable
Step voltage inside the grid	3 553.1	10.4823	Acceptable
Step voltage outside the grid	3 553.1	13.0001	Acceptable

that the process of the analysis and follow-up effects of lightning can be made with four levels of protection algorithms, but level I is preferred for the use as it is good for efficient treatment of the effects. Furthermore, in this paper, we clarified the analysis by the CDEGS software that can process the problems and which in turn was implemented by supplementary stations depending on LPS technique. According to the IEC 62305-3 standard of LPLs, the attachment through the substation top and the grounded structure takes place for lightning stroke at a critical distance from the construction. This distance was specified as the radius of the level applied in the rolling sphere shape of locating lightning down conductors on the structures. The analysis was used according to [44–46]. The last paragraph in the abstract of this paper has been proven based on the characteristic of the four protection levels, especially the first level, and this is shown in Table 9, as the values of the surge impedance Z_w and critical current I_c are the best values from the perspective of reducing the effects of a lightning strike.

6. Conclusions

In this study, a new design for a 110 kV grounding grid urban substation is proposed. According to the optimization process, the LPS is calculated to be placed in the niche corner of the substation. The stepwise execution for designing the earth grid was presented and the design parameters were performed from the risk assessment using the SES shield in the CDEGS software. The results of this study show that the representation of the substation includes the calculation of all parameters that contribute to the appearance of any risks, which are considered to be correctly approved to the international standards. The grounding grid was also computed against any hazards considered in this study. A new design for a 110 kV grounding grid urban substation was optimized by a new lightning level processed according to data and approximate computational methods, lightning strikes on the system were reduced.

A substantial analysis of whether an LPS should be applied when a new substation is designed or an actual structure is updated, was performed by the designer. It was concluded that the lightning risk assessment is an instrument that can be used to determine if an LPS is required. Step and touch voltages were evaluated considering the presence of a human being in the vicinity of a power transmission station in terms of surface resistivity and the results revealed that the approximate methods in this study are proper and reasonably accurate for determining a lightning voltage peak, taking into account a horizontal grounding system.

References

[1] He J., Wang X., Yu Z., Zeng R., *Statistical analysis on lightning performance of transmission lines in several regions of China*, IEEE Transactions on Power Delivery, vol. 30, pp. 1543–1551 (2015).

[2] Franc B., Filipović-Grčić B., Milardić V., *Lightning overvoltage performance of 110 kV air-insulated substation*, Electric Power Systems Research, vol. 138, pp. 78–84 (2016).

[3] Rizk F.A., *Analysis of space charge generating devices for lightning protection: Performance in slow varying fields*, IEEE Transactions on Power Delivery, vol. 25, pp. 1996–2006 (2010).

[4] Takami J., Tsuboi T., Yamamoto K., Okabe S., Baba Y., *Lightning surge characteristics on inclined incoming line to substation based on reduced-scale model experiment*, IEEE Transactions on Dielectrics and Electrical Insulation, vol. 20, pp. 739–746 (2013).

[5] Grcev L., *Modeling of grounding electrodes under lightning currents*, IEEE Transactions on Electromagnetic Compatibility, vol. 51, pp. 559–571 (2009).

[6] Ndungu C., Nderu J., Ngoo L., Hinga P., *Lightning protection of HIV substations at coastal region and enhanced earthing system – Case study*, IEEE AFRICON, pp. 1319–1324 (2017).

[7] Melodi A., Oyeleye M., *Modeling of Lightning Strike Events, and its Correlational with Power Outages in South-West Coast, Nigeria*, International Journal of Electrical and Computer Engineering, vol. 7, pp. 3262–3270 (2017).

[8] Gouda Ossama E., El Dein Adel Z., Amer Ghada M., *Parameters affecting the back flashover across the overhead transmission line insulator caused by lightning*, In: Proceedings of the 14th International Middle East Power Systems Conference (MEPCON'10), Cairo University, vol. 111, pp. 44–49 (2010).

[9] Yong Liu., Bowen Xia., Boxue Du., Masoud Farzaneh, *Influence of Fine Metal Particles on Surface Discharge Characteristics of Outdoor Insulators*, Energies, vol. 9, pp. 1–13 (2016).

[10] Taheri Sh., Gholami A., Mirzaei M., *Study on the behavior of polluted insulators under lightning impulse stress*, Electric Power Components and Systems, vol. 37, pp. 1321–1333 (2009).

[11] Mahdi Izadi, Muhammad Syahmi, Abd Rahman, Mohd Zaina, Abidin Ab-Kadir, Chandima Gomes, Jasronita Jasni, Maryam Hajikhani, *The influence of lightning induced voltage on the distribution power line polymer insulators*, PLOS ONE, vol. 12, pp. 1–12 (2017), DOI: 10.1371/journal.pone.0172118.

[12] Saeedollah Talaei Mobarakei, Taghi Sami, Babak Porkar, *Back Flashover Phenomenon Analysis in Power Transmission Substation for Insulation Coordination*, 11th International Conference on Environment and Electrical Engineering, Italy, pp. 1–5 (2012), DOI: 10.1109/EEEIC.2012.6221567.

[13] Christodoulou C.A., Vita V., Ekonomou L., *Studies for the more effective protection of MV/LV substations against lightning overvoltages*, International Journal of Circuits and Electronics, vol. 2, pp. 11–15 (2017).

[14] Christodoulou C.A., Vita V., Voglitsis D., Milushev G., Ekonomou L., *A heuristic method for the reduction of the outage rate of high-voltage substations due to atmospheric overvoltages*, Applied Sciences, vol. 8, pp. 1–12 (2018), DOI: 10.3390/app8020273.

[15] Christodoulou C.A., Vita V., Mitropoulou A., Oikonomou D.S., Ekonomou L., *Interface construction for the computation of the optimum installation position of metal oxide surge arresters in medium voltage substations*, Proceedings of the 5^{th} IASME/WSEAS International Conference on Energy and Environment (EE' 10), University of Cambridge, United Kingdom, pp. 334–338 (2010).

[16] IEC 62305–1 Ed. 2: *Protection against Lightning – Part 1: General Principles* (2010).

[17] Heidler F., Cvetić J., *A class of analytical functions to study the lightning effects associated with the current front*, European Transaction on Electric Power (ETEP), vol. 12, pp. 141–150 (2002).

[18] Terespolsky B.R., Nixon K.J., *Developing an approximate ion to the Heidler function – with an analytical transformation into the frequency domain*, International Conference on Lightning Protection (ICLP), pp. 1326–1330 (2014).

[19] Mikihisa Saito, Masaru Ishii, *Characteristics of return strokes associated with upward lightning flashes observed in winter*, 34th International Conference on Lightning Protection (ICLP), pp. 1–5 (2018).

[20] Chandrasekaran K., Gururaj S. Punekar, *Horizontal component of electric field due to lightning return strokes*, Journal International Conference on Power and Energy Systems, pp. 1–4 (2011).

[21] Christodoulou C.A., Vita V., Maris T.I., *Lightning protection of distribution substations by using metal oxide gapless surge arresters connected in parallel*, International Journal of Power and Energy Research, vol. 1, pp. 1–7 (2017).

[22] Moreira R.K., Moreira A.K., Coelho G.H.L., Moreira G.T.K., *Design of special lightning protection system for opened sites and structures under construction: Dangerous potentials evaluation and mitigation*, International Symposium on Lightning Protection (XII SIPDA), pp. 348–353 (2013).

[23] Parise G., Martirano L., Lucheroni M., *Level, Class, and Prospected Safety Performance of a Lightning Protection System for a Complex of Structures (LPCS)*, IEEE Transactions on Industry Applications, vol. 46, pp. 2106–2110 (2010).

[24] Sanders M.K., *NFPA 780 standard for the installation of lightning protection systems*, IEEE Industrial and Commercial Power Systems Technical Conference (I&CPS), pp. 1–4 (2011).

[25] Borghetti A., Cozzani V., Mazzetti C., Nucci C.A., Paolone M., Renni E., *Monte Carlo based lightning risk assessment in oil plant tank farms*, 30th International Conference on Lightning Protection (ICLP), pp. 1–7 (2010).

[26] Ballarotti M.G., Medeiros C., Saba M.F., Schulz W., Pinto O., *Frequency distributions of some parameters of negative downward lightning flashes based on accurate-stroke-count studies*, Journal of Geophysical Research-Atmospheres, vol. 117, pp. 1–8 (2012).

[27] Tong C., Wang Q., Gao Y., Tong M., Luo J., *Dynamic lightning protection of smart grid distribution system*, Electric Power Systems Research, vol. 113, pp. 228–236 (2014).

[28] Abd-Elhady A.M., Sabiha N.A., Izzularab M.A., *Experimental evaluation of air-termination systems for wind turbine blades*, Electric Power Systems Research, vol. 107, pp. 133–143 (2014).

[29] Necci A., Antonioni G., Cozzani V., Krausmann E., Borghetti A., Nucci C.A., *A model for process equipment damage probability assessment due to lightning*, Reliability Engineering and System Safety, vol. 115, pp. 91–99 (2013).

[30] Stefanescu S., Botezan A., *Overview of the protection lightning standards suite EN/IEC 62305*, International Conference and Exposition on Electrical and Power Engineering, pp. 504–509 (2016).

[31] *Dehn+Söhne Lightning Protection Guide*, DEHN protects (2014).

[32] Li D., Azadifar M., Rachidi F., Rubinstein M., Paolone M., Pavanello D. *et al.*, *On lightning electromagnetic field propagation along an irregular terrain*, IEEE Transactions on Electromagnetic Compatibility, vol. 58, pp. 161–171 (2016).

[33] Pavanello D., Rachidi F., Rakov V., Nucci C., Bermudez J., *Return stroke current profiles and electromagnetic fields associated with lightning strikes to tall towers: Comparison of engineering models*, Journal of electrostatics, vol. 65, pp. 316–321 (2007).

[34] Grange F., Journet S., Fortin S., Dawalibi F.P., *Transient analysis of soil resistivity influence on lightning generated magnetic field*, International Symposium on Lightning Protection (XII SIPDA), pp. 192–196 (2013).

[35] Liu X.T., Wang W., Yu H., *Electromagnetic Effect on Underground Pipeline of the Lightning Strike 330 kV Transmission Lines*, 4th International Conference on Information Science and Control Engineering (ICISCE), pp. 1487–1491 (2017).

[36] Akbari M., Sheshyekani K., Pirayesh A., Rachidi F., Paolone M., Borghetti A. *et al.*, *Evaluation of lightning electromagnetic fields and their induced voltages on overhead lines considering the frequency dependence of soil electrical parameters*, IEEE Transactions on Electromagnetic Compatibility, vol. 55, pp. 1210–1219 (2013).

[37] He J., Zhang B., *Progress in lightning impulse characteristics of grounding electrodes with soil ionization*, IEEE Transactions on Industry Applications, vol. 51, pp. 4924–4933 (2015).

[38] Sesnic S., Poljak D., Tkachenko S.V., *Analytical modeling of a transient current flowing along the horizontal grounding electrode*, IEEE transactions on electromagnetic compatibility, vol. 55, pp. 1132–1139 (2013).

[39] Yu C., Fu Z., Hou X., Tai H.M., Su X., *Break-point diagnosis of grounding grids using transient electromagnetic apparent resistivity imaging*, IEEE Transactions on Power Delivery, vol. 30, pp. 2485–2491 (2015).

[40] Zhang B., Wu J., He J., Zeng R., *Analysis of transient performance of grounding system considering soil ionization by time domain method*, IEEE Transactions on Magnetics, vol. 49, pp. 1837–1840 (2013).

[41] Alipio R., Visacro S., *Impulse efficiency of grounding electrodes: Effect of frequency-dependent soil parameters*, IEEE Transactions on Power Delivery, vol. 29, pp. 716–723 (2014).

[42] Visacro S., Alipio R., *Frequency dependence of soil parameters: Experimental results, predicting formula and influence on the lightning response of grounding electrodes*, IEEE Transactions on Power Delivery, vol. 27, pp. 927–935 (2012).

[43] Abdaldaim M., Li L., Wang P., *The design of 110kV substation grounding grid with high resistivity soil*, Sixth Asia-Pacific Conference on Antennas and Propagation (APCAP), pp. 1–3 (2017).

[44] Abdaldaim M., Li L., Wang P., *The Design of 220 kV Substation Grounding Grid with Difference Soil Resistivity Using Wenner and Schlumberger Methods*, International Conference on Electricity Distribution (CICED), pp. 2525–2530 (2018).

[45] Trainba M., Christodoulou C.A., Vita V., Ekonomou L., *Lightning overvoltage and protection of power substations*, WSEAS Transactions on Power Systems, vol. 12, pp. 107–114 (2017).

[46] Becerra M., Cooray V., *Time dependent evaluation of the lightning upward connecting leader inception*, Journal of Physics D: Applied Physic, vol. 39, pp. 4695–4702 (2006).