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Comparison Study on the Protection Characteristics of Non-Gap Line Arresters Against Lightning and Switching Transients in High-Voltage Power System

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ABSTRACT: In ultra-high-voltage alternating current (HVAC) transmission systems, switching and lightning transients pose major challenges to insulation coordination. Non-gap line arresters (NGLAs) offer a promising distributed protection solution, capable of suppressing both types of transients when being installed along the transmission corridor. However, the differences in protection performance under varying configurations and installation strategies remain insufficiently understood. This paper establishes a 750 kV, 400 km transmission line model using an ATP-EMTP and MATLAB co-simulation framework to investigate the transient suppression performance of NGLAs with different rated voltages and installation positions. Simulation results show that for switching transients, effective suppression of the 2% statistical overvoltage level below 1.8 p.u. can be achieved when NGLA is installed around an optimal position. Meanwhile, energy absorption of all arresters remains well below the 6 MJ thermal design threshold, confirming both suppression effectiveness and thermal stability. On the other hand, lightning transients exhibit strong spatial locality. NGLA can effectively reduce the lightning transient peak at positions close to lighting strike point. Even slight spatial offsets (1–5 km) drastically reduce its effectiveness in limiting peak voltage. Under typical lightning currents of 30–40 kA, the maximum energy absorbed by arresters remains below 2.2 MJ, demonstrating robust energy endurance. This study highlights the fundamental differences in propagation and protection mechanisms between switching and lightning transients, and underscores the need for differentiated arrester deployment strategies. The findings provide theoretical insight and engineering guidance for optimized NGLA configuration and insulation coordination in HVAC systems.

1. INTRODUCTION

The widespread application of ultra-high voltage alternating current (HVAC) transmission technology has provided reliable support for large-capacity, long-distance power transmission [1–3]. As the rated voltage (V_r) of systems increases, especially for systems with V_r exceeding 330 kV, switching transients have gradually replaced lightning transients as the determining factor in insulation coordination [4–7]. Therefore, effective suppression of switching transients along transmission lines, while also addressing lightning transient suppression, has become a key technology for improving system reliability, reducing insulation costs, and enhancing operational efficiency.

Currently, mitigation methods for switching transients in ultra-high voltage (UHV) systems include closing resistors, controlled phase-selection switching technology, controllable arrester technology, and externally gapped line arresters (EGLA) [8]. While EGLAs are commonly used in HVAC systems for lightning protection, non-gap line arresters (NGLAs) are less frequently applied in high-voltage systems. NGLAs, which lack a gap in their design, are generally more reliable and stable than EGLAs and have been effectively used in lower voltage systems for both lightning and switching transient suppression. However, their application in high-voltage systems is limited due to significantly different performances against lighting and switching transients, which leads to lack of guidelines in insulation coordination implementations [9].

On the other hand, methods like closing resistors, controlled-phase switching, and EGLAs are commonly deployed but come with challenges such as increased complexity, higher costs, and operational difficulties. For instance, closing resistors complicate mechanical and control operations, leading to increased failure risks [10, 11]. The reliability of closing resistors is a concern, as defects and faults often occur over time, resulting in incidents like breaker explosions [12–14]. Controlled-phase switching requires precise timing, and improper settings can cause voltage disturbances [15]. Controllable surge arresters, while effective, have complex systems and high costs [16]. EGLAs, while effective for lightning faults, do not mitigate switching transients [17, 18]. Given these challenges, a reliable and practical solution to suppress both lightning and switching transients is needed. NGLAs offer a promising alternative. This study investigates their performance in high-voltage HVAC systems, providing a comparative analysis of their effectiveness and limitations.

In recent years, extensive research has been conducted on suppressing switching overvoltages in EHV and UHV systems.

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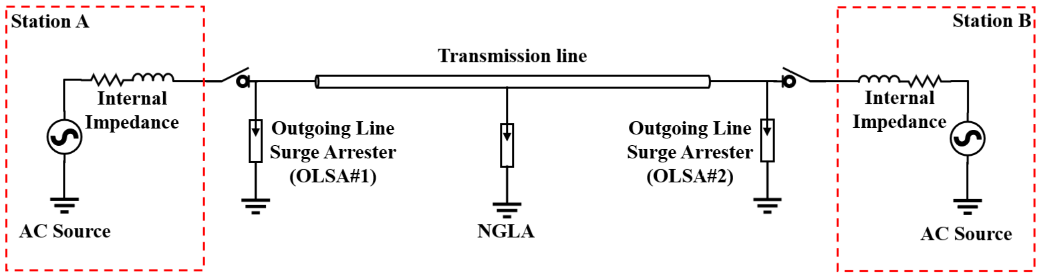

FIGURE 1. Schematic diagram of arrester installation along the line.

Regarding the removal of closing resistors, Ribeiro and McCallum pointed out that properly configured metal-oxide surge arresters can control overvoltages within acceptable limits, thus avoiding the maintenance issues associated with closing resistors [19]. Studies on 500 kV Henan system also showed that after removing closing resistors, switching overvoltages generally remained around 1.7–1.8 p.u., with arrester energy absorption within a safe range, indicating technical feasibility [20]. For converter stations, Ma et al. found that in 750 kV AC filters, the main capacitor branch suffered the most severe overvoltage, and a closing resistor about 400 Ω could effectively reduce both inrush current and overvoltage [21]. Lou et al. studied Baihetan-Yuecheng 500 kV project and reported that even without closing resistors, insulation requirements could still be met by using line arresters and controlling system voltage [22]. Field applications have also confirmed the effectiveness of transmission line arresters. For instance, the Salt River Project in the United States installed high-energy arresters at critical spans of a 500 kV line, successfully reducing overvoltages and avoiding costly tower modifications [23]. At higher voltage levels, He et al. proposed low-residual and controllable arresters, which suppressed switching overvoltages to about 1.2–1.6 p.u. and improved voltage distribution along the line, providing a new technical path for removing closing resistors in UHV systems [24].

Therefore, the study, which eliminates the need for closing resistors, lowers insulation levels, and meets lightning protection requirements, has engineering and economic significance [25–27]. This paper uses ATP-EMTP simulation software to investigate the switching transient and lightning transient levels in a 750 kV system with a 400 km transmission line under no-load reclosing conditions. It also analyzes the differences in the effectiveness of lightning and switching transient suppression when installing NGLA along the line. This study provides theoretical guidance for the collaborative suppression of lightning and switching transients using NGLAs.

This paper employs an ATP-MATLAB co-simulation platform to systematically investigate the suppression performance of NGLAs against switching overvoltages and lightning transients in a 750 kV AC transmission system. By simulating different voltage ratings, installation positions, and transient types, the study compares the mitigation effectiveness of NGLAs under both switching and lightning conditions, providing engineering references for insulation coordination and overvoltage protection design in ultra-high-voltage systems.

The structure of the paper is as follows. Section 2 introduces the system modeling, simulation configuration, and the co-simulation framework and evaluation methodology used to analyze switching and lightning transient responses. Section 3 examines the suppression performance of NGLAs against switching overvoltages. Section 4 focuses on the spatial suppression capability and limitations of NGLAs under lightning transients. Section 5 presents a comparative analysis of NGLA performance under switching and lightning transients. Finally, Section 6 summarizes the key findings and proposes practical recommendations for optimized NGLA deployment tailored to different transient scenarios.

2. SIMULATION MODEL AND METHODOLOGY

2.1. The Simulation Model

To investigate transient phenomena caused by various switching operations, this study focuses on two representative worst-case scenarios: no-load line energization and single-phase reclosing. A representative 750 kV transmission system is selected for analysis, with its simplified equivalent circuit illustrated in Fig. 1.

To reduce modeling complexity while preserving the dominant electromagnetic characteristics that influence transient behavior, the system is appropriately simplified. The modeling approach is outlined as follows:

1) The transmission line is represented using the J-MARTI frequency-dependent distributed parameter model, which accurately captures wave propagation, reflection, and attenuation effects. The modeled line adopts a single-circuit configuration with a six-bundle conductor (DC resistance of 0.08 Ω/km) and two overhead ground wires, each with a DC resistance of 0.43 Ω/km.

2) The surge protection devices under study are two standard NGLAs with rated voltages of $V_r = 600$ kV and $V_r = 648$ kV, denoted as Y20W-600/1380 and Y20W-648/1491, respectively. Their electrical characteristics are summarized in Table 1.

3) To assess the lightning transient response under back-flashover conditions, a standard negative lightning current waveform of 2.6/50 μs is applied, with peak amplitudes ranging from 30 kA to 40 kA. This setup emulates typical cloud-to-ground discharges and allows evaluation of the NGLA's capability in clamping high-frequency transients and mitigating insulation stress.

TABLE 1. Parameter of arresters under study.

V_r [kV]	Continuous Operating Transient [kV]	Lightning Transient Peak [kV]	Switching Transient Peak [kV]
600	462	≤ 1380	≤ 1142
648	498	≤ 1491	≤ 1234

4) Circuit breakers are modeled using a statistical switching scheme, incorporating 200 simulations with randomized closing times. The closing instant follows a Gaussian distribution with a mean of 50 ms and a standard deviation of 2.88 ms, in accordance with the mechanical characteristics of actual high-voltage breakers.

5) An ATP-EMTP model is developed based on real operating conditions. Source magnitudes and phase angles are adjusted to match steady-state power flow and node voltages. Source impedance is derived from bus voltage and three-phase short-circuit current, ensuring consistency with system-level electromagnetic behavior during transient events.

2.2. ATP-MATLAB Co-Simulation Model

To determine the optimal positioning for NGLAs, an ATP-MATLAB co-simulation framework is developed, enabling automated simulation and analysis under varying installation schemes. This integrated approach is necessitated by two critical challenges: (1) the need to iteratively adjust NGLA locations along a long transmission corridor, and (2) the requirement for statistically meaningful evaluations of switching transient responses under randomized breaker operations. The manual process of reconfiguring simulation cases and extracting relevant waveform data would be both time-consuming and error-prone. Hence, MATLAB is introduced to automate the generation, execution, and data collection of ATP-EMTP simulation cases, thereby significantly enhancing efficiency and ensuring consistency across thousands of iterations.

The implementation flow of the co-simulation framework is illustrated in Fig. 2. Specifically, MATLAB scripts are responsible for dynamically modifying the ATP model to shift the NGLA to designated locations at 5 km intervals along the 400 km line. Each simulation run incorporates a statistical breaker model with randomized closing times to emulate practical operational variability. After simulation, key transient metrics — such as 2% overvoltage levels and energy absorption — are automatically extracted and organized for further analysis and plotting.

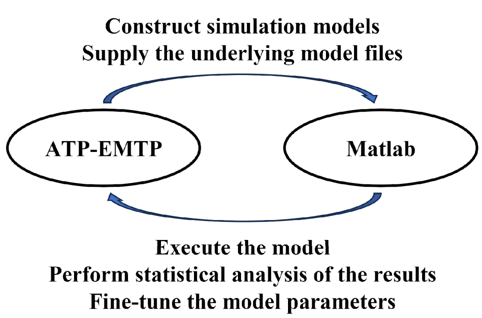

FIGURE 2. Combined ATP-MATLAB simulation routine.

This simulation scenario targets the worst-case condition for transient phenomena, where no mitigation measures — such as shunt reactors or closing resistors — are installed along the transmission line. This assumption simulates the maximum electrical stress imposed on surge arresters and the insulation system during transients, thereby providing a conservative and rigorous boundary for performance evaluation.

In terms of engineering constraints, system design codes stipulate that the maximum switching transient overvoltage in a 750 kV HVAC system must be suppressed below 1.8 p.u. to meet insulation coordination standards. Additionally, the maximum energy absorbed by a single arrester must not exceed 6 MJ, which corresponds to the thermal design limits of commercially available arresters. These regulatory requirements form the operational boundaries for assessing both the effectiveness and feasibility of each NGLA installation strategy.

3. SUPPRESSION PERFORMANCE OF NGLAS AGAINST SWITCHING OVERVOLTAGE

3.1. Suppression Performance Affected by Installation Location

Based on the extreme conditions described in Section 2, the simulation sets the transmission line length to 400 km and, on this basis, analyzes the transient processes occurring along the line.

By combining the use of two types of surge arresters — Y20W-600/1380 and Y20W-648/1491 — along the transmission line and employing the ATP-MATLAB co-simulation model, this study systematically investigates the suppression performance of switching transients under different arrester voltage ratings and installation positions. In the simulation, NGLAs are sequentially placed at various monitoring points along the line, enabling large-scale automated simulations. The objective is not only to evaluate the effectiveness of various arrester configurations but also to analyze the spatial response of switching transient suppression, with results benchmarked against the 2% statistical switching transient control threshold specified in system design standards.

Simulation results clearly indicate that the installation position of the NGLA has a decisive impact on suppression performance — installing arresters arbitrarily along the line does not guarantee effective mitigation. To better visualize this spatial effect, a boxplot was generated under the condition where both the outlet and line arresters are rated at 600 kV. As shown in Fig. 3, the boxplot illustrates the distribution and variation of

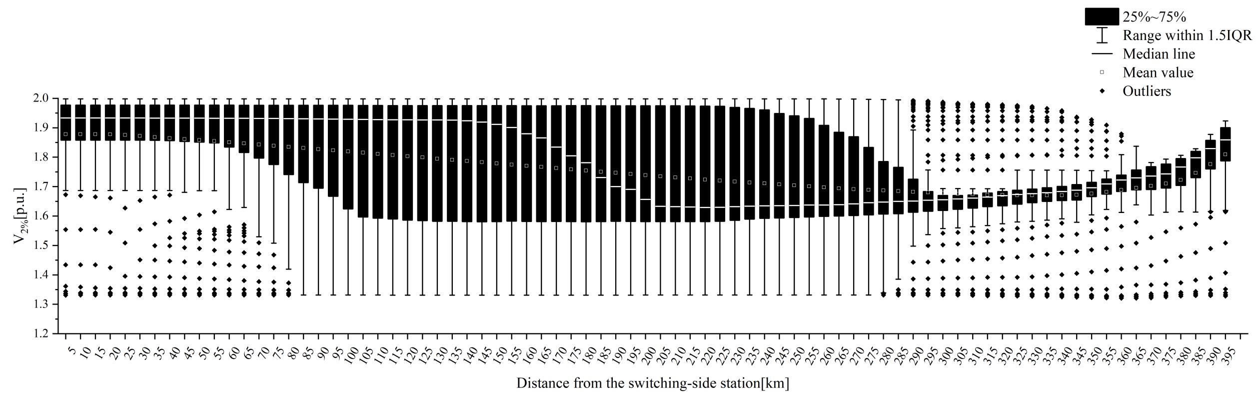

FIGURE 3. Boxplot analysis of switching transient levels along the line with installed surge arresters.

TABLE 2. Switching transient levels and energy absorption under different surge arrester configurations.

Arrester Configuration		Maximum Switching Transient at 2% Operation [p.u.]	Expected Max Switching Transient [p.u.]	NGLA Energy Absorption [MJ]	OLSA Energy Absorption [MJ]	OLSA Absorption Without NGLA [MJ]
OLSA	NGLA					
600 kV	600 kV	1.78	2.00	3.79	3.33	9.44
600 kV	648 kV	1.84	2.00	1.32	6.16	9.44
648 kV	600 kV	1.87	2.09	6.94	0.94	8.76
648 kV	648 kV	1.89	2.09	3.54	2.98	8.76

2% statistical switching transient levels along the line for different arrester installation points.

The boxplot analysis reveals that at most positions, the switching transient level exceeds 1.8 p.u., indicating that many installation locations fail to provide sufficient suppression. Only when the arrester is placed within the 20–30 km range from the substation can the entire line be effectively suppressed below 1.8 p.u., meeting insulation coordination requirements. Therefore, the precise optimization of installation location is essential for effective system protection. Random or densely distributed installation strategies are neither economically viable nor technically adequate.

3.2. Suppression Performance Affected by V_r

Further comparison of different arrester voltage rating combinations shows that the configuration with both outlet and line arresters using Y20W-600/1380 model (with a rated voltage of $V_r = 600\,\text{kV}$) achieves the best overall suppression performance. As shown in Fig. 3, all monitoring points in this configuration exhibit switching transient voltages below 1.8 p.u., meeting operational standards and achieving approximately 0.06 p.u. lower peak values than 600 kV/648 kV configuration. Under the optimal configuration and installation location, Fig. 4 shows that the $V_{2\%}$ distribution curve along the line aligns well with the expected suppression level.

Table 2 summarizes the simulation data under different arrester configurations. The results demonstrate that in the 600 kV/600 kV configuration, energy absorption is well balanced: the line and outlet arresters absorb 3.79 MJ and 3.33 MJ, respectively — well below the 6 MJ design threshold. In contrast, when the voltage ratings are mismatched, the lower-rated arrester bears most of the energy, often exceeding 6 MJ, posing a significant risk of thermal damage.

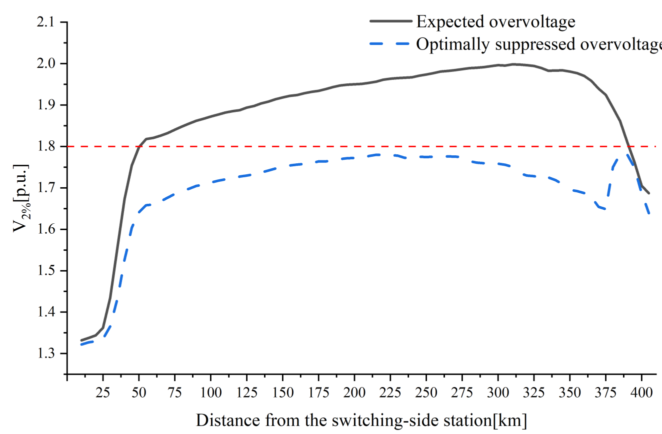

FIGURE 4. Schematic diagram of lightning strike locations.

More critically, line arresters with lower voltage ratings (e.g., $V_r = 600\,\text{kV}$) consistently exhibit superior transient suppression capability across all configurations. This is primarily due to their lower residual voltage characteristics, which allow them to intervene earlier during the initial rise of the transient waveform, effectively limiting the voltage peak. This finding confirms that reducing the voltage rating of line arresters and optimizing their placement is a practical and effective strategy to enhance system withstand capability while reducing insulation costs.

In conclusion, arrester configurations should prioritize consistent voltage ratings and be carefully deployed at key locations based on the propagation characteristics of switching transients. Notably, an effective suppression range of approximately 5–10 km exists around the optimal installation point, within which the desired mitigation performance can still be reliably achieved.

4. SUPPRESSION PERFORMANCE OF NGLAS AGAINST LIGHTNING TRANSIENTS

To evaluate the protective performance of NGLAs against direct lightning strikes, this study conducts simulation analysis focusing on the transient suppression effectiveness and energy absorption characteristics of surge arresters under different voltage ratings and installation locations. In HVAC power systems, back-flashovers caused by lightning are the primary threat. Therefore, two scenarios are investigated in this study:

1) The lightning strike point is set exactly at the NGLA installation location, which coincides with the optimal position previously identified for switching transient suppression.

2) The lightning strike point is offset from the NGLA location by 1 km, 2 km, 3 km, 4 km, and 5 km, respectively.

The schematic diagram of the lightning model is shown in Fig. 5. In the simulation, the lightning current is modeled using a standard 2.6/50 μs negative polarity waveform, with peak current amplitudes ranging from 30 kA to 40 kA, consistent with the characteristics of typical cloud-to-ground lightning discharges. The used surge arresters remain the same as before, rated at 600 kV and 648 kV.

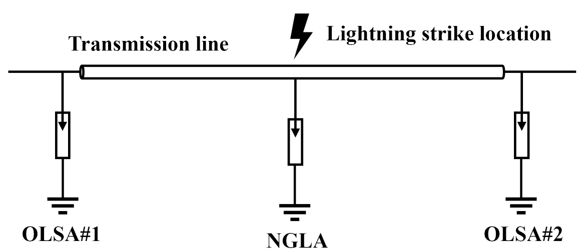

FIGURE 5. Schematic diagram of lightning strike locations.

4.1. Suppression Performance Affected by Installation Location

To further evaluate the lightning transient suppression capability of NGLAs, a comparative simulation study is conducted to analyze their performance when NGLA is installed at various distances from the lightning strike point.

Figure 6 presents a comparison of transient voltage waveforms at the lightning strike point under several representative scenarios. In the simulation setup, an NGLA rated at 600 kV is selected as a representative case and is installed either directly at the strike point or at offset distances ranging from 1 km to several kilometers. The analysis primarily focuses on two key indicators: peak transient voltage and waveform duration.

Simulation results show that the peak voltage at the strike location remains nearly unchanged regardless of how close or far the NGLA is installed. This is because the peak value of the lightning transient is reached in the very early stage of the surge, before the arrester can effectively interact with the wavefront. As a result, unless the arrester is located exactly at the strike point, it has minimal effect on the peak voltage magnitude.

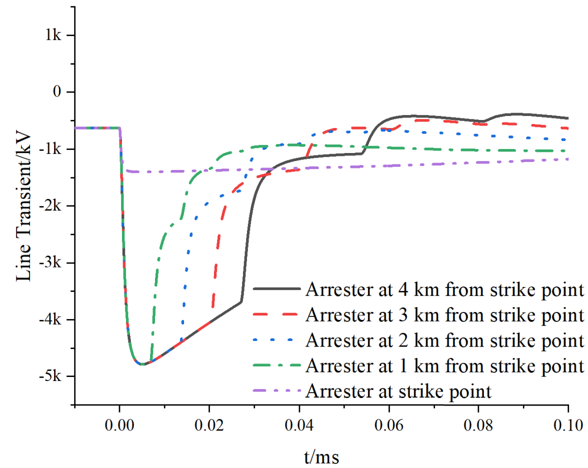

FIGURE 6. Lightning transient waveforms for various arrester installation locations.

However, the tail of the waveform — namely, its decay duration — is significantly affected by the arrester's proximity. When the NGLA is installed closer to the lightning strike point, it can absorb more of the residual energy and shorten the overall waveform duration. As the installation distance increases, the arrester becomes less effective at dissipating energy, leading to longer transient durations.

These observations highlight a critical limitation: NGLAs can only provide effective protection against lightning surges when being installed directly at or very near the strike location. Their spatial protection range is narrow, and relying solely on NGLAs for full-line lightning protection would require high-density installation, which is generally not economically or logistically feasible.

Therefore, while NGLAs are suitable for localized lightning protection, their limited spatial effectiveness necessitates the consideration of complementary measures for broader protection coverage across the transmission line.

4.2. Suppression Performance Affected by V_r

To further evaluate the suppression capability of NGLAs against lightning transients, a comparative simulation study is conducted to analyze the effects of installing NGLAs with different voltage ratings at the lightning strike point. As shown in Fig. 7, installing an NGLA at the lightning strike point significantly reduces the magnitude of the lightning transient compared to the case without an NGLA.

Table 3 summarizes the energy absorbed by arresters with different voltage ratings and the resulting transient magnitudes at the lightning strike point under varying lightning current levels.

The results show that the energy absorbed by the arrester increases approximately linearly with the magnitude of the lightning current. For instance, the NGLA rated at 600 kV absorbs about 1.38 MJ under a 30 kA lightning current, which rises to

TABLE 3. Arrester energy absorption at various lightning current levels.

Lightning Current [kA]	Energy Absorbed by Arrester ($V_r = 600$ kV) [MJ]	Energy Absorbed by Arrester ($V_r = 648$ kV) [MJ]	Lightning Transients Peak ($V_r = 600$ kV) [MV]	Lightning Transients Peak ($V_r = 648$ kV) [MV]
30	1.38	1.07	1.36	1.45
32	1.52	1.26	1.37	1.46
34	1.68	1.37	1.38	1.47
36	1.84	1.56	1.39	1.47
38	1.99	1.67	1.39	1.48
40	2.15	1.83	1.40	1.49

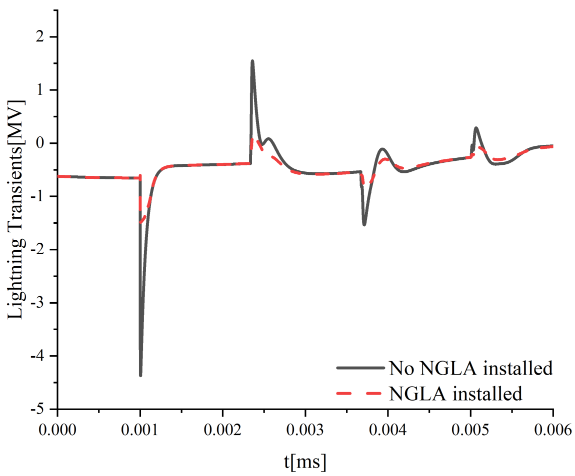

FIGURE 7. Lightning transients under different NGLA installation conditions.

2.15 MJ at 40 kA. Similarly, the NGLA rated at 648 kV absorbs approximately 1.07 MJ at 30 kA, increasing to 1.83 MJ at 40 kA. This suggests that while both types of arresters effectively limit the lightning-induced transient energy, the 600 kV arrester consistently absorbs more energy under the same lightning current, reflecting its stronger engagement in the early stage of surge suppression. This is primarily due to its lower protection level, which allows it to clamp voltage at a lower threshold and thereby initiate current conduction earlier in the transient process.

Moreover, the simulation results indicate that the residual voltage across both arresters remains nearly constant despite variations in current amplitude. This characteristic is significant from an insulation coordination perspective, as it ensures predictable voltage stress on protected equipment under a wide range of lightning current conditions. Stable residual voltage behavior enhances design reliability and reduces the need for excessive insulation margins.

Even under the maximum stress condition of 40 kA, the energy absorbed by either arrester remains well below the 6 MJ thermal failure threshold. This validates that the NGLAs, originally selected for switching transient suppression, are also capable of safely handling typical lightning strikes without suffering thermal degradation or initiating protective failure mechanisms. Thus, from an energy withstand perspective, these arresters exhibit robust thermal performance, enabling dual functionalities: mitigating both switching and lightning transients.

This dual-purpose capability simplifies system design by eliminating the need for separate sets of devices to address different types of transients, ultimately reducing installation complexity, footprint, and maintenance cost. It also offers greater design flexibility in achieving insulation coordination, particularly in compact substations or mountainous transmission corridors where equipment space and accessibility are limited.

However, it must be emphasized that this favorable result is obtained under the idealized condition where the lightning strike coincides exactly with the arrester installation point. In practical operation, such perfect alignment is statistically rare. Since lightning strikes are stochastic in nature and can occur at virtually any location along the line, the ability of a single arrester to suppress a lightning transient diminishes rapidly as the strike point deviates from its installation node. Therefore, a more detailed investigation is required to assess the spatial effectiveness and protection coverage of NGLAs for lightning transients under offset strike conditions, which is addressed in the following section.

5. SUPPRESSION DIFFERENCES BETWEEN LIGHTNING AND SWITCHING TRANSIENTS

Simulation results demonstrate that lightning and switching transients exhibit fundamentally different propagation characteristics, which impose distinct requirements and limitations on the deployment strategy of surge arresters.

Switching transients are typically characterized by lower frequency content and longer waveform durations. These waveforms propagate along the entire transmission line and reflect at impedance discontinuities such as substations or terminal points. Consequently, switching transients have a broad spatial influence and can be effectively suppressed by installing NGLAs at critical locations. Notably, they exhibit good suppression performance within a 5–10 km adjustment range around the optimal installation point. With only a few arresters placed at strategically selected positions, overvoltages along the entire line can be effectively mitigated, achieving a well-balanced solution between technical effectiveness and economic feasibility.

In contrast, lightning transients present as fast-rising, high-frequency surges with extremely steep wavefronts. The voltage peak occurs almost instantaneously at the strike point, and the energy is concentrated in a very narrow temporal and spatial window. Simulation results further confirm that only when an NGLA is installed exactly at or in very close proximity to the lightning strike point can it significantly affect the transient waveform. When the arrester is offset by just a few kilometers, its ability to suppress the voltage peak diminishes markedly, although it may still absorb part of the waveform tail. This spatial limitation means that sparse placement of NGLAs cannot provide comprehensive lightning protection for long-distance transmission corridors.

To visualize this comparison more intuitively, Fig. 8 illustrates the optimal installation zones for surge arresters under switching and lightning transient conditions. As shown, switching transient suppression benefits from installation within a 5–10 km adjustable range around the optimal location, while lightning transient suppression relies heavily on the arrester being located exactly at or near the lightning strike point.

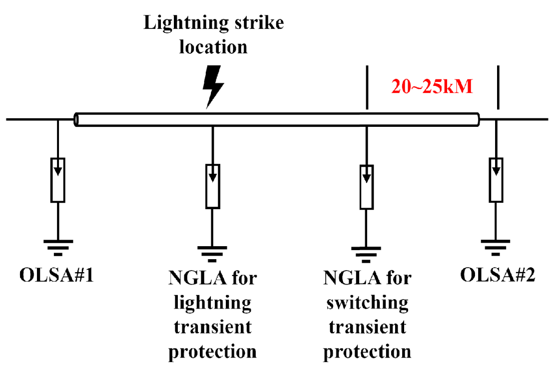

FIGURE 8. Schematic diagram of arrester installation for lightning and switching transient suppression.

In conclusion, while NGLAs demonstrate excellent wide-area suppression and economic advantages for switching transients, their effectiveness in lightning protection is spatially constrained. Therefore, protection schemes should adopt differentiated strategies based on the transient type: for switching transients, optimize arrester deployment at key locations; for lightning transients, consider high-density NGLA placement or supplement with auxiliary protective measures (e.g., overhead ground wires, shielding angle optimization, or tower-mounted protection devices). Through appropriate differentiation of strategies, high-voltage system protection design can achieve both technical adequacy and economic efficiency.

6. CONCLUSIONS

This paper presents a comprehensive numerical and simulation-based study, using an ATP-EMTP and MATLAB co-simulation framework, on the protection performance of NGLAs against switching and lightning transients in a 750 kV HVAC transmission system under extreme operating conditions. The key conclusions are summarized as follows:

1) For switching transients, optimal suppression is achieved when both the outgoing line surge arrester (OLSA) and NGLA adopt the Y20W-600/1380 configuration. When NGLA is installed within a 5–10 km range around the optimal location, the 2% statistical overvoltage can be effectively limited below 1.8 p.u., ensuring compliance with insulation coordination standards while avoiding thermal overload.

2) For lightning transients, effective suppression is highly location-dependent. Significant mitigation of peak transient voltage is observed only when the NGLA is installed precisely at or very near the lightning strike point. Even slight positional deviations (1–5 km) result in a sharp drop in suppression effectiveness, although some energy in the waveform tail can still be absorbed.

3) Switching and lightning transients exhibit fundamentally different spatial and temporal propagation characteristics. Therefore, differentiated deployment strategies are essential: NGLAs are well suited for regional switching transient suppression through strategic positioning, while lightning protection may require high-density installation or supplementary methods such as overhead ground wires or tower-based shielding.

Overall, this study demonstrates the dual protective capability of NGLAs when they are appropriately configured. The findings provide valuable engineering insight and theoretical guidance for insulation coordination, arrester selection, and deployment strategies in ultra-high-voltage power systems.

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REFERENCES

[1] Ma, Z., X. Zhou, Y. Shang, and L. Zhou, "Form and development trend of future distribution system," *Proceedings of the CSEE*, Vol. 35, No. 6, 1289–1298, 2015.

[2] Arafat, E. and M. Ghassemi, "Switching overvoltage analysis in conventional and unconventional transmission lines," in *2024 IEEE Kansas Power and Energy Conference (KPEC)*, 1–4, Manhattan, KS, USA, 2024.

[3] Yang, S. and G. A. Franklin, "Switching transient overvoltage study simulation comparison using PSCAD/EMTDC and EMTP-RV," in *2013 Proceedings of IEEE Southeastcon*, 1–5, Jacksonville, FL, USA, 2013.

[4] Abbasi, E., H. Seyedi, and K. Strunz, "Simulation and analysis of the effect of single-pole auto-reclosing on HV transmission lines switching overvoltages," in *2009 IEEE Power & Energy Society General Meeting*, 1–9, Calgary, AB, Canada, 2009.

[5] Li, Y., J. He, J. Yuan, C. Li, J. Hu, and R. Zeng, "Failure risk of UHV AC transmission line considering the statistical characteristics of switching overvoltage waveshape," *IEEE Transactions on Power Delivery*, Vol. 28, No. 3, 1731–1739, 2013.

[6] Chen, X., J. Guo, T. Lu, W. Shi, T. Lei, and C. Li, "Recommended volt ampere characteristics of MOA in the lightning invasion over-voltage calculation of UHV AC substation and its influence on simulation results," in *2020 IEEE International Conference on High Voltage Engineering and Application (ICHVE)*, 1–4, Beijing, China, 2020.

[7] Guo, T., T. Liang, W. Shen, *et al.*, "Analysis on a resonance faults incident of 35 kV capacitor voltage transformer," in *2025 International Conference on Electrical Automation and Artifi-*

cial Intelligence (ICEAAI), 980–984, Guangzhou, China, 2025.

[8] He, J., J. Yuan, Y. Li, C. Li, J. Hu, and R. Zeng, "Equivalent waveform parameters of switching overvoltages in UHV systems," *IEEE Transactions on Power Delivery*, Vol. 28, No. 3, 1740–1749, 2013.

[9] Zhao, Z., M. Li, T. Zhang, and Y. Tian, "Overvoltage and insulation coordination study for UHVDC transmission system that is hierarchically connected to 500 kV and 1000 kV AC grids on line side," in *18th International Conference on AC and DC Power Transmission (ACDC 2022)*, 1514–1519, Online Conference, China, 2022.

[10] He, J., Y. Zhou, Z. Li, and J. Yuan, "Feasibility of using one-column-varistor arresters in 1000-kV UHV substations," *IEEE Transactions on Power Delivery*, Vol. 31, No. 4, 1533–1541, 2016.

[11] Yamagata, Y., K. Tanaka, S. Nishiwaki, N. Takahashi, T. Kokumai, I. Miwa, T. Komukai, and K. Imai, "Suppression of VFT in 1100 kV GIS by adopting resistor-fitted disconnector," *IEEE Transactions on Power Delivery*, Vol. 11, No. 2, 872–880, 1996.

[12] Zhang, Y., X. Zhang, S. Li, and Y. Xie, "Feasibility study on canceling closing resistance of 750 kV short line circuit breaker," in *International Conference on Information Control, Electrical Engineering and Rail Transit*, 61–67, Springer, 2023.

[13] Legate, A. C., J. H. Brunke, J. J. Ray, and E. J. Yasuda, "Elimination of closing resistors on EHV circuit breakers," *IEEE Transactions on Power Delivery*, Vol. 3, No. 1, 223–231, 1988.

[14] Li, Z., P. Zhou, Y. Lou, and L. Wang, "Feasibility research on canceling breaker closing resistor of UHV transmission lines," *High Voltage Engineering*, Vol. 41, No. 11, 3721–3727, 2015.

[15] Yang, P., S. Chen, and J. He, "Effect of different arresters on switching overvoltages in UHV transmission lines," *Tsinghua Science & Technology*, Vol. 15, No. 3, 325–328, 2010.

[16] Shu, H., W. Lou, Y. Tang, Z. Yang, and Y. Han, "Research study on the multi-strike energy model and control strategy optimization of controllable arrester," *Electric Power Systems Research*, Vol. 241, 111349, 2025.

[17] Wang, B.-S., S.-W. Wang, Y. Xiong, X.-N. Wang, L. Tang, and Z.-Q. Zuo, "The development of the UHV a.c. arresters," *European Transactions on Electrical Power*, Vol. 22, No. 1, 94–107, 2012.

[18] Giraudet, F., "Various benefts for line surge arrester application and advantages of externally gapped line arresters," in *2019 International Conference on High Voltage Engineering and Technology (ICHVET)*, 1–6, Hyderabad, India, 2019.

[19] Ribeiro, J. R. and M. E. McCallum, "An application of metal oxide surge arresters in the elimination of need for closing resistors in EHV breakers," *IEEE Transactions on Power Delivery*, Vol. 4, No. 1, 282–291, 1989.

[20] Kou, X., "Study on dismantling the closing resistor of 500 kV breaker in Henan power grid," in *2010 International Conference on E-Product E-Service and E-Entertainment*, 1–4, Henan, China, 2010.

[21] Ma, F., X. Chen, C. He, X. Zhu, J. Deng, and H. Ni, "Research on the closing inrush current and overvoltage of 750 kV AC filter breakers," in *2020 IEEE International Conference on High Voltage Engineering and Application (ICHVE)*, 1–4, Beijing, China, 2020.

[22] Lou, Y., Z. Zha, Z. Li, and H. He, "Study on cancelling closing resistor of circuit breaker in long distance outlet of 500 kV power plant," in *2022 7th Asia Conference on Power and Electrical Engineering (ACPEE)*, 1456–1461, Hangzhou, China, 2022.

[23] Bunov, P., L. Klingbeil, M. Schubert, B. Gossler, D. Biswas, and J. Hunt, "Transmission line arresters application for control of switching overvoltages on 500-kV transmission line," in *2014 IEEE PES T&D Conference and Exposition*, 1–5, Chicago, IL, USA, 2024.

[24] He, J., C. Li, J. Hu, and R. Zeng, "Deep suppression of switching overvoltages in AC UHV systems using low residual arresters," *IEEE Transactions on Power Delivery*, Vol. 26, No. 4, 2718–2725, 2011.

[25] Meng, P., Y. Zhou, J. Wu, J. Hu, and J. He, "Novel ZnO varistors for dramatically improving protective effect of surge arresters," in *2018 34th International Conference on Lightning Protection (ICLP)*, 1–6, Rzeszow, Poland, 2018.

[26] Ding, T., J. Gao, Z. Shuai, J. Nie, and T. Jiang, "Analysis of lightning overvoltage on the transmission line near a substation under multiple lightning strikes," in *2025 IEEE Industry Applications Society Annual Meeting (IAS)*, 1–4, Taipei, Taiwan, 2025.

[27] Cui, T., Z. Wang, T. Liang, X. Wu, Z. Fu, T. Guo, and J. Guo, "Impact of lightning strike waveform and position on transient overvoltage in a 500 kV HVAC system," in *2025 International Conference on Electrical Automation and Artificial Intelligence (ICEAAI)*, 313–317, Guangzhou, China, 2025.