

IMPROVING RELIABILITY OF LOW-VOLTAGE DISTRIBUTION NETWORKS UNDER LIGHTNING OVERVOLTAGES

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Abstract

Low-voltage (LV) distribution networks are highly vulnerable to lightning-induced overvoltages, which represent a significant cause of transformer failures, equipment damage, and service interruptions in regions with high lightning activity. Conventional protective measures—such as improved grounding and primary medium-voltage (MV) surge arresters—are necessary but often insufficient to suppress secondary surges at the LV side. This paper analyzes the physical mechanisms of surge current injection into transformer neutrals, the influence of network topology, and the role of transformer design in generating internal dielectric stress. Comparative evaluation of surge protective devices (SPDs) demonstrates that coordinated deployment of MOV- and hybrid-based arresters at both transformer terminals and consumer service entrances significantly reduces insulation stress and equipment damage. Simulation results and field evidence confirm that such coordinated strategies improve key reliability indicators, including mean time between failures (MTBF) and system average interruption frequency index (SAIFI), while also reducing economic losses. The findings highlight that preventive investments in SPDs are cost-effective, yielding an order-of-magnitude reduction in lightning-related failures. From a reliability-centered asset management perspective, SPD deployment should be considered a strategic measure for enhancing resilience and sustainability of LV distribution networks.

Keywords: low-voltage distribution networks; lightning overvoltages; surge protective devices (SPDs); transformer reliability.

I. Introduction

The reliability of low-voltage (LV) distribution networks is directly linked to their resilience against lightning-induced overvoltages. In regions with high lightning activity, such overvoltages are a leading cause of transformer failures and equipment damage, resulting in prolonged outages and significant economic losses. Although the effectiveness of low-voltage surge arresters (SPDs) has been demonstrated, their application in utility networks remains limited, largely due to cost-benefit considerations.

Lightning strikes can inject currents of tens of kiloamperes into power systems. Even when a direct hit is absorbed by medium-voltage (MV) arresters, a substantial fraction of the discharge current may enter the neutral conductor and propagate into the LV side, leading to damaging *secondary side surges*. Such events are not adequately mitigated by conventional earthing practices alone. For example, field studies in Australia [1] demonstrated that damage rates to pole-mounted

transformers decreased from 2 incidents per 100 units annually to just 0.3 when coordinated secondary SPDs were installed. Similar patterns have been reported in North America [2] and Europe [3].

The economic dimension of this problem is also noteworthy. A single transformer failure involves not only the direct replacement cost (ranging from several thousand to tens of thousands of dollars) but also indirect losses associated with outage durations, customer compensation, and reputational impact for utilities. Table 1 provides a simplified comparison of direct and indirect costs against the investment required for coordinated SPD installation.

Table 1: Cost comparison between lightning damage and protective investments

Item	Typical Range (USD)	Notes
Transformer repair/replacement	5,000 – 15,000	Depends on rating and logistics
Customer equipment damage claims	2,000 – 20,000	Sensitive loads (IT, medical)
Outage-related economic losses	10,000 – 50,000	Depends on downtime duration
Installation of secondary SPDs	500 – 2,000 per unit	Including transformer and service entrance

As the table illustrates, preventive investments in SPDs are significantly lower than the cumulative costs of recurrent lightning-related failures. Thus, from a reliability-centered asset management perspective, SPD deployment should be viewed as a strategic investment rather than an optional expense.

Recent studies highlight that coordinated use of secondary SPDs at transformer substations and service entrances can substantially reduce equipment failures and improve overall supply reliability. Moreover, modern MOV-based arresters exhibit enhanced reliability and compact design, making them technically and economically feasible for widespread adoption.

II. Problem Statement

Conventional protection measures—such as improving grounding resistance at poles and installing primary (MV-side) surge arresters—are necessary but often insufficient to mitigate *secondary-side surges* observed on the low-voltage (LV) network. The insufficiency has both physical and operational causes:

Mechanism of surge injection and internal transformer stress. A direct lightning stroke to a medium-voltage (MV) conductor generates a discharge current of the order of tens of kiloamperes. This stroke current is partitioned between the path to pole earth and the path into the transformer neutral. At the early transient stage the division is dominated by the inductance of the two paths (the shorter, lower-inductance pole earth path initially attracts more current), while later the steady state division is governed by resistances. When a non-negligible portion of the stroke current flows into the neutral conductor, the resulting voltage drop along the neutral induces currents in the phase conductors and forces surge currents through the transformer secondary windings. These currents produce rapid internal voltage distributions that can cause turn-to-turn insulation stress, partial discharges and eventual dielectric breakdown inside the transformer even when external (terminal) voltages appear to be moderate. Balanced (symmetrical) LV surges can induce large equal-but-opposite voltages across halves of the primary winding, creating severe internal stress with minimal net terminal voltage; unbalanced surges can produce high terminal overvoltages and flashovers in service equipment.

Limitations of primary arresters and grounding improvements. Primary MV arresters are designed to divert the majority of the stroke current to earth at the MV side, but they do not prevent current injection into the neutral entirely and therefore cannot fully eliminate LV surge phenomena. Similarly, lowering pole grounding resistance reduces the steady-state share of current to the neutral but does not change the transient inductive division during the first microseconds of the stroke. Thus, even well-grounded systems remain susceptible to damaging LV transients unless the LV side is specifically protected.

Impact of network topology and equipment design. Single-service (single-customer) connections and long radial LV circuits increase the effective impedance seen by surge currents and therefore elevate the neutral voltage rise at the transformer terminals. Transformers with non-interlaced (non-interleaved) secondary windings exhibit higher surge impedance at fast front times and are therefore more vulnerable to symmetric surges. While interlacing reduces surge impedance (improving performance under symmetric surges), it does not adequately protect against asymmetric events (e.g., single-phase flashovers or localized arrester operation), which can still generate destructive internal voltages. Cable construction also matters: open-wire lines have higher mutual coupling and inductance compared to triplex or shielded cable, leading to larger induced neutral voltages and higher LV surge currents.

Magnitude and statistical relevance of the problem. Empirical and simulation studies indicate the following typical magnitudes and effects: MV stroke currents commonly range from ~10 kA (typical subsequent stroke) to >25–30 kA in severe but less probable events (e.g., a 29.2 kA stroke with ≈5% exceedance probability). The resulting LV secondary surge currents are usually smaller—often below 1 kA for a single service—but their rapid rise time and the transformer's internal distribution produce disproportionate insulation stress. Field evidence from multiple utilities shows that failure rates of pole-mounted transformers in high lightning regions can exceed average rates by more than a factor of two, and secondary-side surges have been estimated to contribute to as much as 40–50% of transformer failures in some studies [1-3].

Consequences for consumers and utilities. The direct consequences include insulation breakdown, partial or full winding short-circuits, changes in turns ratio and long-duration overvoltages at consumer terminals that damage sensitive electronics. Indirect consequences are increased outage frequency and duration, higher maintenance and replacement costs, customer claims and reputational damage for distribution utilities. From a reliability metrics perspective, frequent secondary-side surge events reduce the mean time between failures (MTBF) of transformers, increase the system average interruption frequency index (SAIFI) and raise expected annualized costs.

Coordination and unintended effects. Installing protection only at the MV side or only at transformer terminals without coordinated SPDs at service entrances can lead to load redistribution of surge energy, increasing voltages at unprotected points [4]. As illustrated in simulation studies, arresters placed at the transformer alone may reduce stresses locally but leave customer service entrances vulnerable; conversely, partial installation of SPDs along a line can sometimes raise peak voltages at the remaining unprotected points due to reflected and redistributed energy.

Taken together, these physical mechanisms, network topologies and statistical findings justify the conclusion that conventional measures—while necessary—are not sufficient. Targeted LV protection (properly rated and coordinated SPDs at transformers and across service entrances), informed by network topology and surge statistics, is required to materially reduce transformer failures and improve overall distribution reliability.

To better understand the limitations and potential of different surge protective devices, their comparative characteristics are summarized in Table 2. The table highlights the wide disparity in clamping voltages, energy absorption capacities, and response times across technologies, emphasizing that no single device provides a universal solution. Instead, coordinated application of SPDs—matching energy handling at transformer terminals with fast-response protection at service entrances—is required to achieve reliable lightning protection.

The visualized data in Figure 1 provide a clearer representation of the relative energy-handling capability of SPDs. As shown, TVS diodes occupy the lowest range, typically below 500 J, which makes them unsuitable for transformer-level protection but highly effective for sensitive electronic equipment. Gas discharge tubes (GDTs) offer similar energy ranges but excel in handling very high surge currents, thus complementing other technologies [5-7]. MOVs demonstrate a broader and significantly higher energy absorption capability, ranging from about 500 J to more than 2000 J, making them the most widely adopted choice for low-voltage transformer protection. Hybrid devices that combine MOVs with either GDTs or TVS diodes achieve the highest robustness, exceeding 3000 J, while also balancing fast response with large energy handling.

Table 2: Comparative characteristics of surge protective devices (SPDs) used in LV networks

SPD Type	Typical Clamping Voltage (V)	Energy Absorption Capability (J)	Response Time (ns)	Advantages	Limitations	Typical Application
MOV (Metal Oxide Varistor)	400 – 600 (LV)	500 – 2,000+	<25	Nonlinear V-I, compact, high energy handling	Degrades after multiple surges, thermal runaway risk	Transformer LV terminals, service entrance panels
GDT (Gas Discharge Tube)	500 – 1,000	10 – 500	100 – 1,000	Very high surge current capability (>20 kA), long life	Slow response, follow current risk	Telephone/data lines, secondary protection stages
TVS Diodes	12 – 200	10 – 500	<1	Ultra-fast response, precise clamping	Low energy capability	Sensitive electronics, point-of-use protection
Hybrid SPD (MOV + GDT/TVS)	300 – 600	1,000 – 3,000	<25 (MOV) <1 (TVS)	Combines speed and energy handling	Higher cost, complexity	Coordinated LV surge protection (critical loads)

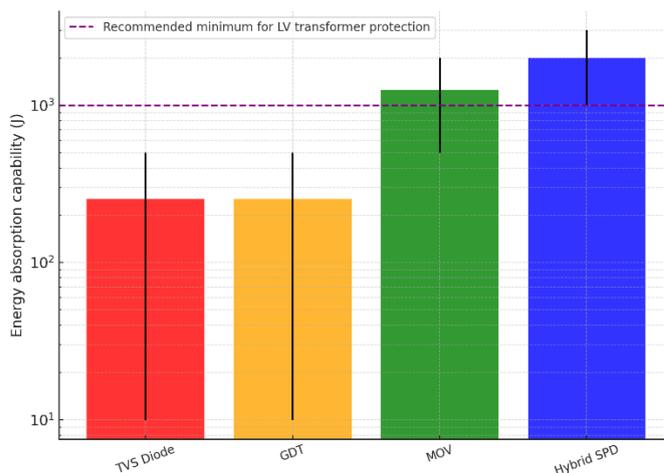


Figure 1: Comparative Energy Absorption Capability of SPDs

The dashed reference line in Figure 1 indicates the recommended minimum energy absorption capacity of around 1000 J for surge protective devices used in low-voltage transformer applications. Both MOV and hybrid solutions meet or exceed this threshold, underlining their practical suitability for utility-scale deployment. In contrast, TVS and standalone GDTs should be considered only as complementary, localized protection stages.

III. Problem Solution

Enhancing the reliability of low-voltage networks under lightning conditions requires a comprehensive and coordinated surge protection strategy that takes into account the physical mechanisms of secondary overvoltage generation and is applicable within utility asset management frameworks. A key element of this strategy is the installation of secondary surge arresters on transformers. Gapless MOV arresters, mounted directly on the low-voltage terminals of distribution transformers, provide a low-impedance path for surge currents entering the neutral, thereby effectively reducing both balanced and unbalanced secondary overvoltages. The optimal varistor rating in the range of 440–480 V ensures proper coordination with primary arresters and minimizes the risk of thermal damage, while close coupling to the transformer neutral and grounding minimizes inductive losses. The operation of such an arrester can be illustrated by its V–I characteristic (Fig. 2), showing nonlinear resistance and voltage clamping behavior.

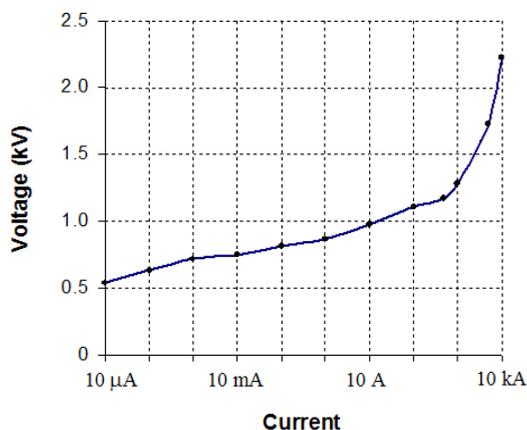


Figure 2: V/I characteristic of the secondary MOV arresters

Equally important is coordinated protection at consumer service entrances. Local surge protective devices installed at building entries and near sensitive equipment reduce the risks of local overvoltages caused by reflections and line discontinuities [8-10]. It is recommended to use devices complying with international standards (Type-1/Type-2 at the service entrance, Type-3 at points of use), with clamping voltages not exceeding 2 kV in areas with high lightning activity. Coordination based on energy capacity and short bonding connections ensures that devices are not overloaded and allows efficient distribution of surge energy. To illustrate this, line configurations are considered: without arresters, with transformer-only protection, and with protection at all consumer service entrances except one (Fig. 3).

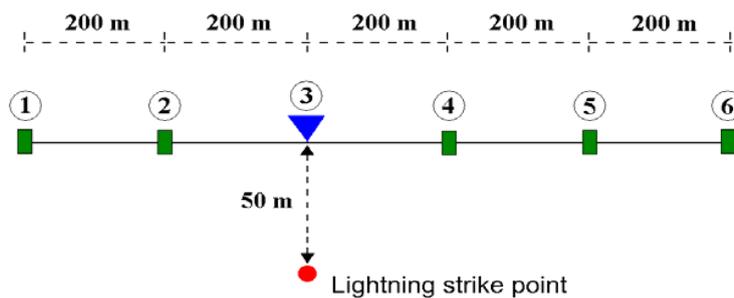


Figure 3: Low-voltage line configurations

Transformer design optimization also contributes to reliability enhancement. Interlaced secondary windings reduce impedance for symmetric surges, lowering voltage amplitudes within the transformer. However, for unbalanced surges, this measure alone is insufficient and must be combined with low-voltage SPDs to ensure complete equipment protection [11-13]. The current distribution between pole grounding and transformer neutral after a direct lightning strike to the medium-voltage line illustrates the effect of winding configuration on secondary overvoltage magnitudes (Fig. 4).

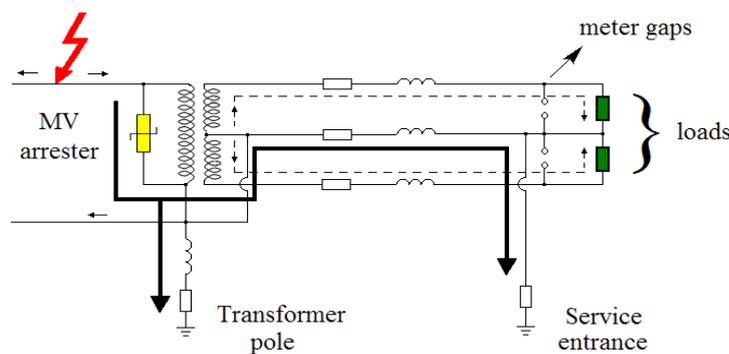


Figure 4: Injection of current into the neutral due to a direct strike to the MV line

The use of shielded or triplex cables and optimization of line routing play a significant role as well. Effective protection is achieved through reduced induced voltages and neutral rise compared to open-wire lines [14]. Simulation of phase-to-neutral voltages along the line during subsequent lightning strikes shows that protected configurations significantly reduce overvoltage amplitudes at all connection points, while unprotected sections remain vulnerable (Fig. 5-8).

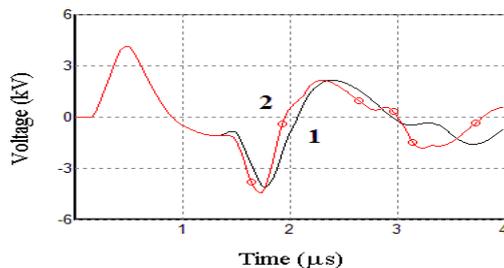


Figure 5: Phase-to-neutral induced voltages at Point 4 of Figure 3 when the stroke location is in front of it, at a distance of 50 m. $I = 12$ kA. Curve 1: configuration 1; curve 2: configuration 2.

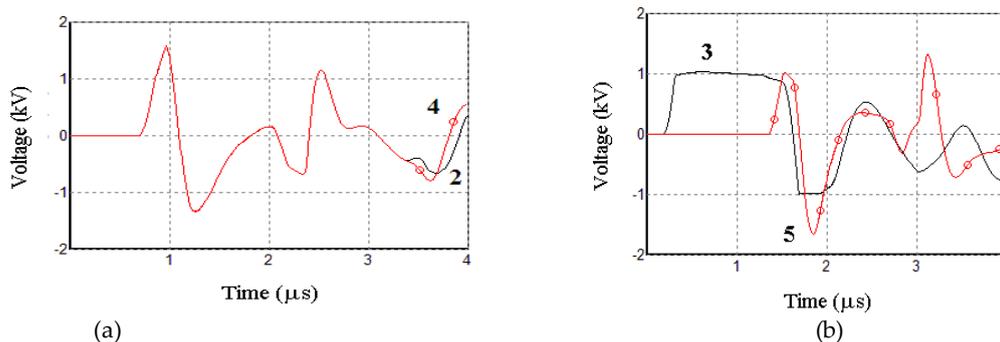


Figure 6: Phase-to-neutral induced voltages at points 2, 3, 4, and 5 of Figure 3 considering a typical subsequent stroke current ($I = 12$ kA). Configuration 2 (arresters only at the transformer terminals).

a) Points 2 (curve 2) and 4 (curve 4) b) Points 3 (curve 3) and 5 (curve 5)

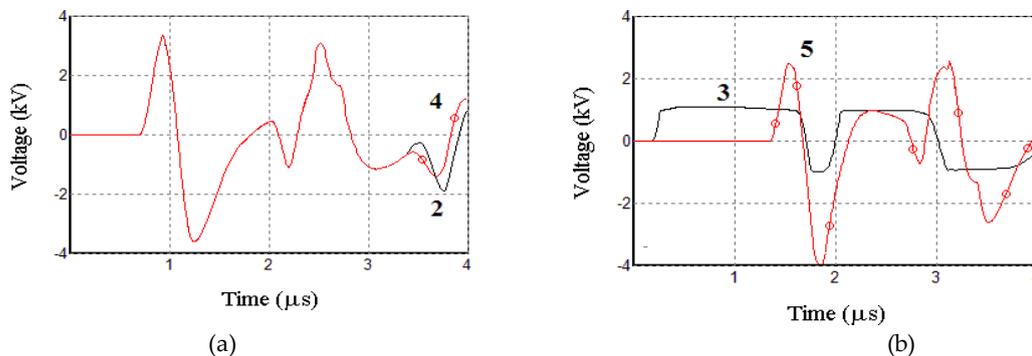


Figure 7: Phase-to-neutral induced voltages at points 2, 3, 4, and 5 of Figure 3 considering a subsequent stroke current with amplitude $I = 29.2$ kA. Configuration 2 (arresters only at the transformer terminals):

a) Points 2 (curve 2) and 4 (curve 4), b) Points 3 (curve 3) and 5 (curve 5)

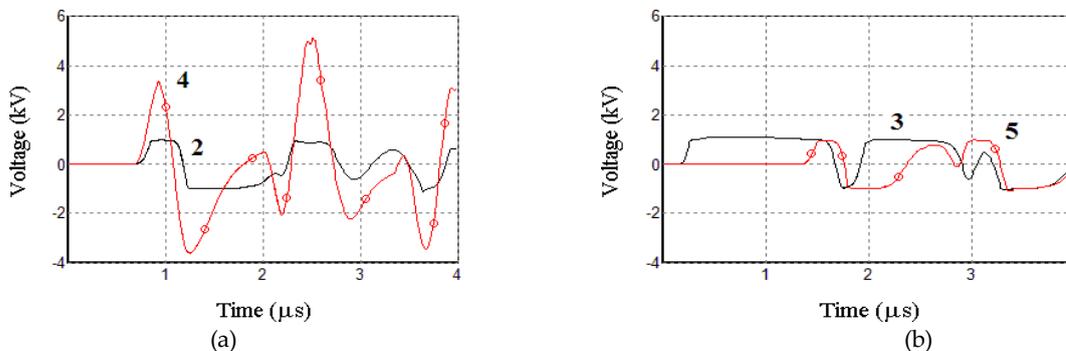


Figure 8: Phase-to-neutral induced voltages at points 2, 3, 4, and 5 of Figure 3 considering a subsequent stroke current with amplitude $I = 29.2$ kA. Configuration 3 (arresters at points 1, 2, 3, 5, and 6). a) Points 2 (curve 2) and 4 (curve 4), b) Points 3 (curve 3) and 5 (curve 5)

For practical design and operation, it is recommended to use a specification table with indicative SPD characteristics at different points in the network (Table 3).

Table 3: *Recommended specification matrix*

Location	SPD Class	Nominal Clamping	Key Requirement
Transformer LV terminals	Type-2 / MOV	440–480 V	High limp, thermal protection, close coupling
Service entrance	Type-2	≤ 2 kV	Energy handling per 8/20 μ s
Point of use	Type-3	As low as possible	Protect individual devices, supplement upstream SPDs

The combined implementation of these measures, including modeling, pilot deployment, and monitoring of protective devices, significantly reduces internal transformer stress and consumer equipment damage, providing positive economic benefits through decreased outage durations and reduced maintenance costs. Field experience and research indicate that coordinated installation of surge protection on transformers and consumer service entrances can reduce lightning-related damage by approximately an order of magnitude, making this strategy both reliable and economically justified.

IV. Conclusion

The study demonstrates that conventional lightning protection measures, such as improved grounding and primary MV surge arresters, are not sufficient to prevent damaging secondary surges in low-voltage (LV) distribution networks. Physical mechanisms of surge current injection into transformer neutrals, combined with network topology and transformer design features, create conditions under which secondary overvoltages can significantly reduce the reliability of distribution assets.

A reliability-centered approach requires the coordinated application of surge protective devices (SPDs) at both transformer terminals and consumer service entrances. Analysis of technical characteristics shows that MOV- and hybrid-based arresters offer the most effective balance of energy-handling capability, fast response, and operational durability. Their deployment reduces insulation stress inside transformers, minimizes consumer equipment damage, and contributes to improved reliability indices such as MTBF and SAIFI.

Economic analysis confirms that the cost of SPD installation is substantially lower than the cumulative expenses associated with transformer failures, outage-related losses, and customer compensation. Field evidence indicates that coordinated SPD strategies can reduce lightning-related failures by approximately an order of magnitude, leading to both technical and financial benefits for utilities.

From a broader perspective, the integration of surge protection into asset management frameworks should be treated as a strategic investment in system reliability. Future work should focus on long-term monitoring of SPD performance, development of adaptive protection coordination methods, and statistical modeling to further refine reliability predictions for lightning-prone regions.

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