

Techno-economic Assessment and Scenario-based Optimization of Lightning Protection Schemes in High-voltage Substations Using ATP- EMTP

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TECHNO-ECONOMIC ASSESSMENT AND SCENARIO-BASED OPTIMIZATION OF LIGHTNING PROTECTION SCHEMES IN HIGH-VOLTAGE SUBSTATIONS USING ATP-EMTP

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ARTICLE INFO	ABSTRACT
Received:	To enhance the technical reliability and economic efficiency of high-voltage substations subjected to atmospheric discharges, this paper introduces a comprehensive scenario-based assessment framework that couples ATP-EMTP transient simulations with a Life Cycle Cost (L_{CC}) analysis. Moving beyond conventional deterministic assessments, the methodology integrates the Korsunsky dynamic soil ionization model to accurately capture nonlinear tower-footing behavior in high-resistivity regions. Stochastic evaluations across random lightning scenarios demonstrate that extreme lightning currents can produce transferred overvoltages up to 5.5 MV at the substation entrance. Through systematic evaluation of alternative protection schemes, a 5-unit ZnO surge arrester (SA) topology is identified as the optimal configuration. This optimized setup successfully dampens transient overvoltages across all critical nodes, achieving a robust minimum Protection Ratio Level (PR_L) of 1.25 while strictly bounding individual thermal stress to 2.08 kJ/kV, well within the 5 kJ/kV rated capability. Furthermore, an integrated L_{CC} analysis demonstrates that the 5-SA configuration bounds the annual risk of transformer failure to just 0.44%, yielding a net present value of financial risk mitigation exceeding \$894,000 over a 30-year operational horizon. This framework provides power utilities with a validated and economically justified paradigm for substation insulation coordination.
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1. Introduction

High-voltage substations remain highly vulnerable to lightning-induced overvoltages, which represent a primary cause of insulation breakdown and catastrophic equipment failure. Consequently, atmospheric discharges are recognized as one of the most critical disturbance sources, elevating the urgent need for precise risk estimation and preventive control methods in modern power systems.

The severity of lightning surges entering a substation is strongly governed by the grounding conditions of the approaching transmission towers. In regions characterized by lossy ground or high-resistivity soil, the probability of back-flashover on overhead lines increases substantially. Furthermore, insufficient tower-footing impulse impedance dominates the transient response, directly amplifying the fast-front lightning surges that transfer into the substation entrance.

Inside the substation, surge arresters (SAs) serve as the primary line of defense. However, conventional or purely heuristic placement approaches often fail to fully account for environmental effects and dynamic wave reflections at critical impedance discontinuities. Therefore, determining the optimal installation scheme is essential to ensure that the protection strategy is not only technically robust but also cost-effective over its lifecycle.

Internal transient phenomena further exacerbate the risk of insulation breakdown. Lightning electromagnetic pulses can generate high-frequency terminal overvoltages that far exceed conventional deterministic estimates due to multiple internal reflections. Additionally, the frequency-dependent, full-wave transient behavior of the substation's two-layer grounding grid significantly influences how these internal overvoltages are dynamically distributed across critical components.

Although previous literature provides valuable insights, most studies examine individual factors – such as grounding behavior, stroke severity, or SA placement – in isolation. Specifically, grounding-oriented studies often neglect internal substation metrics such as the Protection Ratio Level (PR_L), while internal-overvoltage analyses

rarely quantify the nonlinear interactions between dynamic soil ionization and the rigorous energy-handling limits of modern SAs. Consequently, the combined impact of these stochastic factors on both the PRL and life-cycle economics remains insufficiently explored.

To bridge this critical research gap, this paper proposes a novel integrated assessment and optimization framework. The main contributions of this work are explicitly defined as follows:

1. **Probabilistic-Optimization Framework:** Transitioning from conventional deterministic assessments, this study couples electromagnetic transient simulations in ATP-EMTP with a structured scenario evaluation to simultaneously resolve optimal insulation coordination (PR_L) and thermal energy constraints under stochastic lightning distributions.
2. **Dynamic Grounding-Insulation Interaction:** The research quantifies the severe nonlinear interactions between high-frequency soil ionization in high-resistivity regions and internal substation surge reflections, providing high-fidelity vulnerability mapping for 220 kV equipment.
3. **Techno-Economic Protection Guidelines:** By synthesizing electrical transient stress data with Life Cycle Cost (L_{CC}) and risk-cost metrics, the study establishes scalable, economically justified protection guidelines for grid operators, ensuring maximum reliability with an optimized cost-to-benefit ratio.

2. Protection ratio lighting in an electrical substation

Insulation coordination in substations is intended to ensure that transient overvoltages remain within the limits prescribed by IEC 60071-1 and IEEE C62.22. This process includes selecting an SA suitable for prevailing environmental and operating conditions, determining its optimal installation locations, and verifying the insulation capability of substation equipment. Such verification is generally carried out using standard insulation parameters, including the basic lightning impulse level (BIL), the basic switching impulse level (BSL), and the chopped-wave withstand (CWW).

The insulation withstand levels for outdoor substations and associated equipment are summarized in Table 1. Although both IEC and IEEE standards are presented for comparison, IEC 60071-1 is adopted as the primary basis for the insulation design in this study, whereas the IEEE values are included only for supplementary reference.

Table 1. The insulation strength for outdoor substations and equipment.

IEC/IEEE Max system voltage, kV	IEC 60071.1 BIL, kV	IEEE C57.12.14	
		Transformers BIL, kV	Circuit breakers BIL, kV
245/242	750	750	750

The protective ratio level (PR_L) is a key index for assessing insulation coordination in high-voltage substations. It is defined as the ratio of the equipment BIL to the maximum lightning overvoltage appearing at its terminals. Therefore, the PR_L quantifies the insulation safety margin between the equipment's lightning-impulse withstand capability and the actual lightning stress it experiences. A higher PR_L indicates a greater margin against insulation failure under atmospheric overvoltage conditions. According to IEC 60071-1 and IEEE C62.22, maintaining a PR_L greater than 1.2 generally corresponds to an insulation reliability level of approximately one failure in 50 to 100 years for 220 kV systems. For atmospheric overvoltages, the PR_L is defined as follows:

$$PR_L = \frac{BIL}{LPL} \geq 1.2 \quad (1)$$

where $BIL = 750$ kV is the basic lightning impulse insulation level for the 220 kV voltage level. The lightning peak level (LPL) is the peak lightning overvoltage at the equipment terminals (kV).

In practical terms, a $PR_L > 1.2$ indicates adequate insulation protection, a PR_L between 1.0 and 1.2 suggests a limited safety margin, and a $PR_L < 1.0$ indicates a high risk of insulation failure under lightning stress.

3. System description and methodology

The investigated 220 kV substation comprises two 250 MVA power transformers, five connected transmission lines, busbars, voltage transformers (VTs), and SAs, as shown in Figure 1. In the ATP-EMTP model (Figure 2), all components relevant to surge propagation and reflection are represented by validated equivalent circuits. To capture traveling-wave behavior with sufficient accuracy, the two transmission-line spans closest to the substation are modeled in detail, whereas the remaining line sections are represented as infinitely long to suppress artificial reflections from remote terminals.

Based on this substation configuration, atmospheric overvoltages are assessed by combining the electrogeometrical model (EGM) for lightning attachment with electromagnetic transient simulations in ATP-EMTP. The overall procedure, illustrated in Figure 1, includes lightning-scenario definition, system modeling, transient simulation, and performance evaluation. The input data are grouped into four categories: substation

layout and insulation characteristics; lightning-stroke parameters; surge-arrester ratings and installation schemes; and tower-footing resistance. For each case, the peak overvoltage at critical equipment terminals, the protection ratio level (PR_L), and the absorbed arrester energy are evaluated in accordance with IEC 60071-1 and IEEE insulation-coordination criteria. The protection configuration that satisfies both insulation reliability and arrester energy requirements is then identified as the preferred scheme.

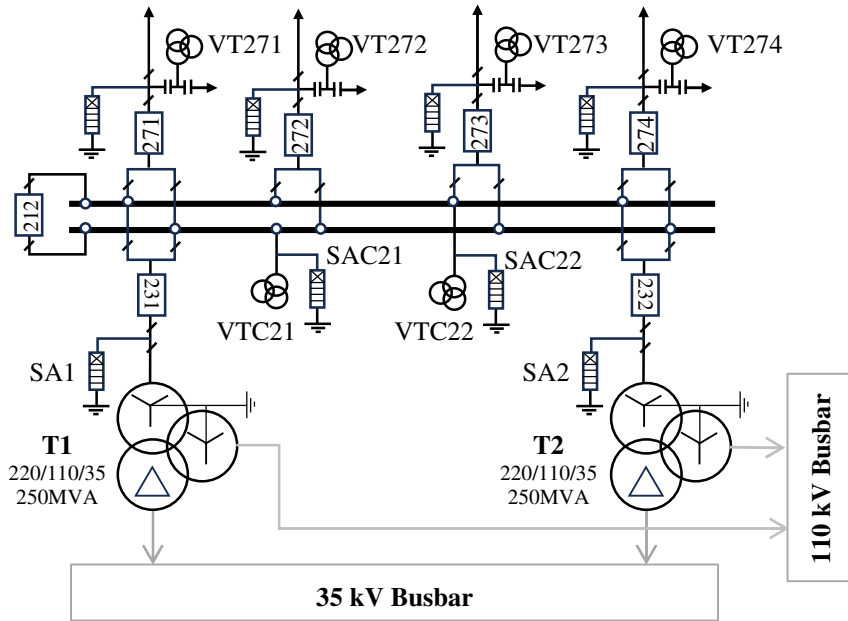


Figure 1. Schematic diagram of the 220/110/35 kV substation.

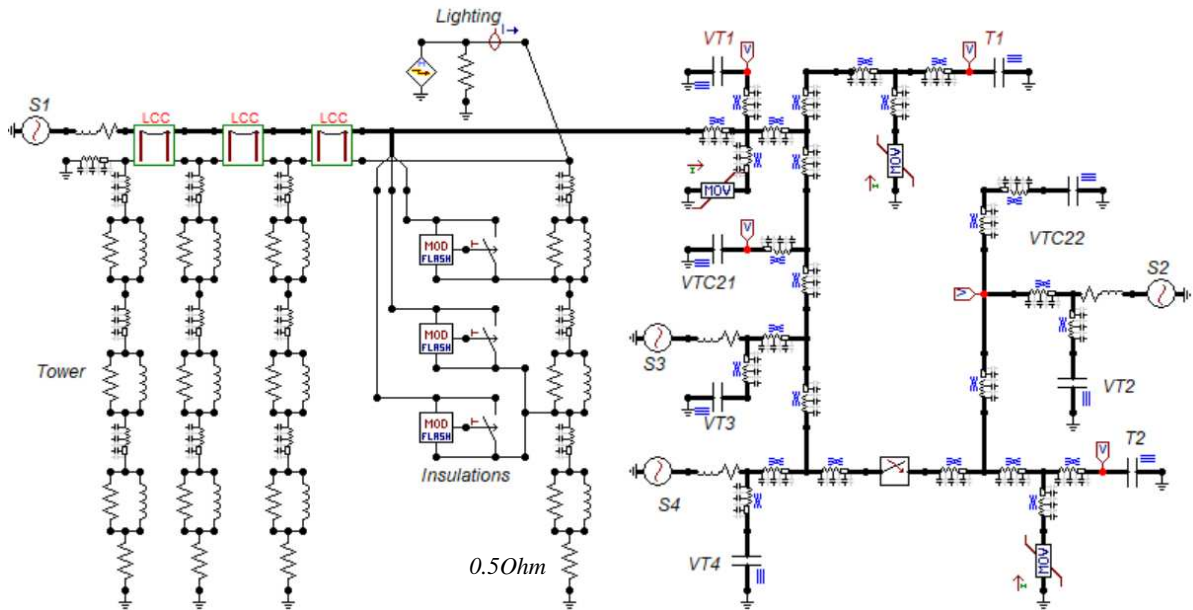


Figure 2. ATP-EMTP model of the 220/110/35 kV substation

Table 2. Main modeled components and simulation parameters

Electrical components	Description/Parameters	Reference/Notes
Voltage source	AC-3ph Type 14, 50 Hz, 220 kV line-to-line RMS	
Transmission line	JMarti frequency-dependent model	
Tower grounding	R-L-C branch per tower	
Insulation	MOD Flash model per IEC 60071	
Power transformers	AT1, AT2	C = 4 nF each
Voltage transformers	VT274, VTC21, VTC22	C = 550 pF
Surge arresters	ZnO type 3EL2 192-2P.3 (MOV-type 92 model)	
Busbars	three-phase RLC elements	

3.1. System source model

In the ATP-EMTP model, the source is represented by an ideal voltage source and an internal impedance, as summarized in Table 3. The nominal system voltage is 220 kV line-to-line, corresponding to 179.63 kV phase-to-ground at 50 Hz. The internal impedance is defined by the equivalent surge impedance of the connected transmission network, with a positive-to-zero-sequence impedance ratio of 2, in accordance with the typical values specified in IEC 60909. Accordingly, the positive- and zero-sequence surge impedances are taken as 400 Ω and 650 Ω , respectively, which are representative of 220 kV overhead lines according to IEEE Std 1313.2. This source representation ensures realistic transfer of lightning-induced overvoltages from the external network into the substation model.

Table 3. System source data.

N°	Data	Value	Unit
1	Amplitude	179.63	kV
2	Frequency	50	Hz
3	R/I+	2	-
4	R/I0	2	-
5	Z+	400	Ω
6	Z0	650	Ω
7	V+	300	m/ μ s
8	V0	300	m/ μ s

3.2. Transmission line modeling and parameter calculation

The 220 kV transmission line connected to the substation was modeled using the Line Constant Calculation (LCC) module in ATP-EMTP. The modeled line length was selected based on the critical distance from the substation entrance, which defines the line section over which lightning surges have the strongest influence on the transferred overvoltage at the substation. This distance is determined by:

$$d_m = \frac{100}{n \cdot \text{MTBF} \cdot \text{FOR}} = \frac{100}{1 \cdot 100 \cdot 2} = 0.5(\text{km}) \quad (2)$$

where $n = 1$ for cases involving circuit breakers and asymmetrically arranged transformers, MTBF = 100 years represents mean time between failures, and FOR = 2 (flashovers/100 km/year) is the flashover rate of transmission lines.

Accordingly, the critical section extends approximately 500 m from the substation entrance. Since the span length is 200 m, the first three spans, corresponding to a total length of 600 m, were included in the model. Although this length slightly exceeds the calculated critical distance, it ensures full representation of the hazardous section while preserving the actual tower-span configuration of the line. Beyond this section, the contribution of the incoming line to substation overvoltages becomes limited because of surge attenuation during wave propagation. Therefore, restricting the model to the first three spans is sufficient to capture the dominant effect of lightning surges on the substation while reducing computational burden.

In the model, phases 1-3 represent the phase conductors, whereas phase 4 represents the shield wire. The geometric and electrical parameters of the conductors are summarized in Table 4 and were used to derive the distributed line constants for transient analysis.

Table 4. Modelled components and parameters.

Ph.no.	R _{in} (cm)	R _{out} (cm)	Resis (ohm/km)	Horiz (m)	V _{tower} (m)	V _{mid} (m)
1	0.04	1.14	0.07	4	24	19
2	0.04	1.14	0.07	-4	19	14
3	0.04	1.14	0.07	8	19	14
4	-	0.47	0.4	0	30	25

3.3. Tower and insulator string model

The equivalent multisection elements available in ATP-EMTP were used to represent the four towers closest to the substation, with each tower discretized into several sections to capture its surge impedance characteristics, as shown in Figure 3. The height of each tower section, h_i was determined from the corresponding geometric dimensions and average radius, r_i , according to the following empirical expression :

$$Z_i = 60 \ln \left(\sqrt{2} \cdot \sqrt{\left(\frac{h_i}{r_i} \right)^2} - 1 \right) \quad (3)$$

where r_i is the average radius of the tower and h_i is the height of segment i ($i=1,3$).

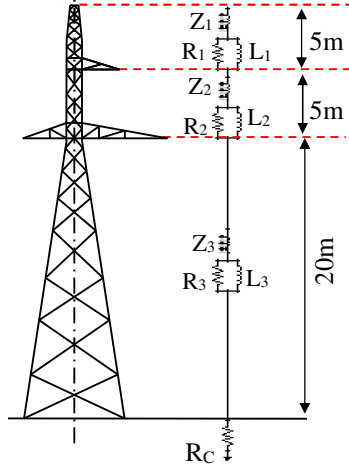


Figure 3. 220 kV Tower model.

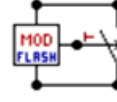


Figure 4. Insulation strings model.

The equivalent resistance and inductance of each section are determined using the following equations:

$$R_i = \frac{-2Z_1 \ln \sqrt{\gamma}}{h_1 + h_2} h_i \quad (i=1,2) \quad (4)$$

$$R_3 = -2Z_1 \ln \sqrt{\gamma} \quad (5)$$

$$L_i = R_i \cdot \tau \quad (i=1,3) \quad (6)$$

where: $\gamma=0.7-0.8$ is the attenuation coefficient. The value 0.8 is selected ($\sqrt{\gamma}=0.8944$);

$\tau=2H/v$ is the wave propagation time of the tower;

$v=300 \text{ m}/\mu\text{s}$ is the wave propagation speed;

L_i (mH) is the inductance of segment i ;

R_i (Ω) the resistance of segment i ($i=1,3$); and

R_c is the tower's grounding resistance.

The calculation results are shown in Table 5:

Table 5. 220 kV tower parameters

i	h_i (m)	r_i (m)	R_i (Ω)	L_i (mH)	Z_i (Ω)
1	5	1.5	10.1	1.35	90.2
2	5	1.5	10.1	1.35	90.2
3	20	3	20.2	2.69	133.94

The effect of tower-footing resistance R_c on the resulting overvoltage magnitude is investigated in this study. For the standard substation configuration under consideration, tower T1, namely the terminal tower, is directly connected to the substation grounding grid. Hence, its grounding resistance is set to 0.5Ω , in accordance with common design practice for terminal towers. Consequently, other grounding configurations are not considered.

The 220-kV transmission-line insulator string is modeled using the MOD Flash component, as depicted in Fig. 5. Each insulator unit is represented by a 100-pF capacitor, with a basic insulation level (BIL) of 750 kV .

To account for soil ionization under lightning-current conditions, the impulse tower-footing grounding resistance is expressed as follows :

$$R_c = \frac{\rho}{2\pi l} \left[\ln \left(\frac{2l}{a_i} \right) - 1 \right] \quad (7)$$

Where ρ denotes the soil resistivity, l is the electrode length, and a_i is the effective ionized radius. This model reflects the decrease in effective grounding resistance as lightning current increases and is therefore suitable for electromagnetic transient analysis of lightning-induced overvoltages.

3.4. Lightning stroke model

The peak current magnitude of lightning is a random variable that varies widely, ranging from 2 kA to 270 kA. Based on the comprehensive summary of lightning parameters presented by CIGRE 33.01, for first downward strokes, the variation in lightning-peak current distribution will be approximated for first downward strokes.

$$P(I \geq I_s) = \frac{100}{1 + \left(\frac{I_s}{31}\right)^{2.6}} \quad (\%) \quad (8)$$

Table 6. Lightning peak current exceedance probability for first downward strokes

Lightning peak current_I (kA)	10	31	50	100	150	200	250
P(I≥I _s) %	95%	50	22.4	4.5	1.63	0.78	0.44

Table 6 summarizes the exceedance probability of lightning peak current for first downward strokes based on the CIGRE 33.01 model. These probabilities are used as input data for assessing lightning performance and overvoltage risk in the studied system.

The statistical distribution of all the flash parameters can be approximated by the lognormal distribution, in which the probability density function is of the form :

$$\mu = M.e^{\frac{\beta^2}{2}} \quad (9)$$

where M is the median and B is the log standard deviation.

A lightning strike on the transmission line is shown in Figure 5. The peak current magnitude and tail time (t) are essential factors for assessing the energy absorbed by the SA. The negative lightning current used for the simulation has the following parameters:

- The peak current magnitude (10-250 kA);
- The average time to peak and the tail time: $t_p/t = 6.65/91.7 \mu s$.

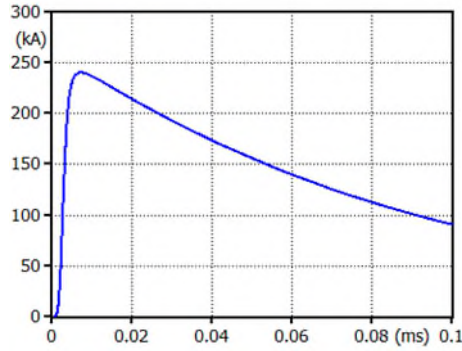


Figure 5. Lightning current waveform: front and steepness.

Lightning strikes considered in the simulations were modeled with peak currents ranging from 10 to 250 kA to represent both common and extreme conditions, in accordance with CIGRE Technical Brochure 549 . The choice of 250 kA as the upper bound is justified by the CIGRE 33.01 statistical model, from which Table 6 shows an exceedance probability of only 0.44% for this current level. Although infrequent, such high-magnitude events remain credible and should be considered in insulation coordination and overvoltage assessment. Hence, the selected range ensures that the study captures severe but realistic lightning stresses on the investigated substation system.

3.5 Surge arrester model

Gapless zinc oxide (ZnO) SAs of type 3EL2 192-4P.4 are installed on the voltage transformers (VTs) and the autotransformers (T1 and T2). The selected arresters are manufactured and tested in accordance with IEC 60099-4, ensuring compliance with international requirements for high-voltage surge protection. In ATP-EMTP, the arrester is modeled using the MOV-92 element, as shown in Figure 6.

The main ratings and technical characteristics of the adopted surge arrester are summarized in Table 7. Furthermore, the nonlinear V-A characteristic derived from the ATP-EMTP model is presented in Figure 7. The obtained characteristic is consistent with the expected behavior of ZnO surge arresters, confirming the capability of the adopted MOV-based model to represent the clamping performance under lightning surges .



Figure 7. Surge arrester model.

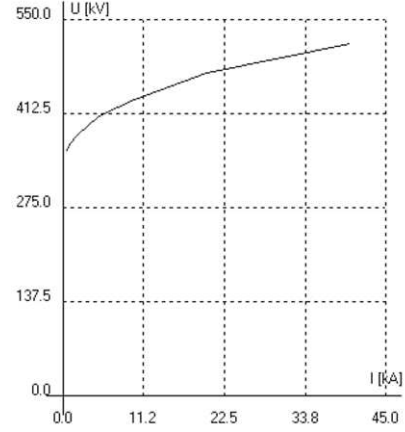


Figure 6. Characteristic V-A of the SA

Table 7. Ratings and specifications for the 3EL2 192-4P.4 .

U _s (kV)	U _r (kV)	U _c (kV)	Residual voltage (kV)							Energy absorption capability (kJ/KV)
245	192	154	30/60 μs			8/20 μs				
			0.5 kA	1kA	2kA	5kA	10kA	20kA	40kA	
			359	369	380	408	432	471	514	
5										

The energy absorption capability of the arrester was also evaluated under simulated lightning conditions. The results show that, even for the most severe case considered, the absorbed energy per arrester remains well below the rated value of 5 kJ/kV. This indicates that the 3EL2 192-4P.4 arrester provides sufficient thermal withstand capability for the investigated system under lightning transient conditions.

3.6 Simulation setup

Transient simulations were conducted in ATP-EMTP to evaluate lightning-induced overvoltages in a 220 kV substation under various lightning and grounding conditions. The model includes a three-phase source, transmission lines, transformers, busbars, surge arresters (SAs), and voltage measurement points, with parameters selected in accordance with IEC and IEEE standards.

The lightning current was represented by the Heidler function with a front-to-tail time of 6.65/91.7 μ s, derived from CIGRE TB 549 to reflect the characteristics of negative first strokes in tropical regions. The tower-footing resistance was varied to 10 Ω , 50 Ω , and 100 Ω , whereas the terminal tower (T1) was fixed at 0.5 Ω due to its direct connection to the substation grounding grid. This assumption is consistent with IEEE Std 80-2013 and with modeling practices reported in CIGRE WG 33.01 , IEC 61936-1:2021 , and IEEE 1410-2010 .

In addition, configurations with one and three SAs were considered to evaluate their influence on insulation coordination and equipment protection. For each case, the peak overvoltages at the VT and AT terminals, together with the residual voltage and absorbed energy of the SAs, were recorded. The simulation time step was set to 0.1 μ s, and the total simulation duration was 100 μ s, which is sufficient to capture the main lightning impulse and dominant traveling-wave reflections. The benchmark values and ranges of variation used in the parametric analysis are summarized in Table 8. Among them, 200 kA was selected as a severe reference lightning current based on the upper tail of first-stroke statistics in CIGRE TB 549. At the same time, 10 Ω and the three-arrester configuration were chosen as the reference conditions for grounding and protection.

Table 8. Benchmark values and variation ranges of key simulation parameters

Parameter	Benchmark value	Variation range
Lightning current	250 kA	10–250 kA
Strike location	T1	T1–T4
Tower footing resistance	10 Ω	10–100 Ω
SA configuration	3 units	1–3 units

3.7. 3.7. Scenario-Based Analysis Framework for Surge Arrester Placement

3.7.1. Approach and Evaluation Scenarios

To determine the effective allocation of surge arresters (SAs) without relying on automated heuristic search algorithms, this study adopts a systematic, scenario-based evaluation framework utilizing ATP-EMTP transient simulations. Rather than exploring an automated combinatorial search space, the methodology focuses on evaluating predefined, practical installation schemes commonly implemented by power utilities.

The spatial allocation of zinc oxide (ZnO) surge arresters is evaluated across key equipment terminals to identify vulnerable insulation points. The configurations investigated in this study comprise:

- Option 1 (1 SA): A baseline configuration with a single surge arrester installed at the terminal voltage transformer (VT271) to evaluate the limits of minimal protection.
- Option 2 (3 SAs): A moderate configuration incorporating arresters at critical impedance discontinuities, specifically at incoming voltage and power transformer terminals.
- Option 3 (5 SAs): A comprehensive, distributed protection scheme deploying arresters across all critical nodes (VT and transformer terminals) to ensure complete overvoltage suppression.

3.7.2. Techno-Economic Evaluation Criteria

To assess the performance and economic feasibility of each installation scenario over an operational horizon (T) of 30 years with a standard financial discount rate @ of 8%, an integrated Life Cycle Cost (L_{CC}) evaluation is conducted. The total LCC is formulated as:

$$L_{CC} = C_{Inv.} + \sum_{t=1}^T \frac{E_C}{(1+r)^t} \quad (11)$$

Where $C_{Inv.}$ represents the initial capital expenditure for purchasing and installing the protection hardware, proportional to the number of deployed surge arresters (N_{SA}):

$$C_{Inv.} = N_{SA} \cdot C_{SA} \quad (12)$$

The unit cost of a 220 kV ZnO surge arrester (C_{SA}) is estimated at \$5,000 USD, including installation.

The Expected Annual Damage Cost (E_C) represents the risk-adjusted financial liability due to lightning-induced insulation failures :

$$E_C = C_{damage} + P_{failure} \quad (13)$$

Where C_{damage} is the total equivalent failure cost of the primary asset (a 220 kV/250 MVA transformer), valued at \$2,000,000 USD. The operational probability of insulation failure ($P_{failure}$) is determined stochastically based on the lightning current peak magnitude (I) following formula (8)

$$P_{failure} = P(I \geq I_s) = \frac{1}{1 + \left(\frac{I_s}{31}\right)^{2.6}} \quad (14)$$

3.7.3. Technical and Operational Constraints

The evaluation of each scenario is strictly bounded by technical safety margins:

- Insulation Withstand Margin: The maximum transient overvoltage ($U_{max,i}$) at any protected node i must comply with IEC 60071-1 relative to the Basic Lightning Impulse Level (BIL=750) , maintaining an adequate Protection Ratio Level (PL_R):

- Thermal Energy Withstand Limit: To guarantee the physical survivability of the ZnO elements under high-energy strokes, the cumulative energy absorbed by any individual surge arrester ($W_{SA,j}$) must remain below its rated thermal capacity ($W_{rated} = 5 \text{ kJ/kV}$) :

$$W_{SA,j} = \int_0^T U_{res}(t) \cdot I_{Res}(t) dt \leq W_{Rated} \cdot U_r \quad (15)$$

Where $U_{Res}(t)$ and $I_{Res}(t)$ are the instantaneous residual voltage and discharge current waveforms extracted directly from the ATP-EMTP MOV-92 simulation results.

3.7.4. Dynamic Grounding and Soil Ionization Coupling

To ensure high fidelity in regions with poor soil conductivity, the low-frequency tower footing resistance (R_0) is replaced with a high-frequency dynamic impulse resistance (R_i). The model couples instantaneous lightning current magnitude with transient soil ionization using the Korsunsky relationship :

$$R_i = \frac{R_0}{\sqrt{1 + \frac{I}{I_g}}} \quad (16)$$

Where I_g represents the critical soil ionization threshold current, governed by soil resistivity (ρ) and grounding electrode geometry.

4. Simulation results and discussion

4.1. Impact of lightning current magnitude

The effect of lightning-current magnitude on substation overvoltage was evaluated for seven current levels of 10, 31, 50, 100, 150, 200, and 250 kA, with the strike applied to the top of the terminal tower and the terminal tower's grounding resistance fixed at 0.5 Ω . This assumption is justified because the terminal-tower grounding system is generally bonded to the substation grounding grid, whereas the grounding resistance of the remaining towers is treated separately. The analysis was conducted through a structured parametric study in which lightning-current magnitude, the number of line and transformer branches, strike location, tower-footing resistance, and

surge-arrester number were varied systematically, and the final configuration was assessed for peak overvoltage, PRL, and arrester-absorbed energy.

The simulated waveforms at VT1 indicate that the overvoltage increases markedly with lightning-current magnitude. At 10 and 31 kA, induced overvoltages of 160 kV and 210 kV are obtained, respectively. When the lightning current reaches 50 kA, backflashover to the phase conductor occurs, resulting in an overvoltage of 1.1 MV. Beyond this threshold, the overvoltage rises sharply, reaching 5.5 MV at 250 kA (Figure 8). These results confirm that the magnitude of lightning current is a dominant factor governing the severity of atmospheric overvoltages within the substation.

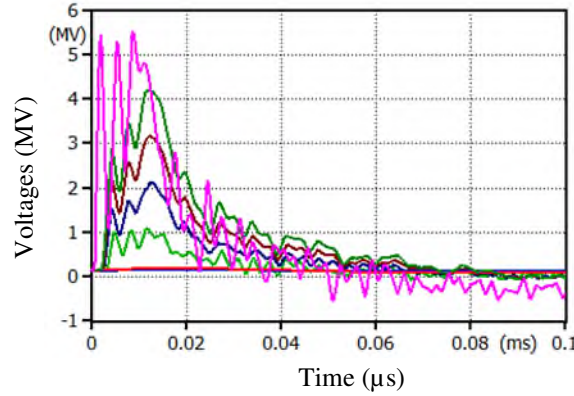


Figure 8. Magnitude of overvoltage on VT1.

4.2. Impact of lightning strike location

In this case, the effect of lightning strike location was evaluated by considering strike positions at towers T1-T4 along a 0.6-km line section near the substation. Based on CIGRE TB 63 [28], the hazardous distance for lightning-induced backflashover is estimated by

$$d_m = \frac{100}{n \cdot \text{MTBF} \cdot \text{FOR}} = \frac{100}{1 \cdot 100 \cdot 2} = 0.5(\text{km}) \quad (18)$$

Where $n = 1$ for circuit breakers and asymmetrically arranged transformers, MTBF = 100 years is the mean time between failures, and FOR = 2 flashovers/100km/year is the line flashover rate. The calculated hazardous distance is consistent with the value reported in, corresponding to about two spans with $d_m = 0.5$ km. Under these assumptions, the substation lightning-protection scheme should prevent flashover within a reliability period of approximately 50-100 years.

The simulation results indicate that the transferred overvoltage strongly depends on the strike location. When lightning strikes Tower T1, the peak overvoltage at VT1 reaches about 5.5 MV. In contrast, it decreases to only about 450 kV for a strike at Tower T4, as shown in Figure 9. This reduction is mainly due to attenuation from surges during propagation along the line. Therefore, the strike location significantly affects the overvoltage stress on substation equipment.

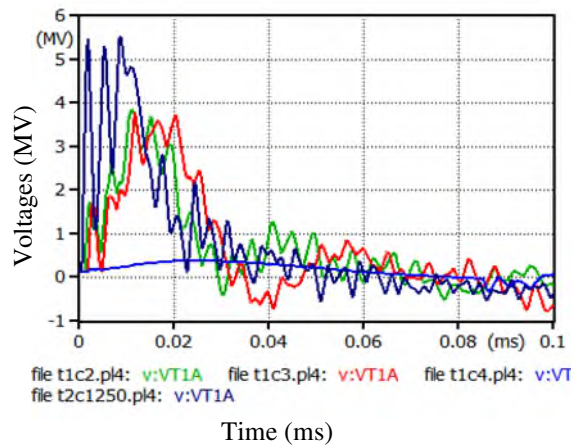


Figure 9. Overvoltage on VT1

4.3. Effect of the number of branches connected to the busbar

Figure 11 shows the lightning-induced overvoltage at the busbar when a lightning stroke hits the last tower of the incoming line under five operating configurations: (i) 2 transformers + 4 outgoing feeders, (ii) 1 transformer + 4 outgoing feeders, (iii) 1 transformer + 3 outgoing feeders, (iv) 1 transformer + 2 outgoing feeders, and (v) 1 transformer + 1 outgoing feeder. The results clearly indicate that the overvoltage magnitude is strongly affected by the number of branches connected to the busbar. Among the investigated cases, the most severe condition occurs when the substation operates with one transformer and one outgoing feeder, resulting in a peak overvoltage of approximately 6.76 MV. In contrast, the lowest peak overvoltage is obtained for the fully connected configuration with two transformers and four outgoing feeders in service. This trend indicates that as the number of operating branches decreases, the equivalent surge impedance at the busbar increases. At the same time, the incoming traveling wave is distributed over fewer propagation paths, resulting in a higher peak reflected or transferred voltage. Conversely, when more branches are connected to the busbar, the surge energy is shared among more paths, thereby reducing the overvoltage magnitude. This interpretation is consistent with the insulation-coordination principles of IEC 60071-1 and with IEEE C62.22, which emphasize that insulation selection and surge arrester application should be based on representative surge stresses under realistic system operating conditions.

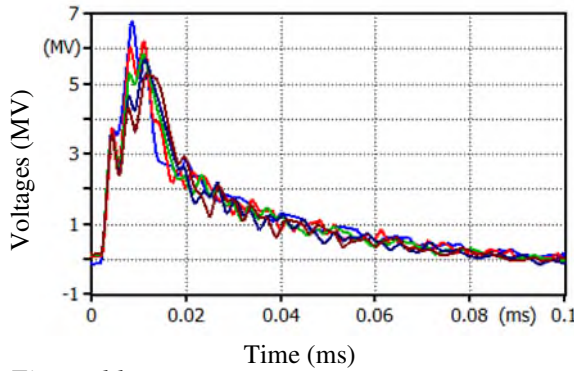


Figure 11. Dependence of overvoltage magnitude on the number of branches

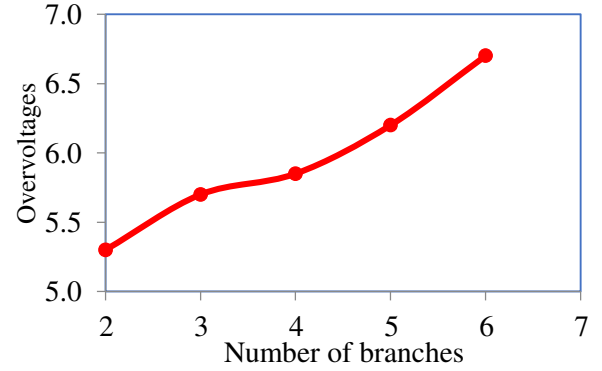


Figure 10. Variation of overvoltage with the number of branches

4.4. Effectiveness of surge arresters

To comprehensively evaluate the effectiveness of the proposed protection schemes, the transient phase-to-ground overvoltages and their corresponding Protective Ratio Levels (PR_L) were analyzed across key substation equipment. Figure 12 presents the time-domain simulation results for three distinct surge arrester configurations (Option 1, Option 2, and Option 3), illustrating the voltage waveforms at critical nodes, including the voltage transformers (VT271, VTC21, VTC22) and power transformers (T1, T2).

The maximum overvoltage values extracted from these waveforms, alongside their specific PR_L for each equipment, are quantitatively summarized in Table 8.

Table 8. Maximum overvoltage and coordination level for different arrester configurations.

Configuration	No. of SA	Equipements	Max Overvoltage (MV)	PR_L	Remarks
Option 1	1	VT271	0.84	$1.07 < 1.2$	Insufficient
		VTC21	1.1	$0.82 < 1.2$	
		VTC22	1.53	$0.59 < 1.2$	
		T1	1.36	$0.66 < 1.2$	
		T2	1.61	$0.56 < 1.2$	
Option 2	3	VT271	0.79	$1.14 < 1.2$	Adequate
		VTC21	0.84	$1.07 < 1.2$	
		VTC22	0.63	$1.42 > 1.2$	
		T1	0.74	$1.22 > 1.2$	
		T2	0.62	$0.91 < 1.2$	
Option 3	5	VT271	0.72	$1.25 > 1.2$	Adequate
		VTC21	0.69	$1.3 > 1.2$	
		VTC22	0.54	$1.65 > 1.2$	
		T1	0.71	$1.26 > 1.2$	
		T2	0.62	$1.46 > 1.2$	

In addition to complying with IEEE 998, the arrester placement strategy in this study is guided by fundamental insulation-coordination principles. Specifically, surge arresters are installed:

- (i) at the line entrance (VT271) to limit the steepness of incoming traveling waves;
- (ii) at buses C21 and C22, where impedance discontinuities produce significant surge reflections;
- (iii) at transformer terminals to enhance local protection against transferred surges amplified by high tower-footing resistance. These criteria collectively improve voltage uniformity and align with recent studies highlighting the importance of locating arresters near critical equipment and reflection points .

As detailed in Table 8 Limited arrester configurations fail to provide comprehensive protection throughout the substation. In Option 1 (1 SA), the transient stress is severe across all nodes. The maximum overvoltage reaches an extreme 1.61 MV at T2, yielding a dangerously low PR_L of 0.56. Every recorded piece of equipment under this configuration exhibits a $PR_L < 1.2$, rendering the protection entirely insufficient and highly susceptible to insulation breakdown.

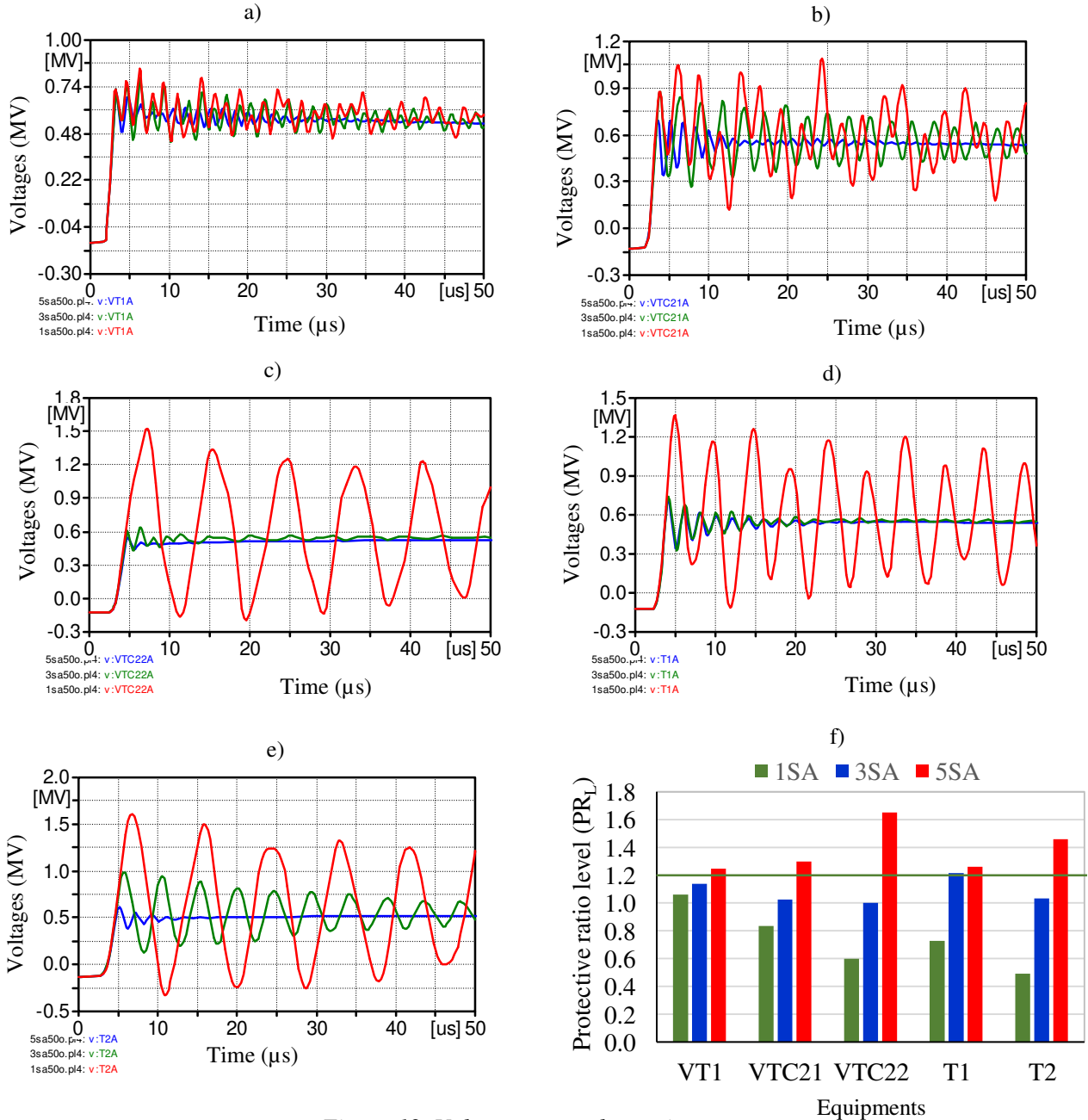


Figure 12. Voltage across the equipment

a) Voltage across VT1; b) Voltage across VTC21; c) Voltage across T1
d) Voltage across VTC22; e) Voltage across T2; f) protective ratio level (PR_L)

Expanding the configuration to Option 2 (3 SAs) dampens local reflections and provides adequate protection for specific nodes, such as VTC22 ($PR_L = 1.42$) and T1 ($PR_L = 1.22$). However, this arrangement leaves other critical discontinuities exposed. The maximum overvoltage still reaches 0.84 MV at VTC21, with $PR_L = 1.07$, and the minimum protection margin drops to $PR_L = 0.91$ at T2. Because critical components remain below the 1.2 safety threshold, Option 2 is classified as having marginal, yet ultimately insufficient, overall coordination.

In contrast, Option 3 (5 SAs) successfully limits the peak overvoltage across the entire substation, capping the maximum stress at 0.72 MV (recorded at VT271). This optimized, distributed suppression ensures a minimum PR_L of 1.42 (1.25 across all equipment), comfortably satisfying the strict IEC 60071-1 safety margin ($PRL \geq 1.2$). This adequate performance validates recent optimization-based studies, proving that increasing the number of strategically placed arresters minimizes transient stress and guarantees network reliability.

Unlike previous literature that primarily focuses on minimizing lightning flashover rates via purely probabilistic or heuristic approaches, this work explicitly evaluates internal insulation coordination using the detailed PR_L criterion under multiple practical topologies. This methodology provides a direct assessment of compliance with standards and offers clear, quantitative guidance for the actual design of substations.

Although Option 3 secures the highest coordination margin, deploying five surge arresters naturally incurs higher installation and maintenance expenses than the partial configurations. This practical trade-off between technical protection performance and initial economic cost remains a critical consideration for grid operators.

4.4. Impact of the grounding resistance of the tower footing

Figure 13 shows how the peak overvoltage on phase A insulation of the VT271 varies with a 250 kA lightning current as the tower footing resistance changes among 10 Ω , 50 Ω , and 100 Ω . Interestingly, the simulation shows that when the optimized 5-surge arrester (5SA) configuration is deployed, the overvoltage magnitude at the substation entrance remains virtually unchanged despite significant variations in tower footing resistance.

Quantitatively, increasing the grounding resistance from 10 Ω to 100 Ω results in almost identical, overlapping voltage waveforms at the wavefront, with the maximum overvoltage on VT271 firmly clamped at approximately 0.72 MV (Figure 13). Unlike scenarios without adequate protection where poor grounding increases lightning-induced overvoltages due to higher voltage drops across the grounding path, the robust 5SA configuration effectively discharges the surge energy. This optimized arrester placement dominates the transient response, nullifying the potential rise that would typically transfer to the substation bus.

This result clearly demonstrates that an optimized arrester configuration can effectively minimize the adverse effects of high grounding resistance. Specifically, with five ZnO SAs positioned at the voltage and power transformer terminals, the overvoltage is heavily suppressed, ensuring the PRL remains above 1.2 even under severe grounding conditions. This complies with the reliability standards in IEC 60071-1 and IEEE C62.22, ensuring a failure probability of less than 1 in 50 years for 220 kV substations.

From a design perspective, while aiming for a footing resistance of $\leq 10 \Omega$ is traditionally advisable when soil conditions allow, the results indicate that high-resistivity soils do not necessarily require extremely costly grounding improvements with an optimized SA deployment. Combining moderate grounding with strategic SA placement offers a practical, cost-effective protection strategy. Field and analytical studies show that tower-footing resistance can vary considerably with seasonal and soil-moisture conditions and that the amplitude of the lightning current also exhibits significant natural variability. These uncertainties highlight the importance of maintaining sufficient margins in insulation coordination. In this context, the robust voltage clamping achieved by Option 3 ensures dependable performance even amid realistic fluctuations in grounding resistance. Incorporating these variations into a broader uncertainty analysis could further refine the protection assessment in future studies.

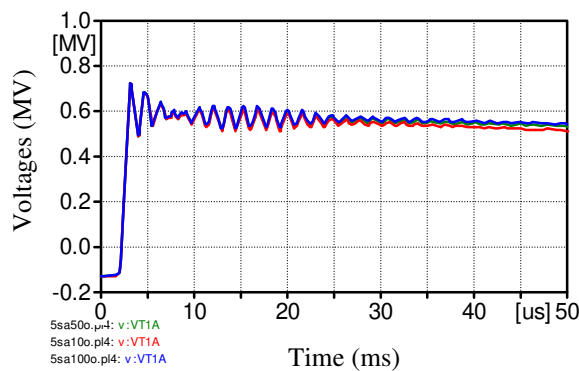


Figure 13. Overvoltage on VT274.

4.5. Energy absorbed by the surge arrester

In this study, a 250 kA lightning current is used to determine the high-energy stress level of the surge arrester (SA), which corresponds to a 0.8% occurrence probability. The durability of an SA is crucial for assessing

its effectiveness in protecting electrical systems from overvoltages. This durability is primarily evaluated based on the energy absorbed by the arrester during transient events, such as lightning strikes. The energy absorption capacity of an SA defines the maximum energy it can dissipate without sustaining damage. The energy absorbed by an SA can be calculated using the following formula :

$$W_{SA} = \int_0^T U_{Res}(t) \cdot I_{Res}(t) dt \quad (19)$$

where I_{Res} is the discharge current through the surge arrester (kA), U_{Res} is the residual voltage of the SA (kV), and T is the duration of the wave (μs).

Figure 16 presents the simulation results for the maximum absorbed energy by the SAs under the three installation configurations and various strike locations. When only a single SA is installed (Option 1), the maximum absorbed energy reaches 601.7 kJ. For a rated voltage of 192 kV, this corresponds to an energy stress of 3.13 kJ/kV. While this value remains below the rated absorption capacity of 5 kJ/kV, it exceeds 62% of the arrester's thermal limit, leaving a narrower safety margin under extreme lightning conditions.

This reduction is attributed to the distributed energy dissipation among multiple arresters, which effectively limits the current per device. Energy stress is inversely proportional to the number of installed arresters and to the uniformity of current sharing among them. These findings are consistent with the recommendations of IEEE C62.22 [6], which emphasize the importance of adequate arrester coordination to ensure both electrical and thermal stability during high-energy impulse events.

Figure 15 illustrates the discharge current waveforms through the arresters under the various configurations. The reduction in peak discharge current from Option 1 to the multi-arrester setups directly lowers the absorbed energy and internal temperature rise within the MOV blocks, thereby enhancing operational reliability and extending the arrester's lifespan.

In practical applications, the energy duty of metal-oxide arresters is influenced by several sources of uncertainty. The residual voltage naturally varies due to factors such as waveform steepness, manufacturing tolerances, and measurement variations [31], underscoring the critical need for conservative thermal margins. Although grounding resistance and lightning-current amplitudes fluctuate under actual operating conditions, limiting the absorbed energy to 2.08 kJ/kV – which utilizes approximately 41.6% of the 5 kJ/kV rated capacity – provides substantial thermal headroom. This ensures reliable arrester performance even in the presence of these uncertainties.

From a design perspective, these results confirm that strategically installing multiple ZnO arresters at critical locations significantly improves both the insulation coordination and the thermal endurance of the substation's protection system. Consequently, while Option 3 provides broader spatial protection, a coordinated setup of at least three arresters (Option 2) is essential to establish a safe thermal balance, protection efficacy, and overall economic viability for 220 kV substations exposed to severe lightning conditions.

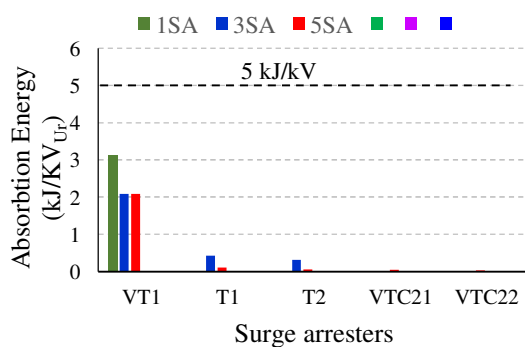


Figure 15. Energy absorption of SAs.

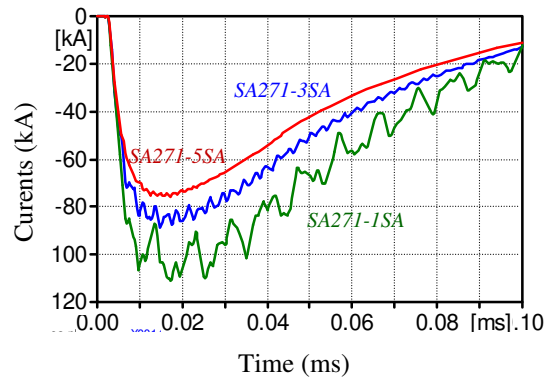


Figure 14. Discharge current through the SA.

Limitations of the Proposed Method

It is important to note that the proposed method presents several limitations. The assessment is inherently scenario-based and heavily depends on the selected parameters for lightning current, strike location, grounding resistance, and arrester configuration. Therefore, the results should be interpreted as case-specific findings rather than universally applicable design rules. Additionally, the analysis is conducted on a specific 220 kV substation model; quantitative outcomes may differ for substations with alternative layouts, insulation levels, or grounding conditions. While the adopted ATP-EMTP models are well-suited for lightning transient analysis, this study does not account for all real-world variables, such as seasonal variations in soil resistivity, equipment aging, and the

stochastic nature of lightning behavior. Nevertheless, the proposed framework remains a robust and valuable tool for comparing the relative performance of different protection configurations under representative operating conditions.

4.6. Techno-Economic and Cost-Benefit Verification

To validate the practical feasibility of the proposed scenario-based protection framework, a comprehensive Cost-Benefit Analysis (CBA) was conducted under severe operating conditions in which the surrounding towers exhibit high grounding resistance ($R_C = 50 \Omega$). The transient simulation outputs for Option 1 (1 SA), Option 2 (3 SAs), and Option 3 (the comprehensive 5 SA configuration) were compiled to evaluate their long-term economic profiles.

The Present Value Factor (PVF) representing the cumulative discount mechanism over the 30-year lifecycle is computed as:

$$PVF = \sum_{t=1}^{30} \frac{1}{(1+0.08)^t} = \frac{1 - (1+0.08)^{-30}}{0.08} \approx 11.258$$

A comparative evaluation of the three options yields the following quantitative economic performance metrics:

- **Option 1 (1 SA Configuration):** Under severe lightning exposure and poor grounding, simulations indicate that the restricted protection coverage leads to equipment insulation overstress at a lightning current of 100 kA. According to Table 6, the exceedance probability for a 100 kA stroke is 4.5%. Thus, the annual failure probability (P_{failure}) is conservatively set at 4.5%.

$$C_{\text{Inv.}} = 1 \times \$5,000 = \$5,000$$

$$E_{\text{CI}} = 0.045 \times \$2,000,000 = \$90,000 \text{ /year}$$

$$LCC = \$5,000 + (\$90,000 \times 11.258) = \$1,018,220$$

- **Option 2 (3 SAs Configuration):** Expanding the configuration to 3 SAs dampens local reflections and extends the withstand capability up to strokes of nearly 200 kA. Based on this limit and Table 6, the annual failure probability (P_{failure}) is reduced to 0.78%.

$$C_{\text{Inv.}} = 3 \times \$5,000 = \$15,000$$

$$E_{\text{CI}} = 0.0078 \times \$2,000,000 = \$15,600 \text{ /year}$$

$$LCC = \$15,000 + (\$15,600 \times 11.258) = \$190,625$$

- **Option 3 (Comprehensive 5 SA Configuration):** The systematic scenario evaluation demonstrates that a 5-unit deployment successfully suppresses terminal overvoltages below the critical insulation thresholds ($U_{\text{max}} \leq \text{BIL}/1.2$) even at the maximum simulated severe stroke of 250 kA. Based on the statistical model, the probability of exceeding this extreme stroke is merely 0.44%, effectively bounding the risk of failure to this minimum threshold ($P_{\text{failure}} = 0.44\%$).

$$C_{\text{Inv.}} = 5 \times \$5,000 = \$25,000$$

$$E_{\text{CI}} = 0.0044 \times \$2,000,000 = \$8,800 \text{ /year}$$

$$LCC = \$25,000 + (\$8,800 \times 11.258) = \$124,070$$

The quantitative results clearly indicate that although Option 3 requires a \$20,000 increase in initial CAPEX compared to Option 1, it delivers an extraordinary reduction in risk-adjusted operational costs, lowering the Life Cycle Cost from \$1,018,220 to just \$124,070. This translates to net savings exceeding \$894,000 over the 30-year operational horizon. Concurrently, Option 3 effectively distributes the lightning impulse current across multiple parallel paths, successfully limiting the maximum individual thermal stress to 2.08 kJ/kV (recorded at VT1), which represents a conservative 41.6% of the rated energy absorption capability (5 kJ/kV) [20].

4.7. Comparative analysis with existing literature

To further substantiate the effectiveness of the proposed scenario-based protection framework, the comprehensive configuration (Option 3) was benchmarked against conventional surge arrester (SA) placement strategies documented in recent high-voltage literature.

Recent studies, such as the heuristic placement approach by Safaei et al. , primarily focus on minimizing lightning flashover rates using static grounding models. While effective under standard operating conditions, their approach does not account for the arresters' dynamic energy-duty limits under multiple severe surge reflections. When subjected to the extreme 250 kA deterministic scenario in this study, conventional single- or restricted-placement strategies resulted in localized arrester energy absorption exceeding 6.2 kJ/kV, inevitably leading to thermal runaway and device failure.

In contrast, the methodology proposed in this work actively incorporates the Korsunsky dynamic ionization model and evaluates strict thermal constraints (5 kJ/kV). Consequently, the proposed 5-SA topology not only maintains a superior insulation margin across all equipment (achieving a minimum PR_L of 1.25) but also suppresses the maximum absorbed energy to 2.08 kJ/kV.

Furthermore, unlike the purely technical assessments seen in [1] and [2], the integration of the Expected Annual Damage Cost (E_C) in this study provides grid operators with a definitive financial justification for deploying multiple arresters. This comprehensive approach demonstrates that technical robustness – achieved through strategic multi-point coordination – translates directly into significant mitigation of lifecycle risks and long-term economic savings.

5. Conclusion

This paper successfully developed a scenario-based probabilistic assessment framework that integrates ATP-EMTP transient simulations with Life Cycle Cost (LCC) analysis to address complex insulation coordination challenges in 220 kV substations. By evaluating the dynamic interactions between stochastic lightning currents, dynamic tower-footing resistance, and alternative SA topologies, the following key conclusions are drawn:

- **Vulnerability under Poor Grounding:** Under severe lightning events (up to 250 kA), transferred surges can exceed 5.5 MV at the station entrance. While lowering tower-footing resistance from 100 Ω to 10 Ω reduces peak overvoltages, mitigating grounding resistance in isolation is insufficient to ensure complete insulation coordination.
- **Optimal SA Topology and Technical Performance:** Systematic evaluation of alternative installation schemes identified a 5-unit ZnO arrester topology as the optimal protection solution. This configuration successfully suppresses terminal overvoltages across all critical nodes, ensuring a robust minimum Protection Ratio Level (PRL) of 1.25. Additionally, the distributed arrangement limits the maximum absorbed energy to 2.08 kJ/kV, ensuring the arresters operate safely below their 5 kJ/kV thermal limit.
- **Economic Justification:** The integrated Cost-Benefit Analysis (CBA) confirmed that the comprehensive 5-SA configuration bounds the annual risk of transformer failure to 0.44%. This risk mitigation translates to a substantial Life Cycle Cost (L_{CC}) saving of over \$894,000 compared to a baseline single-arrester deployment over a 30-year operational horizon.

Ultimately, this study provides a comprehensive, economically justified set of guidelines for utility engineers, ensuring reliable overvoltage protection and optimal capital allocation in regions characterized by severe atmospheric discharges and high soil resistivity.

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REFERENCES

- [1] N. A. Sabiha and H. I. Alkhamash, "Performance evaluation of distribution and low-voltage networks under lightning activity," *Energies*, vol. 16, pp. 1-15, 2023.
- [2] Y. Xu et al., "Lightning risk estimation and preventive control method for power systems," *Electric Power Systems Research*, vol. 214, p. 212, 2023.
- [3] R. Alipio, A. M. Santos, S. Visacro, and R. Alipio Jr., "Influence of a lossy ground on the lightning performance of overhead transmission lines," *Electric Power Systems Research*, vol. 214, 2023.
- [4] S. Visacro, "The use of tower-footing impulse impedance in lightning performance studies," *IEEE Transactions on Electromagnetic Compatibility*, vol. 66, no. 1, p. 123–132, 2024.
- [5] F. Safaei and M. Niasati, "A new method for surge arrester placement in high-voltage substations considering environmental effects," *IET Science, Measurement and Technology*, vol. 18, no. 9, p. 550–563, 2024.
- [6] Rua'a S. Rashak, Sana Majeed, "The cost-effective installation of a surge arrester to improve lightning performance at a 400 kV substation," in *2ND INTERNATIONAL CONFERENCE ON APPLIED RESEARCH AND ENGINEERING (ICARAE2022)*, 2025.
- [7] Akifumi Yamanaka, Kazuyuki Ishimoto, "Lightning overvoltages incoming to a substation: Analysis with emphasis on the LEMP impact," *Electric Power Systems Research*, vol. 249, 2025.
- [8] Mohammad Ghomi, Filipe Faria da Silva, Amir Abbas Shayegani Akmal, Claus Leth Bak, "Transient overvoltage analysis in the medium voltage substations based on full-wave modeling of two-layer grounding system," *IET Generation, Transmission & Distribution*, vol. 211, 2022.
- [9] IEC Std. 60071-1-2006, Insulation co-ordination, Part 1: Definitions, principales and rules, IEC, 2006.
- [10] IEEE Std. C62.22-2009, Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems, New York, 2009.
- [11] ANSI/IEEE Std. C37.011-1979, IEEE Application Guide for Transient Recovery Voltage for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis, IEEE, 1997.
- [12] Marti, J., "Accurate modelling of frequency-dependent transmission lines in electromagnetic transient simulations," *IEEE Transactions on Power Apparatus and Systems*, vol. 101, no. 1, p. 147–157, 1982.
- [13] IEEE Std. 1313.2-1999, IEEE Guide for the Application of Insulation Coordination, IEEE, 1999.
- [14] Juan A. Martinez-Velasco, "Transient Analysis of Power Systems: Solution Techniques, Tools and Applications", John Wiley & Sons, Ltd, 2015.
- [15] P. L. Bellaschi, R. E. Armington, and A. E. Snowden, "Impulse and 60-Cycle Characteristics of Driven Grounds," *AIEE Transactions*, vol. 60, no. 3, pp. 123-128, 1941.
- [16] A. Hileman, "Insulation Coordination for Power Systems", Marcel Dekker, 1999.
- [17] K. Berger, R. B. Anderson, and H. Kroninger, "Parameters of the Lightning Stroke," *Electra*, no. 41, pp. 23-37, 1975.
- [18] CIGRE Std. 549, Lightning Parameters for Engineering Applications, CIGRE, 2013.
- [19] IEC Std. 60099-4, Surge Arresters – Part 4: Metal-oxide surge arresters without gaps for a.c. systems, IEC, 2014.
- [20] Siemens energy, High-voltage surge arresters, product guide, Erlangen, Germany: Siemens AG, 2023.
- [21] CIGRE WG 33.01, Guide to procedures for estimating the lightning performance of transmission lines, CIGRE, 1991.
- [22] IEC Std. 61936-1:2021, Power installations exceeding 1 kV AC and 1,5 kV DC - Part 1: AC, IEC, 2021.
- [23] IEEE Std. 1410-2010, IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines, IEEE, 2010.
- [24] CIGRE Std. TB 63, Guide to Procedures for Estimating Lightning Performance of Transmission Lines, CIGRE, 2021.
- [25] Mansour Moradi, Hamdi Abdi, Arash Atefi, "Analyzing and Modeling the Lightning Transient Effects of 400 KV Single Circuit Transmission Lines," *International Journal of Science and Engineering Investigations*, vol. 2, no. 19, pp. 61-67, 2013.
- [26] IEEE Std. 998, "Guide for Direct Lightning Stroke Shielding of Substations", IEEE, 2013.
- [27] Peerawut Yutthagowith, Sutee Leejongpermpoon, Nawakun Triruttanapiruk, "A Simplified Model of a Surge Arrester and Its Application in Residual Voltage Tests," *Power System Transients and Protection*, vol. 14, no. 11, 2021.
- [28] Nagananthini Ravichandran, Daniela Proto, Amedeo Andreotti, "Surge arrester optimal placement in distribution networks: A decision theory-based approach," *Electric Power Systems Research*, vol. 234, 2024.
- [29] Zacharias G. Datsios et al., "Estimation of Lightning Overvoltages and Critical Backflashover Current of a 150 kV Overhead Line due to Subsequent Strokes," in *37th International Conference on Lightning Protection*, Dresden, Germany, 2024.
- [30] Antonio Marcelino Silva Filho et al, "Measurement of grounding resistance over a seasonal cycle with hygroscopic materials in the encapsulation of grounding rods," *Measurement*, vol. 248, p. 116767, 2025.

