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Enhancing Surge Protection Scheme in Distribution Networks of Nepal for Lightning Overvoltage Analysis at Goldhunga Feeder (using EMTP-RV)

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Abstract

Lightning-induced overvoltages pose a major threat to Nepal's Integrated Nepal Power System (INPS), particularly in mountainous regions with high lightning activity. This study analyzes surge behavior and mitigation strategies across 132 kV, 66 kV, and 33 kV transmission lines, as well as 11 kV and 0.4 kV distribution networks, focusing on a case study of the 11 kV Goldhunga feeder in Tarkeshwor Municipality, Kathmandu Valley. The feeder is modeled using field data from the Nepal Electricity Authority (NEA), while higher-voltage lines are represented using typical INPS configurations adapted from IEEE/CIGRÉ standards, incorporating NEA-specific conductor types (e.g., ACSR Dog for 33 kV, ACSR Panther for 66/132 kV), tower footing resistance (10–100 Ω), and insulation levels suited to Nepal's high lightning ground flash density (up to 25.31 strokes/km²). EMTP-RV simulations with 2020–2023 lightning data evaluate critical factors such as Metal Oxide Surge Arrester (MOSA) placement, arrester lead length, TFR, and secondary-side protection. Results show that locating MOSAs within 3 m of transformer terminals, keeping lead lengths below 1 m, and maintaining TFR under 10 Ω significantly reduces peak overvoltages and surge transfer risks, while secondary-side arresters effectively suppress transferred surges to protect transformers and downstream equipment. Conversely, inadequate protection at lower voltages (11 kV and 0.4 kV) causes severe voltage stress and equipment failures. These findings provide a robust, evidence-based framework for optimizing lightning protection in Nepal's lightning-prone, topographically challenging grid, enhancing reliability, minimizing outages, and offering valuable insights for other mountainous power systems worldwide.

Keywords—*Lightning overvoltage, MOSA, surge transference, EMTP-RV, Tower Footing Resistance, Nepal*

1. INTRODUCTION

Nepal's electrical power system, particularly its 33 kV and 11/0.4 kV distribution network, faces significant challenges in ensuring power continuity and equipment protection. The Goldhunga 11 kV distribution feeder in Tarakeshwar Municipality is considered a critical area because it supplies densely populated communities and essential services, traverses complex terrain at altitudes of 1300–1550 m, and is exposed to comparatively higher lightning incidence than adjacent feeders [1]. These characteristics make it more vulnerable to supply interruptions. Among the leading causes of disruptions are voltage surges, which can result in severe overvoltages and equipment failures [2,3]. Lightning-induced surges present a significant threat to high-voltage equipment, underscoring the need for robust insulation coordination and optimized surge protection tailored to this feeder [3,4].

To mitigate these damaging surges effectively, Metal Oxide Surge Arresters (MOSAs) serve as indispensable components in modern networks. However, their mere installation does not always guarantee adequate protection; improper ratings or suboptimal placement may leave equipment vulnerable to severe overvoltages [1]. This reality highlights the critical need for comprehensive system-level analyses to determine optimal placement, proper rating selection, and effective operational strategies for MOSAs [3,13,15].

When lightning strikes an overhead distribution line, such as those in Nepal's 33 kV network and the Goldhunga 11 kV feeder, it induces substantial voltages across phase conductor insulators [4]. Given the highly unpredictable nature of lightning, the protection range must be carefully evaluated in design calculations to ensure reliable and safe operation. Both lightning and switching surges contribute to overvoltages that significantly influence substation design and insulation coordination [9]. In higher-voltage systems, including 132 kV and 66 kV transmission lines, lightning surges generally pose a greater challenge than switching surges, as their severity is largely independent of the system voltage. This highlights the need for robust lightning protection measures [3,17].

Several mitigation strategies can be employed to reduce outages caused by lightning, including reducing tower footing resistance (TFR), enhancing line insulation, and installing ground wires [1,14,18]. However, certain techniques, such as ground wires on complex structures or under-built shield wires, may be economically or practically infeasible in Nepal's diverse terrain [5]. Conversely, the use of line surge arresters, especially MOSAs, is widely recognized as the most efficient and economically viable solution for achieving high lightning performance in transmission and distribution lines, particularly in regions with high soil resistivity [5,16]. For example, studies in Swaziland have shown that reducing footing resistance to 10 Ω or lower through techniques like crowfoot earthing significantly reduces transformer failure rates [6].

A detailed investigation of surge impacts in and around substations is essential to accurately evaluate overvoltage levels and their probabilities throughout the facility [10]. At higher system voltages, implementing overvoltage protection using MOSAs is generally more cost-effective than solely increasing insulation withstand levels. MOSAs are distinguished by their fast response times, high energy absorption capacity, and ability to suppress follow-on AC currents, thereby maintaining system continuity after activation [2,5].

This study focuses on evaluating protection strategies for line voltages ranging from 66 kV to 11 kV and from 132 kV to 33 kV, which reflect the typical transmission and distribution configurations of Nepal's Integrated Nepal Power System (INPS) [6]. Specifically, the 11 kV Goldhunga feeder is modeled based on actual field parameters obtained from NEA records, while representative 33 kV, 66 kV, and 132 kV lines are modeled using standard IEEE/CIGRÉ configurations adapted to Nepalese operating conditions. This hybrid approach ensures both practical relevance and methodological consistency in the simulations. The simulation analyses are conducted using EMTP-RV software [7], a globally recognized platform for transient and surge studies [2,3]. Key aspects of the analysis include assessing the influence of arrester distances from power transformers and other critical substation equipment, as well as the impact of tower footing resistance (TFR) on these distances [1,12]. For instance, research on 33 kV wood-pole distribution lines demonstrates the application of metal-oxide surge arresters (MOSAs) with a 10-kA nominal discharge current, 32 kV MCOV, and 3.6 kJ/kV energy capability, emphasizing the importance of precise arrester placement [4,8]. Moreover, the effect of lead length on arrester performance is also crucial, as shorter lead lengths are consistently shown to improve surge mitigation effectiveness [11].

Nepal experiences substantial lightning activity, with over one million strokes recorded annually between 2016 and 2020 [7], predominantly during the pre-monsoon and monsoon seasons [5]. The geographical distribution of these strokes is highly non-uniform due to Nepal's complex topography. Mountainous and hilly regions, particularly in the central and eastern parts of the country, exhibit higher lightning stroke densities, while the flat Terai region generally experiences lower densities. This uneven distribution, combined with steep elevation changes and variable soil resistivity, significantly influences lightning-induced overvoltages on distribution networks, making location-specific protection strategies essential for system reliability.

2. METHODOLOGY

Effective arrester placement is essential for mitigating overvoltage surges [13]. In this study, arrester performance is analyzed by positioning arresters at various distances from the power transformer (3 m, 6 m, 9 m, 12 m, and 15 m), with a focus on the transference of surges from the transformer's primary to secondary side [12]. The analysis considers the surge current flowing through the arrester immediately after sparkover, representing the energy clamped by the device. Although a lightning current magnitude of 10 kA represents a high-magnitude event occurring in only about 1% of strikes [8], this conservative assumption ensures that the arrester's protective capability is evaluated under extreme conditions. The study also examines the influence of tower footing resistance (TFR) on the operation of metal-oxide surge arresters (MOSA), highlighting its critical role in controlling residual voltages and limiting surge transference.

The study further investigates system behavior during lightning surges without secondary-side MOSAs to understand potential vulnerabilities. Computations are performed for strikes at different points along the line, and the impact of arrester lead length is also assessed [11]. All analyses are conducted using EMTP-RV software [2,3,7], ensuring robust and precise transient simulation results.

3. SIMULATION

3.1 Tower Footing Resistance

Tower footing resistance (TFR) is a critical parameter, comprising two primary components: the inherent resistance of the tower's metallic structure and the resistance offered by the surrounding soil to current dissipation [1]. In Nepal's 33 kV and 11/0.4 kV systems, although tower structures may be similar, actual TFR values vary significantly due to diverse local soil conditions and grounding effectiveness. Techniques such as crowfoot earthing are commonly employed to reduce TFR and enhance system resilience [6].

For short line segments, assuming a uniform TFR might be acceptable for simplification. However, for longer lines such as the 45 km line considered in this study, assuming uniform TFR is unrealistic. Variations in soil resistivity, grounding design, and environmental conditions lead to non-uniform footing resistance across towers [14,18]. Areas with elevated TFR are particularly critical, as they significantly influence lightning surge behavior, potentially increasing flashover risks and causing widespread outages [1].

In EMTP-RV, TFR can be modeled using a nonlinear resistor to account for soil ionization effects under high lightning currents [3,4]. The dynamic behavior of TFR during impulse currents is often represented using soil resistivity (ρ) and soil ionization gradient (E_0), as described by:

$$R_i = \left(1 + \frac{I}{I_g}\right) R_0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where:

- R_i is the instantaneous footing resistance during a lightning strike,
- R_0 is the nominal (low-current) footing resistance (e.g., 10 Ω),
- I is the lightning strike current (kA),
- I_g The limiting current required to initiate soil ionization, approximated by:

$$I_g = \frac{\rho}{2\pi E_0 R_0^2} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2)$$

Here, E_0 It is typically about 400 kV/m.

This non-linear modeling approach allows a more accurate representation of the tower grounding performance under high-current lightning impulses, where local soil resistivity is effectively reduced due to ionization [3]. Considering these variations is essential in Nepal's diverse terrain to ensure robust lightning resilience [14].

3.2 Surge Transference

Transformers used in Nepal’s 33 kV, and 11/0.4 kV overhead distribution networks are highly susceptible to voltage surges, particularly in mountainous and lightning-prone regions [12]. Both direct strikes and induced surges can lead to severe internal insulation failures and permanent equipment damage. Surge transference refers to the phenomenon where surge energy propagates from the primary (high-voltage) winding to the secondary (low-voltage) side when lightning strikes the primary feeder [12]. This transferred surge can induce substantial overvoltages on the secondary side, threatening end-user equipment and causing system-wide outages. Distribution transformers, designed primarily for low-voltage operations, are particularly vulnerable as they lack the high-energy transient withstand capabilities of larger power transformers. Key parameters influencing this phenomenon include surge amplitude, waveform characteristics, transformer turns ratio, secondary cable length, and surge frequency content [12]. High-frequency lightning surges, due to their sharp rise times, are transmitted quickly. Longer secondary cables increase the likelihood of harmful surges reaching sensitive equipment downstream. Additionally, impedance mismatches can cause partial reflections, compounding internal stress.

Therefore, a comprehensive analysis of surge transference is vital for effective surge protection planning. Evaluating configurations such as no arresters, arresters only on the primary side, and arresters on both sides is crucial to identify the most effective approach for minimizing surge-related damages in Nepalese distribution systems [13,15].

3.3 Connecting Conductor Length

The connecting conductor length, or arrester lead length, is the physical distance between a surge arrester and the protected equipment or line. Precise evaluation of this length is essential during arrester installation, as it significantly affects the protective performance and energy dissipation capability [11]. Shorter lead lengths generally offer superior protection against overvoltages.

The protective voltage V_p equipment terminals with an arrester installed are given by:

$$V_p = V_{res} + L\frac{di}{dt} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3)\ [11]$$

where:

- V_{res} is the residual voltage across the arrester during discharge,
- L is the inductance of the connecting leads,
- $\frac{di}{dt}$ is the surge current rise rate.

This occurs because the connecting leads behave as inductors. When a surge with a steep current rises high $\frac{di}{dt}$ passes through them [11], the inductive voltage ($L\cdot\frac{di}{dt}$) adds to the arrester's residual voltage. Longer leads have higher inductance, so the resulting voltage at equipment terminals can exceed safe limits, even if the arrester itself clamps at a low residual voltage.

3.4 Parameter Representation and Modeling

Accurate lightning performance analysis for distribution and transmission lines necessitates detailed parameter modeling, typically using advanced tools like EMTP-RV [2,3,7]. These tools capture frequency-dependent behaviors crucial for transient surge simulations.

Transmission lines are modeled using frequency-dependent line models that define distributed parameters R(f), L(f), C(f), and G(f) as functions of frequency. The propagation constant γ(f) and characteristic impedance$Z_C(f)$ are given by:

$$\gamma(f) = \sqrt{R(f) + j2\pi f L(F)(G(f) + j2\pi f C(F)}\ldots\ldots\ldots\ldots (4)$$

$$Z_C(f) = \sqrt{\frac{R(f)+j2\pi f L(F)}{G(f)+j2\pi f C(F)}}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

These parameters determine the behavior of traveling voltage and current waves. Cable sections are modeled using distributed parameter (CP) models with detailed impedance characteristics.

Surge arresters are represented using IEEE-standard nonlinear models (e.g., IEEE Std C62.11), incorporating frequency-dependent V-I characteristics [3,4]. The fundamental MOV behavior is described as:

$$I = kV^{\propto}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

where:

- I is the current through the MOV element,
- V is the voltage across it,
- K is a constant,
- α is the non-linearity exponent (typically 10–60).

EMTP-RV typically approximates this relationship using multiple linear segments or equivalent circuits that include non-linear resistances and parasitic inductive/capacitive elements, thus accurately reproducing arrester dynamics under different surge conditions. Additional characteristics are detailed in Table 1, shown below.

Tower models often use impedance-based representations, combining lumped R-L branches and grounding impedance via non-linear resistors reflecting local soil resistivity. Surge propagation speed is generally set at 90% of the speed of light, per IEEE recommendations.

In Nepal's 33 kV and 11/0.4 kV systems, this advanced modeling approach is crucial for accurately assessing lightning performance and optimizing protective strategies across diverse terrains. In the simulations, soil resistivity values ranging from 100 Ωm (wet alluvial plains) to 1000 Ωm (rocky hill terrains typical of Kathmandu) were assumed, reflecting the wide variation in local grounding conditions that critically influence surge dissipation and protection effectiveness [1].

Table 1: Arrester parameters calculated (Balaju substation side visit)

Parameter	**132 kV**	**66 kV**	**33kV**	**11kV**	**0.4 kV (LV)**
L1(μH)	15.0	8.0	12.0	4.0	1.2
L0(μH)	0.20	0.12	0.16	0.06	0.02
R1(Ω)	65	35	50	18	6
R0(Ω)	100	55	80	30	10
C1 (nF)	0.12	0.22	0.14	0.42	0.65

4. RESULTS AND INTERPRETATION

Table 2: For the analysis, the five different cases are considered

Case No.	**Description**
Case 1	Evaluation of system behavior with arrester installation
Case 2	Assessment of tower footing resistance (TFR) influence on arrester effectiveness
Case 3	Analysis of surge transference without an arrester on the secondary side
Case 4	Analysis of surge transference with an arrester installed on the secondary side
Case 5	Investigation of the impact of arrester connecting conductor (lead) length on surge transference

Case-1:

A case of Evaluation of system behavior with arrester installation position from the transformer is observed. Its observation is shown in Tables 3 & Table 4.

Table 3: Observation for 66 kV

Arrester Distance from Transformer (m)	**Rise in Voltage for Lightning Strike at 0.5 km (kV)**	**Rise in Voltage for Lightning Strike at 20 km (kV)**
3 m	90.5	85.7
6 m	140.2	103.5
9 m	145.8	107.4
12 m	150.6	112.9
15 m	195.7	128.6

Table 4: Observation for 132 kV

Arrester Distance from Transformer (m)	**Rise in Voltage for Lightning Strike at 0.5 km (kV)**	**Rise in Voltage for Lightning Strike at 20 km (kV)**
3 m	190.5	182.6
6 m	265.8	272.4
9 m	285.4	276.7
12 m	290.2	281.5
15 m	335.6	288.3

Case-2:

The assessment of tower footing resistance (TFR) influence on arrester effectiveness for TFR values of 10Ω and 20Ω, as observed in lightning strikes at 0.5km, is presented in Tables 5 & and 6. And its analysis is shown in Figures 1 & and 2.

Table 5: Observation of TFR for 66kV

Arrester Distance from Transformer (m)	**Rise in Voltage with TFR = 10 Ω (kV)**	**Rise in Voltage with TFR = 15 Ω (kV)**	**Rise in Voltage with TFR = 20 Ω (kV)**
3 m	90.5	93.1	95.7
6 m	140.2	147.5	155.3
9 m	145.8	162.1	178.4
12 m	150.6	173.3	195.9
15 m	195.7	204.0	212.4

Table 6: Observation of TFR for 132kV

Arrester Distance from Transformer (m)	**Rise in Voltage with TFR = 10 Ω (kV)**	**Rise in Voltage with TFR = 15 Ω (kV)**	**Rise in Voltage with TFR = 20 Ω (kV)**
3 m	190.5	191.3	192.1
6 m	265.8	268.2	270.5
9 m	285.4	286.3	287.2
12 m	290.2	294.4	298.6
15 m	335.6	340.2	344.8

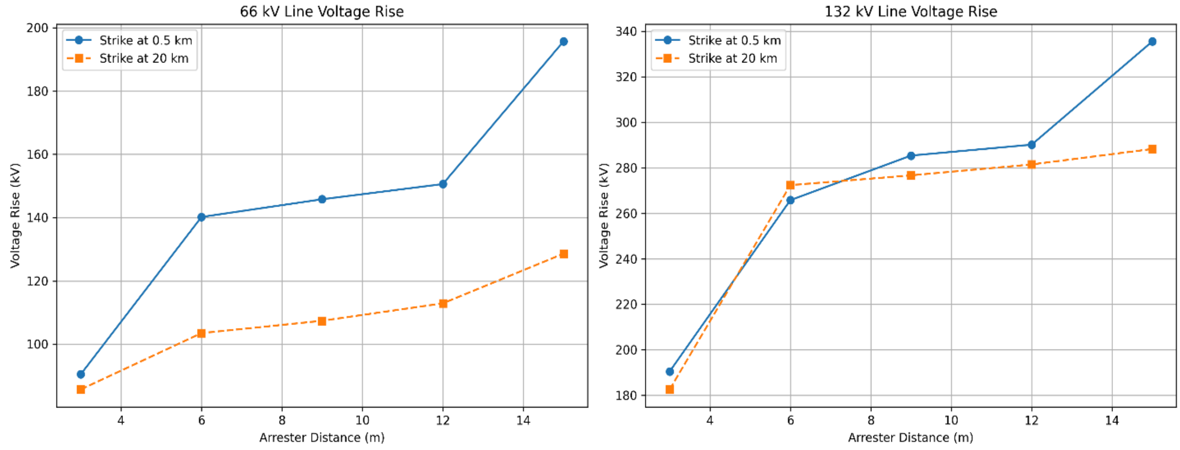

Figure 1: Voltage Rise in 66 kV and 132 kV Distribution Lines Due to Lightning Strikes at Different Distances with Varying Arrester Locations in Nepal

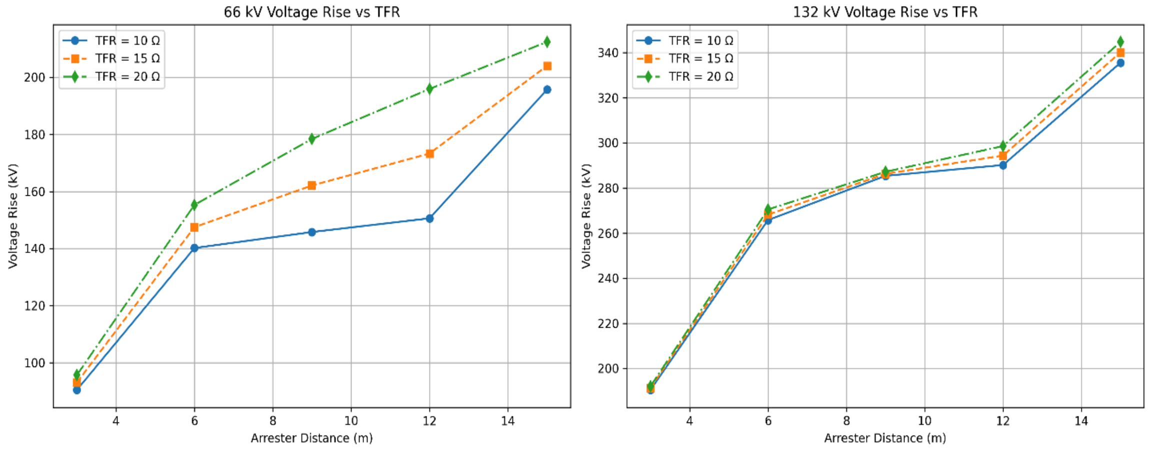

Figure 2: Impact of Tower Footing Resistance (TFR) on Voltage Rise for 66 kV and 132 kV Distribution Lines with Various Arrester Positions in Nepal

Case 3: The effect of surge transference without a secondary-side arrester is presented in Tables 7 and 8 for the 11 kV and 33 kV systems, respectively, and analyzed in Figure 3 and 4.

Table 7: Effect of surge transference at 11 kV w/o Arrester

Arrester Distance from Transformer (m)	**Surge Transference without Arrester (kV) - Lightning Strike at 0.5 km**	**Lightning Strike at 10 km**	**Lightning Strike at 20 km**
3 m	18.5	16.2	14.3
6 m	25.3	24.1	23.4
9 m	27.1	26.0	25.2
12 m	28.0	27.3	26.9
15 m	30.0	29.0	28.4

Table 8: Effect of surge transference at 33 kV w/o Arrester

Arrester Distance from Transformer (m)	**Surge Transference without Arrester (kV) - Lightning Strike at 0.5 km**	**Lightning Strike at 10 km**	**Lightning Strike at 20 km**
3 m	52.5	50.1	44.1
6 m	59.8	58.3	58.8
9 m	62.1	60.9	61.7
12 m	64.3	62.7	62.3
15 m	65.2	63.5	62.6

Case-4: The impact of installing an arrester on the secondary side of the transformer is analyzed in Figures 3 and 4, with corresponding observations summarized in Tables 9 and 10.

Table 9: Effect of surge transference at 11 kV with Arrester

Arrester Distance from Transformer (m)	**Surge Transference with Arrester (kV) - Lightning Strike at 0.5 km**	**Lightning Strike at 10 km**	**Lightning Strike at 20 km**
3 m	14.0	13.9	13.7
6 m	14.4	14.2	14.0
9 m	14.5	14.3	14.2
12 m	14.3	14.2	14.2
15 m	14.3	14.3	14.3

Table 10: Effect of surge transference at 33 kV with Arrester

Arrester Distance from Transformer (m)	Surge Transference with Arrester (kV) - Lightning Strike at 0.5 km	Lightning Strike at 10 km	Lightning Strike at 20 km
3 m	37.5	37.0	36.1
6 m	39.2	38.4	37.3
9 m	39.7	38.8	37.4
12 m	40.1	39.5	38.7
15 m	41.0	40.3	39.7

Table 11: Effect of Surge Transference at 0.4 kV Without Arrester

Arrester Distance from Transformer (m)	Surge Transference without Arrester (kV) - Lightning Strike at 0.5 km	Lightning Strike at 10 km	Lightning Strike at 20 km
3 m	3.2	2.8	2.5
6 m	3.8	3.5	3.2
9 m	4.1	3.9	3.5
12 m	4.3	4.1	3.8
15 m	4.5	4.3	4.0

Table 12: Effect of Surge Transference at 0.4 kV With Arrester

Arrester Distance from Transformer (m)	Surge Transference with Arrester (kV) - Lightning Strike at 0.5 km	Lightning Strike at 10 km	Lightning Strike at 20 km
3 m	2.1	2.0	1.9
6 m	2.3	2.2	2.1
9 m	2.4	2.3	2.2
12 m	2.5	2.4	2.3
15 m	2.6	2.5	2.4

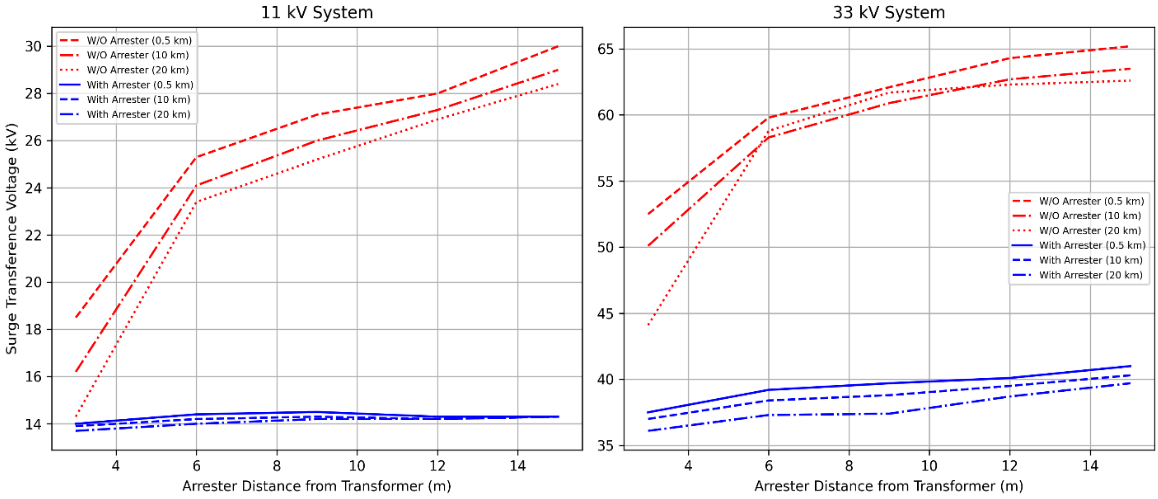

Figure 3 (a): Surge Transference Voltage vs. Arrester Distance from Transformer for 11 kV and 33 kV Distribution Systems under Multiple Lightning Strike Locations

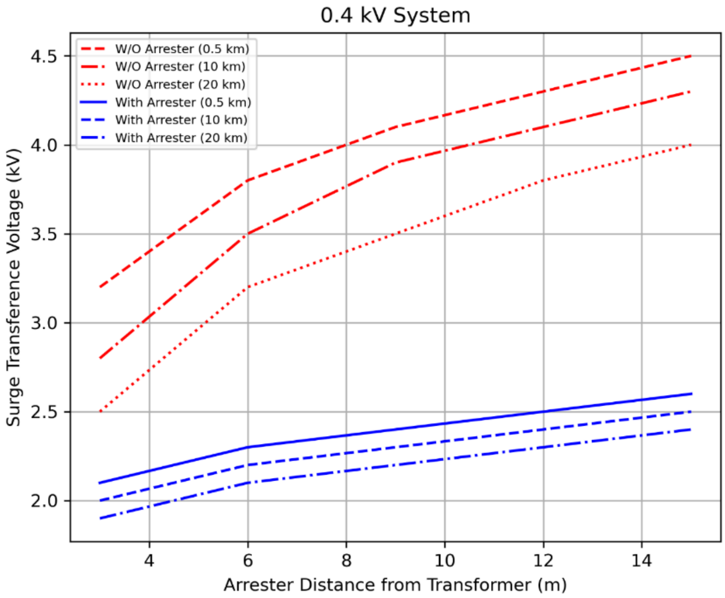

Figure 3 (b): Surge Transference Voltage vs. Arrester Distance from Transformer for 0.4k Distribution Systems under Multiple Lightning Strike Locations

Case-5: The influence of arrester lead length on surge transference under different lightning strike locations is examined in Figures 5 and 6, with detailed observations presented in Tables 11 and 12.

Table 13: Observation for Lead Length at 66 kV (Nepal

Arrester Lead Length (m)	**Rise in Voltage (kV) Lightning Strike at 500 m**	**Lightning Strike at 10 km**	**Lightning Strike at 20 km**
0.5	175.3	150.7	138.0
1.0	204.8	167.9	142.8
1.5	244.5	185.2	144.2
2.0	255.7	198.3	154.5

Table 14: Observation for Lead Length at 132 kV

Arrester Lead Length (m)	**Rise in Voltage (kV) Lightning Strike at 500 m**	**Lightning Strike at 10 km**	**Lightning Strike at 20 km**
0.5	220.3	218.4	216.6
1.0	236.1	232.0	227.5
1.5	264.0	250.2	234.2
2.0	267.0	258.1	234.5

Table 15: Observation for Lead Length at 33 kV

Arrester Lead Length (m)	**Rise in Voltage (kV) Lightning Strike at 500 m**	**Lightning Strike at 10 km**	**Lightning Strike at 20 km**
0.5	55.2	51.3	47.1
1.0	62.3	57.0	52.5
1.5	66.5	61.1	55.2
2.0	68.7	64.5	58.0

Table 16: Observation for Lead Length at 11 kV

Arrester Lead Length (m)	**Rise in Voltage (kV) Lightning Strike at 500 m**	**Lightning Strike at 10 km**	**Lightning Strike at 20 km**
0.5	19.3	18.2	17.1
1.0	22.5	20.6	19.3
1.5	23.7	21.5	20.2
2.0	24.8	22.4	21.1

Table 17: Observation for Lead Length at o.4 kV

Arrester Lead Length (m)	Rise in Voltage (kV) Lightning Strike at 500 m	Lightning Strike at 10 km	Lightning Strike at 20 km
0.5	4.2	3.9	3.6
1.0	4.8	4.4	4.0
1.5	5.1	4.7	4.2
2.0	5.3	4.9	4.4

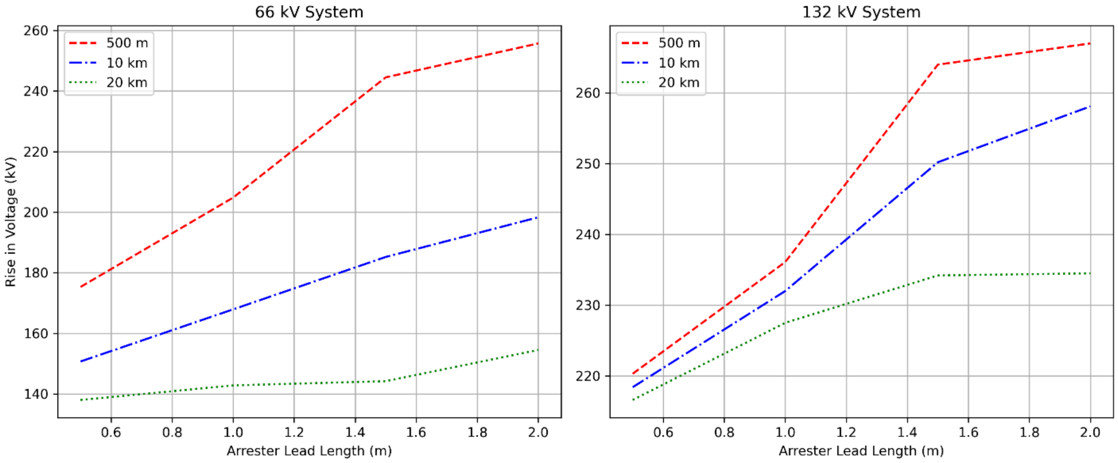

Figure 4 (a): Effect of Arrester Lead Length on Voltage Rise for 66 kV and 132 kV Systems in Nepal under Various Lightning Strike Distances

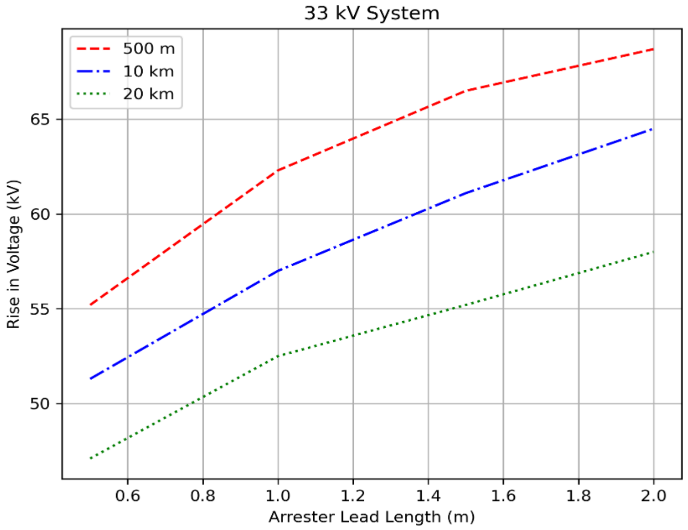

Figure 4 (b): Effect of Arrester Lead Length on Voltage Rise for 33 kV System in Nepal under Different Lightning Strike Locations

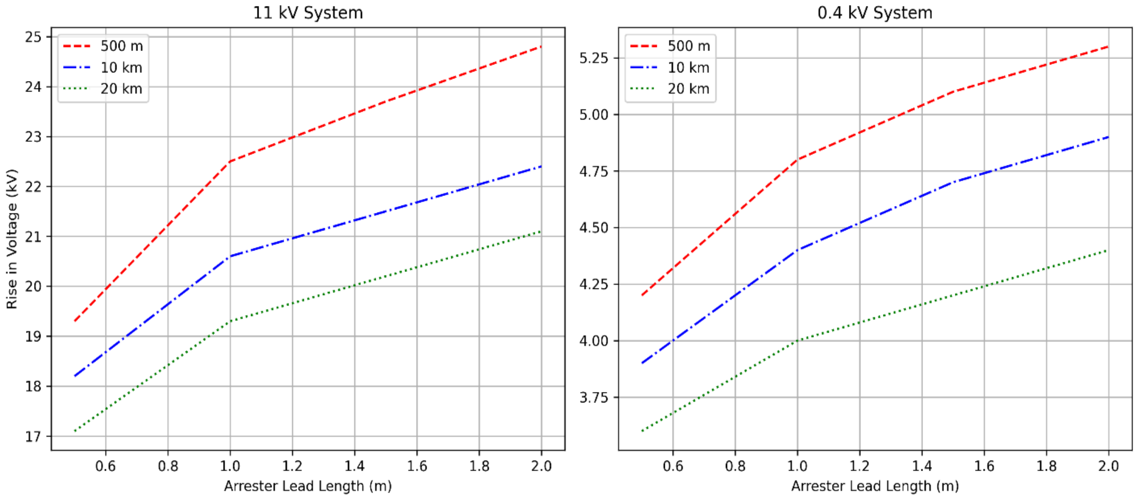

Figure 4 (c): Voltage Rise Response with Arrester Lead Length in 11 kV and 0.4 kV Systems in Nepal during Lightning Strikes at Different Distances

Although the fundamental behavior of surge transference is common across distribution networks globally, its impact is particularly pronounced in Nepal due to the region's mountainous terrain, heterogeneous soil resistivity, and high lightning activity. A detailed analysis indicates that arrester placement, grounding quality, and secondary-side protection are critical in mitigating overvoltages in these conditions. As shown in Tables 3 and 4 and Figures 1 and 2, increasing the arrester distance from the transformer (from 3 m to 15 m) results in a substantial rise in voltage at transformer terminals, especially in higher voltage systems (66 kV and 132 kV). This confirms that installing arresters closer to transformers effectively clamps surge energy before it propagates into the protected zone [1, 4, 13, 15, 16]. These observations are consistent with established insulation coordination principles, which emphasize minimizing inductive voltage drops across arrestor leads and connections to ensure optimal surge protection [11, 13, 15].

Additionally, the impact of tower footing resistance (TFR), as shown in Tables 5 and 6, indicates that higher tower grounding resistance (10–20 Ω) directly increases residual voltages during lightning surges, thereby reducing the protective effectiveness of the arrester [1]. This is consistent with previous studies demonstrating a direct correlation between high TFR and increased flashover rates or elevated surge voltages at equipment terminals, especially in areas with high soil resistivity [14, 17, 18]. Importantly, TFR is distinct from substation earthing: while TFR governs the surge behavior at tower and line locations, proper substation earthing ensures that surge currents are effectively dissipated at the transformer and substation equipment. Both factors play pivotal roles in mitigating surge effects and improving system resilience [6, 14, 18]. Further analysis of secondary-side protection (Tables 7–12 and Figures 3(a), 3(b)) demonstrates the benefits of installing arresters downstream of the main transformer. Without secondary-side arresters, surge voltages transferred to 11 kV and 33 kV systems remain high (up to 30 kV and 65 kV, respectively), posing risks to distribution equipment and end-user assets [12]. Installing arresters on the secondary side significantly reduces these transferred voltages, keeping them within safer operating limits and validating the effectiveness of multi-level protection strategies [2, 12].

Additionally, the influence of arrester lead length (Tables 13–17 and Figures 4(a)–4(c)) reveals that longer connecting conductors cause higher voltage rises at the transformer, especially under nearby lightning strikes (500 m) [11]. This is particularly critical for high-voltage systems, where an increase in lead length from 0.5 m to 2 m results in an up to 80 kV additional voltage rise in the 132 kV system. Even in lower voltage levels such as 11 kV and 0.4 kV, the incremental rise remains non-negligible and may jeopardize insulation integrity [11]. These findings corroborate previous studies emphasizing the significant inductive voltage drop across arrester leads, which can elevate the protective level despite the arrester's inherent clamping capability [11]. These results collectively emphasize that a holistic protection strategy incorporating optimal arrester positioning, minimizing lead length, and ensuring robust earthing is essential for safeguarding Nepalese power distribution networks against lightning-induced overvoltages, a principle validated in similar topographies and regions prone to high lightning activity [7, 8, 9, 14, 18].

5. CONCLUSION

This comprehensive study rigorously investigated the behavior of lightning-induced surges and evaluated advanced mitigation strategies across Nepal’s 132 kV, 66 kV, 33 kV, 11 kV, and 0.4 kV distribution networks, using the Goldhunga 11 kV feeder as a representative case. The Goldhunga feeder, comprising approximately 200 poles, 8-10 distribution transformers (100–300 kVA), mixed terrain conditions (rocky, wet, and densely vegetated areas), and diverse load types including residential, commercial, and critical public services, presents a unique combination of topographical and operational challenges compared to other feeders in the Kathmandu valley. Simulation-based analyses incorporating local lightning data, varying tower footing resistance (TFR), arrester placement distances, secondary-side surge protection, and arrester lead lengths provided a detailed understanding of surge dynamics specific to Nepal’s lightning-prone and mountainous regions. The results demonstrate that optimized arrester placement, particularly close to transformers, combined with low TFR values and minimized arrester lead lengths, significantly reduces peak voltage rises and surge transference risks. Secondary-side arresters are particularly effective in limiting transferred surges, safeguarding transformers and downstream sensitive equipment. Even at lower voltage levels, such as 11 kV and 0.4 kV, improper arrester placement or excessive lead lengths can generate substantial voltage stress, threatening equipment integrity and overall system reliability. Overall, this study provides a scientifically robust framework for implementing tailored lightning protection strategies in Nepal’s distribution networks, enhancing grid resilience, minimizing service interruptions, and ensuring operational safety. The insights gained are also applicable to other mountainous regions with similar soil, load, and lightning conditions, supporting improved lightning performance and a reliable power supply.

6. SUGGESTIONS AND RECOMMENDATIONS

For optimal protection against lightning-induced overvoltages in Nepal's power distribution networks, installing surge arresters as close as possible to transformer terminals is paramount to minimizing voltage rise. It's crucial to maintain low tower footing resistance (under 10 Ω) through advanced grounding. Implementing secondary-side arresters for 11 kV and 33 kV systems will significantly mitigate surge transfer, safeguard downstream equipment, and enhance reliability. Additionally, minimizing arrester lead length is vital for effective surge suppression. To ensure long-term integrity, mandatory periodic assessments and maintenance of protection systems are essential. Furthermore, updating Nepalese national grid standards to align with IEC and IEEE benchmarks, alongside specialized training for utility personnel, will bolster overall system resilience. Future research should prioritize real-time lightning monitoring, adaptive protection, and cost-benefit analyses across Nepal's diverse regions to support grid modernization and proactive surge management.

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