RELIABILITY ASSESSMENT OF LOW-VOLTAGE NETWORKS UNDER LIGHTNING-INDUCED OVERVOLTAGES TRANSFERRED FROM MEDIUM-VOLTAGE SYSTEMS

I.A. Guseynova

•

Azerbaijan State Oil and Industry University, Baku, Azerbaijan
huseynova.ilduze@asoiu.edu.az

Abstract

This article investigates the reliability implications of lightning-induced overvoltages transferred from medium-voltage (MV) systems to low-voltage (LV) networks. Special emphasis is placed on the role of distribution transformers and the importance of accurate modeling for evaluating surge transfer mechanisms. Simulations and experimental comparisons reveal that conventional capacitive PI-circuits significantly overestimate transferred voltages. The study highlights the key parameters influencing surge magnitudes, such as earth resistance, transformer proximity, line configuration, and insulator flashovers. Based on analytical models and real case studies, the paper provides recommendations for enhancing the surge immunity and operational reliability of LV systems under lightning conditions.

Keywords: Lightning-induced overvoltages, reliability, medium-voltage networks, low-voltage systems, insulation coordination.

I. Introduction

In the context of rapid urbanization, the widespread integration of sensitive electronic equipment, and the advancement of smart grid technologies, ensuring the reliability and safety of low-voltage (LV) electrical distribution systems has become a pressing challenge. One of the most critical threats to these systems is the impact of lightning-induced overvoltages, which, although originating in medium-voltage (MV) networks, can be transferred to the LV side via distribution transformers.

These transient overvoltages may result from both direct lightning strikes and nearby electromagnetic impulses. When propagated to the low-voltage level, they can cause insulation breakdown, damage to end-user equipment, and interruptions in power supply. The implications extend beyond individual device failures—potential consequences include fires, long-term degradation of infrastructure, and disruptions in essential services such as healthcare, industrial operations, and communication systems. As a result, the ability to accurately assess and effectively mitigate these surges is vital for maintaining high service reliability and minimizing risks to end-users.

The mechanism of surge transfer from MV to LV systems is inherently complex. It depends on multiple variables, including lightning stroke parameters (amplitude, waveform, rise time), network configuration, grounding impedance, the presence and performance of surge protection devices (SPDs), and, critically, the dynamic response of the distribution transformer. Traditional transformer models, such as the simplified capacitive π-equivalent circuit, often lack the fidelity required to simulate high-frequency transients with sufficient precision.

This paper presents a detailed investigation into the phenomenon of overvoltage transference from MV to LV networks. Using numerical simulations performed in the Alternative Transients Program (ATP), supported by experimental validation, we analyze the evolution of lightning surges as they propagate through transformer couplings and interact with different grounding and network configurations [1–3]. Particular attention is paid to assessing the accuracy of various transformer modeling approaches and identifying their impact on the predicted reliability of LV systems under transient stress.

The overarching aim of this study is to provide power engineers and researchers with a deeper understanding of surge propagation mechanisms and their implications for network resilience. By identifying key parameters and offering improved modeling techniques, this work contributes to the development of more effective protection strategies and enhances the robustness of modern electrical distribution infrastructures.

II. Formulation of the problem

Lightning-induced overvoltages pose a persistent and significant threat to the safety and operational continuity of low-voltage (LV) distribution systems. Even in the presence of conventional protection devices and standardized grounding schemes, harmful transient surges are often capable of propagating to end-user terminals, causing damage to sensitive equipment and compromising system reliability. This vulnerability is primarily due to the complex and highly dynamic nature of surge propagation, particularly under the high-frequency transient conditions associated with lightning strikes.

When a lightning discharge occurs in close proximity to—or directly onto—a medium-voltage (MV) line, it generates a steep-fronted surge current that can couple into the LV network through the magnetic and capacitive links of a distribution transformer [4-7]. The characteristics of this coupling process are governed by several key parameters, including the internal impedance of the transformer, its insulation structure, and the spatial layout of its windings. These elements determine how energy is transferred across voltage levels and how it is distributed throughout the downstream network.

In addition to transformer behavior, several external factors influence the severity and extent of surge transfer. These include the grounding impedance at both the MV and LV sides, the waveform of the incoming surge (including rise time and peak amplitude), and the configuration of the LV distribution feeder —such as the presence of service drops, cable lengths, and consumer loads. The interaction of these factors creates a complex system response that is difficult to predict using traditional modeling techniques.

Conventional transformer models—typically based on lumped-parameter capacitive π-equivalents—fail to capture the detailed high-frequency behavior required for accurate surge analysis. These models often neglect inter-winding coupling effects and frequency-dependent phenomena, which may lead to significant errors in predicting surge amplitudes, wavefront steepness, and propagation timing [8]. Consequently, the results derived from such models may not reliably reflect real-world performance, particularly in the context of fast transients induced by lightning.

To overcome these limitations, the present study develops and validates a high-resolution simulation model that incorporates a more realistic representation of transformer frequency response, detailed grounding impedance characteristics, and spatially distributed consumer load models. The simulated system consists of a 1000-meter LV feeder equipped with service drops, neutral-grounding arrangements, and representative end-user installations, as illustrated in Figure 1. This modeling framework enables in-depth analysis of overvoltage propagation paths, reflection and attenuation mechanisms, and the overall system behavior under various lightning surge conditions.

The ultimate objective of this research is to enhance the effectiveness of surge protection in LV networks by identifying critical system vulnerabilities and formulating engineering recommendations for optimized grounding configurations and strategic placement of surge protective devices (SPDs). Through this approach, the study aims to contribute to the development of more resilient power distribution networks capable of withstanding the growing threat posed by lightning-induced overvoltages.

.

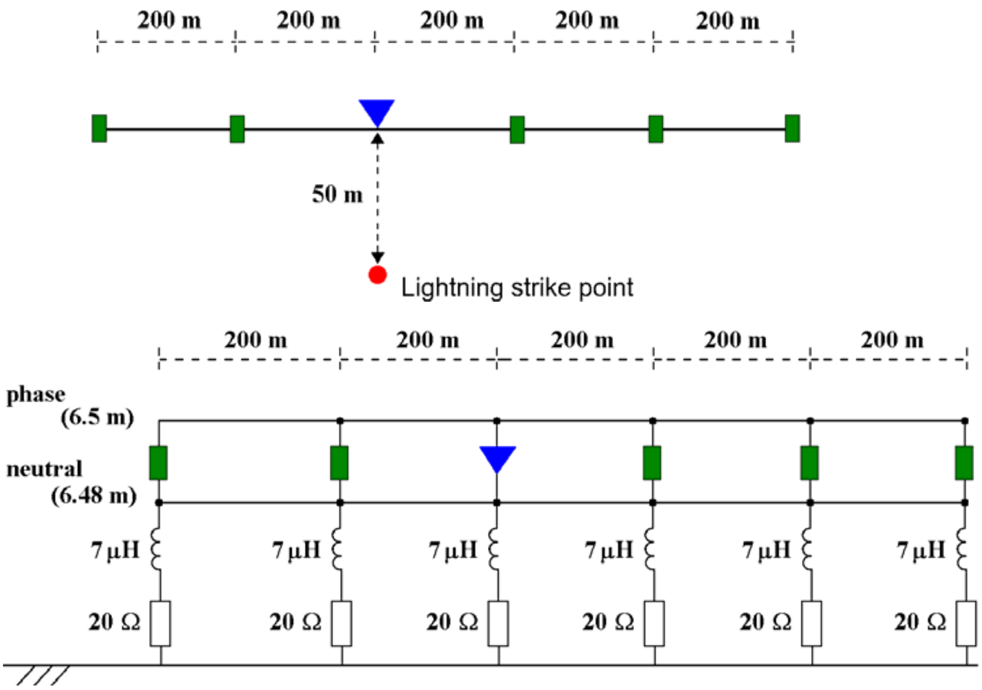

Figure 1: *Configuration of the LV line (top and side views)*

III. Problem solution

To assess the efficiency of grounding and surge protection in low-voltage (LV) power networks under lightning impulse conditions, a simulation-based approach was implemented. The model includes a step-down transformer connected to a low-voltage distribution line, with consumer branches and a lightning surge source applied at the incoming line. The feeder is equipped with grounding points and surge protective devices (SPDs) at critical locations, and its complete topology is shown in Figure 1.

The lightning impulse was modeled using standard waveform parameters of 10/350 μs and 8/20 μs for current and voltage surges, respectively. The applied waveforms are shown in Figure 2, which illustrates the steepness and amplitude of the surge currents. These waveforms were injected into the system to simulate realistic lightning impact conditions.

To study the effects of grounding resistance on the resulting overvoltages, multiple scenarios were simulated with resistance values ranging from 10 Ohm to 50 Ohm. The results demonstrated a clear dependency between the quality of grounding and the magnitude of transient overvoltages observed both at the transformer terminals and at the customer end. These results are summarized in Table 1.

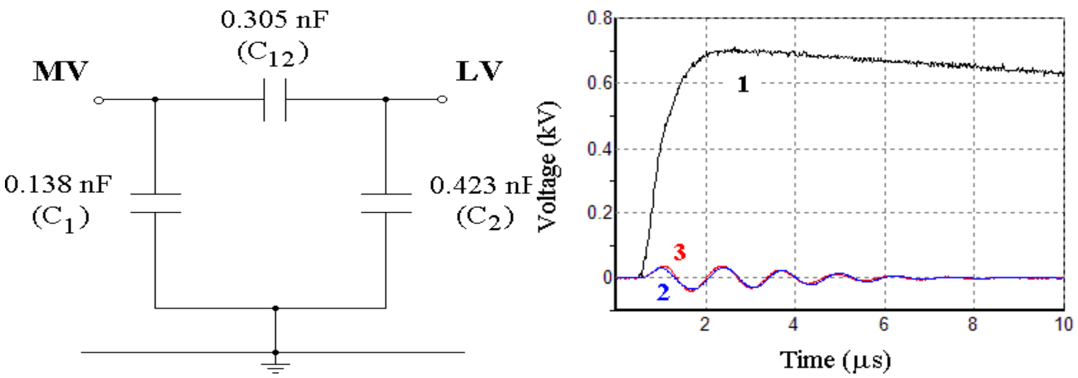

Figure 2: *Impulse waveforms used in the simulations* (10/350 μs and 8/20 μs).

Table 1: *Dependence of overvoltage amplitude on grounding resistance*

Grounding Resistance (Ohm)	Max Overvoltage at Transformer Secondary (kV)	Max Overvoltage at End-User (kV)
10	1.9	2.3
30	2.7	3.0
50	3.3	3.5

The voltage profile along the entire feeder was also evaluated during the impulse event. As shown in Figure 3, overvoltages accumulate and reflect at discontinuities such as branches and terminations. These reflections exacerbate voltage stress at terminal points, potentially endangering end-user equipment.

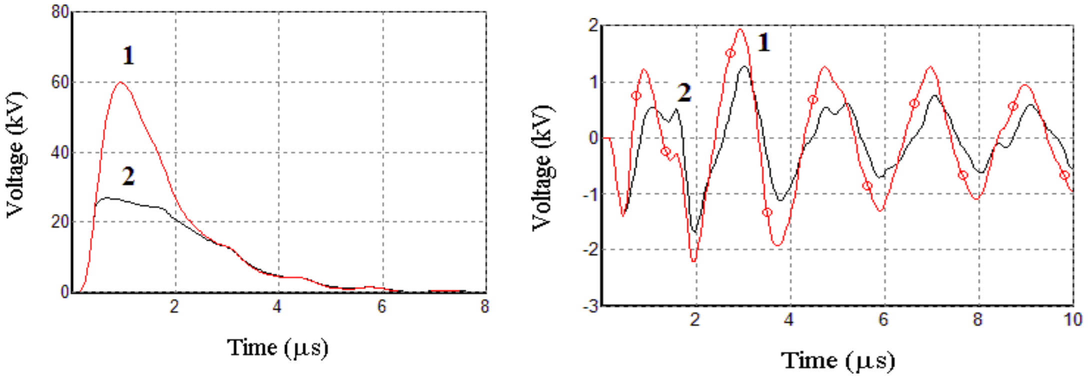

Figure 3: *Voltage profile along the LV feeder during surge propagation*

To mitigate these effects, surge protective devices were introduced at strategic locations—first at the transformer secondary terminal, and then at both the transformer and the far end of the feeder. This allowed evaluation of the cumulative effect of SPD coordination [9-14]. The results of these configurations are presented in Table 2, where it is evident that placing SPDs at both ends provides the most effective suppression of overvoltages.

Table 2: *Effectiveness of surge protection devices (spds)*

SPD Configuration	Max Overvoltage at End-User (kV)	Reduction vs. No SPD (%)
No SPD	3.5	—
SPD at Transformer Secondary	2.1	40%
SPD at Transformer + End of Feeder	1.5	57%

Thus, the simulation results confirm that both the grounding resistance and SPD configuration critically influence the system's ability to withstand overvoltage conditions. Grounding resistance below 10 Ohm significantly enhances protection, while coordinated SPD deployment ensures optimal voltage suppression at sensitive consumer terminals.

General recommendations on the use of surge protective devices (SPDs)

The simulation results presented above clearly demonstrate that effective overvoltage protection in low-voltage (LV) power networks requires a coordinated strategy that combines optimized grounding and appropriately deployed surge protective devices (SPDs). However, to transition from theoretical assessment to practical implementation, it is necessary to develop comprehensive recommendations that account for network topology, grounding modernization costs, and the optimal placement of SPDs.

A key principle in SPD deployment is strategic placement—that is, locating devices at points where overvoltages are most likely to occur or accumulate. Based on the simulation results and existing literature [15-19], the following placement guidelines are recommended:

- Primary SPD Installation: Always install an SPD at the secondary terminal of the distribution transformer. This location is a primary entry point for surges transferred from the medium-voltage (MV) network into the LV system.
- End-of-Feeder Protection: For radial or branched topologies, additional SPDs should be installed at the remote ends of feeders, particularly where sensitive electronic equipment is present.
- Intermediary Nodes: In long feeders (≥500 meters) with multiple branches or critical loads, intermediate SPDs may be installed at major branching points to suppress reflections and limit voltage peaks.
- Topological Consideration: For meshed or looped LV networks, analysis of current paths and impedance mismatch locations should inform SPD placement. In such systems, surge paths can be more complex, necessitating customized coordination studies.

These measures ensure voltage suppression coordination along the feeder and prevent excessive stress at end-user terminals due to reflections and surge wave interactions [20-22].

Criteria for SPD installation based on network topology

The selection and placement of SPDs must consider the topological configuration of the LV distribution system. Table 3 provides generalized guidelines based on typical network structures.

Table 3: *SPD placement recommendations by network topology*

Network Topology	Recommended SPD Locations	Justification
Radial (1–2 branches)	Transformer secondary, end-of-line consumers	Simple paths of surge propagation, concentrated endpoints
Branched (multi-load)	Transformer secondary, major branching nodes, endpoints	Multiple reflection points, cumulative effects
Looped or meshed	Transformer secondary, key nodes based on impedance map	Surge current can flow through multiple paths; placement must be adaptive
Urban compact networks	Building entry points, centralized panelboards	Short cable lengths increase risk to equipment; proximity-based protection

Economic Considerations

One of the often-overlooked aspects of surge protection planning is the **cost-benefit analysis** of grounding system upgrades and SPD installations. Implementing comprehensive protection across a network can be capital intensive, especially for legacy infrastructures [23-25]. Therefore, recommendations must be economically justified, particularly for distribution operators managing large-scale deployments.

Key economic aspects include:

- Grounding Modernization Costs: Reducing grounding resistance below 10 Ohm may require new earth electrodes, soil treatment, or retrofitting existing installations. Estimated costs range from $150 to $500 per site, depending on soil resistivity and space availability.
- SPD Costs and Maintenance: Quality Class II or Class I+II SPDs suitable for LV protection can cost between $50 and $200 per unit. While initial capital costs may be high, the potential reduction in equipment failure and downtime justifies investment in most cases.
- Cost-Effectiveness by Network Type: In radial or rural systems with long feeders, end-user protection offers high returns on investment. In urban networks, centralized protection at building entry points may be more economical.

A structured cost-benefit analysis using outage cost models and customer damage functions can help utilities prioritize protection for the most economically sensitive locations.

IV. Conclusions

The conducted analysis clearly demonstrates the critical role of lightning-induced overvoltages in shaping the reliability and safety of low-voltage (LV) power distribution networks. The transference of surge voltages from the medium-voltage (MV) side to the LV side is not a mere secondary effect but a complex process influenced by multiple interdependent factors, including transformer modeling, line configuration, grounding system topology, and the characteristics of the lightning stroke itself. It has become evident that simplistic models, such as purely capacitive PI-circuits, fail to capture the high-frequency behavior and wave propagation dynamics inherent to real-world lightning interactions, leading to significant inaccuracies in estimating transferred voltages.

Accurate transformer modeling, particularly under transient conditions, emerges as a foundational requirement for any meaningful analysis of surge propagation. The inadequacy of standard transformer equivalent circuits underlines the necessity for high-fidelity models that incorporate inductive and capacitive coupling between windings and ground, enabling precise predictions of voltage stress at the consumer end.

Moreover, the spatial configuration of the LV network, including the distance between grounding points and load connections, plays a decisive role in the amplitude and waveform of the transferred voltages. As simulations have shown, even the number and distribution of connected consumers can materially alter the surge behavior across the network.

These findings emphasize that system-level design, including protective device coordination and earthing strategies, must be approached with a comprehensive understanding of transient surge dynamics.

The presence or absence of MV surge arresters significantly alters the magnitude of induced and transferred voltages. Their application, therefore, must be strategically optimized not only to protect MV equipment but also to mitigate voltage stresses on downstream LV components. Additionally, the findings suggest that the greatest risk to end-user equipment may not arise from the initial lightning stroke but rather from subsequent strokes, which are characterized by sharper rise times and broader frequency content, capable of inducing more destructive voltages.

Ultimately, ensuring the reliability and resilience of LV distribution networks against lightning-induced phenomena requires a multifaceted approach grounded in detailed electromagnetic modeling, empirical validation, and system-wide coordination of protective measures. Without such a comprehensive strategy, utilities and equipment operators remain exposed to elevated failure risks, potentially compromising the continuity and safety of electricity supply.

References

[1] Figueredo, A. J., & Wolf, P. S. A. (2009). Assortative pairing and life history strategy: A cross-cultural study. *Human Nature, 20*(3), 317–330.

[2] Joachims, T. (2002). *Learning to classify text using support vector machines: Methods, theory and algorithms*. Kluwer Academic Publishers.

[3] Rzayeva, S. V., Ganiyeva, N. A., & Piriyeva, N. M. (2024). Modern approaches to electrical equipment diagnostics. *International Journal on Technical and Physical Problems of Engineering (IJTPE)*, *16*(1), 182–189.

[4] Rzayeva, S. V., Piriyeva, N. M., & Guseynova, I. A. (2024). Analysis of reliability of typical power supply circuits. *Reliability: Theory and Applications (RTA)*, *19*(3), 173–178.

[5] Rzayeva, S. V., Piriyeva, N. M., & Ismayilova, S. I. (2025). High and low voltage coordination in electrical power systems. *International Journal on Technical and Physical Problems of Engineering (IJTPE)*, *17*(1), 19–31.

[6] Piriyeva, N. M., Mammadov, N. S., & Rzayeva, S. V. (2025). Development of new methods for protecting substation and overhead lines from overvoltages. *Reliability: Theory & Applications (RTA)*, *1*(82), 683–689. https://doi.org/10.24412/1932-2321-2025-182-683-689

[7] Ahmedov, E. N., Rzayeva, S. V., Mukhtarova, K. M., & Aliyev, N. A. (2025). Innovative enhancements in ground wire configurations for superior lightning protection of overhead power lines. *International Journal on Technical and Physical Problems of Engineering (IJTPE)*, *17*(1), 45–48.

[8] Rzayeva, S. V., & Guseynova, I. A. (2024). Application of automatic monitoring and control systems for reliability of power transmission lines. *Reliability: Theory and Applications (RTA)*, *19*(2), 64–69.

[9] Rahimli, I., Bakhtiyarov, A., Abdullayeva, G., & Rzayeva, S. (2024). Switching processes occurring in electrical networks 10–35 kV. *Przegląd Elektrotechniczny*, *(8)*, 156–159.

[10] Safiyev, E., Piriyeva, N., & Bagirov, G. (2023). Analysis of the application of active lightning rods in lightning protection objects. *Interscience: Electronic Scientific Magazine*, *(6)(276)*, 14–17.

[11] Piriyeva, N. M., Rzayeva, S. V., & Talibov, S. N. (2022). Analysis of surge protection devices for electrical networks. *Internauka: Scientific Journal*, *(43)(266)*, Part 3, 14–17.

[12] Piriyeva, N. M., Rzayeva, S. V., & Mustafazadeh, E. M. (2022). Evaluation of the application of various methods and equipment for protection from emergency voltage in 6–10 kV electric networks of oil production facilities. *Interscience: Electronic Scientific Magazine*, *(39)(262)*, 40–44.

[13] Mamedova, G. V., Kerimzade, G. S., & Piriyeva, N. M. (2022). Electromagnetic calculation of tension devices for winding wires of small cross sections. *International Journal on Technical and Physical Problems of Engineering (IJTPE)*, *14*(4), Issue 53, December.

[14] Piriyeva, N. M., Veliev, Q. A., Abbasov, A. I., & Suleymanov, E. E. (2021). Switching processes in electric networks 10–35 kV. *Energy Problem*, *(2)*, 100–106.

[15] Piriyeva, N. M., & Makhmudov, U. I. (2024). Analysis of substance grounding and surge protection system. *Flaqman Nauki: Nauchnyy Zhurnal*, *(1)(12)*, January, St. Petersburg, State Research Institute "Naprazvitie".

[16] Piriyeva, N., & Kerimzade, G. (2023). Methods for increasing electromagnetic efficiency in induction levitator. *Przegląd Elektrotechniczny*, *(10)*, 192–195.

[17] Obase, P. F., Piantini, A., & Kanashiro, A. G. (2006). Overvoltages on LV networks associated with direct strokes on the primary line. In *Proceedings of the 28th International Conference on Lightning Protection (ICLP)*, Kanazawa, *1*, 479–484.

[18] Obase, P. F., Piantini, A., & Kanashiro, A. G. (2004). Overvoltages on distribution networks caused by direct lightning hits on the primary line. In *Proceedings of the International Conference on Grounding and Earthing and International Conference on Lightning Physics and Effects*, Belo Horizonte, 198–203.

[19] Obase, P. F., Piantini, A., & Kanashiro, A. G. (n.d.). Overvoltages transferred to low-voltage networks due to direct strokes on the primary. [Manuscript reference or conference details needed].

[20] Mammadov, N., Piriyeva, N., & Ismayilova, S. (2024). Research of lightning protection systems for wind electric installations. *Przegląd Elektrotechniczny*, *(9)*, 198–201.

[21] Piriyeva, N. M., Ganiyeva, N. A., & Karimova, R. K. (2025). Innovative approaches to selective automatic reclosing on overhead cable lines. *International Journal on Technical and Physical Problems of Engineering (IJTPE)*, *17*(1), 32–44

[22] .Thakur, K., Dwivedi, D., Babu, K. V. S. M., Parimi, A. M., Yemula, P. K., Chakraborty, P., & Pal, M. (2023). Advancements in arc fault detection for electrical distribution systems: A comprehensive review from artificial intelligence perspective. *arXiv preprint arXiv:2311.16804*.

[23] Sarwar, M., Mehmood, F., Abid, M., Khan, A. Q., Gul, S. T., & Khan, A. S. (2019). High impedance fault detection and isolation in power distribution networks using support vector machines. *arXiv preprint arXiv:1909.10583*.

[24] Huo, Y., Prasad, G., Lampe, L., & Leung, V. C. M. (2021). Power line communication and sensing using time series forecasting. *arXiv preprint arXiv:2110.10219*.

[25] Liu, Y., Singh, A. K., Zhao, J., Meliopoulos, A. P., Pal, B., Ariff, M. A. M., ... & Yu, S. (2020). Dynamic state estimation for power system control and protection. *arXiv preprint arXiv:2012.14927*.