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Enhancing the Reliability Assessment of Line Surge Arresters: A Stress–Strength Approach for System Studies

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Introduction

The topic of surge arrester failures is often discussed, yet frequently misunderstood. While many assume arrester reliability can be characterized using familiar metrics such as *Mean Time Between Failures (MTBF)* or fixed *service life expectancies*, the reality is more complex. The variety of failure modes and the inherent difficulty in estimating the probability of failure (PoF) are often underestimated or neglected.

Surge arrester manufacturers are regularly asked to provide reliability metrics to support asset management decisions. MTBF is commonly requested or proposed as a standard measure, or alternatively, a generic service life estimate—typically 30 to 40 years under “normal conditions”—is provided without substantiated analysis. However, neither of these metrics accurately reflects the actual reliability behavior of a surge arrester.

A surge arrester is a passive protection device, typically based on metal-oxide varistor (MOV) blocks. It does not fail in the same way that relays, circuit breakers, UPS systems, or power transformers do. Unlike those components, arresters do not exhibit random or wear-out failures over time (in theory). Instead, failure occurs when the applied stress exceeds the arrester’s capability, often as a result of accumulated energy, excessive temporary overvoltages, or environmental degradation.

Importantly, surge arresters lack redundancy: if a single MOV block fails, it typically leads to thermal overload and eventually results in a short-circuit condition. In such cases, the arrester is completely damaged and must be replaced. There is no concept of partial failure or repair—a failed arrester cannot be fixed. This aspect is often overlooked by non-specialists, but it has significant implications for asset management and reliability modeling.

MTBF, which assumes a constant failure rate during the useful life phase of the "bathtub curve," is therefore a misleading metric when applied to surge arresters. For example, consider a utility operating 10,000 distribution-class arresters with 20 failures per year. This corresponds to an annual failure rate of 0.2%, or 2 failures per 1,000 arresters per year. Expressed as MTBF, this would misleadingly imply a 500-year lifetime per arrester—a figure that has no practical meaning, since surge arresters fail due to specific stresses, not as a result of random time-based failure processes.

Service life expectancy (e.g., “30–40 years under normal conditions”) is somewhat more meaningful than MTBF but still carries important limitations. Such statements provide no statistical information on the actual probability of failure, and they obscure the fact that arrester performance is highly dependent on application and exposure. In practice, arresters have been observed to fail after only a few weeks in the field, while others continue operating reliably for over 40 years.

The most appropriate and useful reliability metric for surge arresters is the annual probability of failure (PoF/year)—that is, the expected failure rate under actual site-specific service conditions. This approach aligns with utility experience and field data compiled in CIGRÉ surveys [1], and avoids the false assumptions underlying time-based metrics like MTBF.

This paper adopts a reliability framework based on the stress–strength interference model, where failure occurs when actual electrical or environmental stress exceeds the arrester’s tested or expected strength. Where applicable, this model can be refined over time using condition-based indicators, such as resistive leakage current or thermal diagnostics, particularly in substations where critical equipment is protected by station-class arresters.

The primary objective of this paper is to apply this reliability framework specifically to line surge arresters, with a particular focus on externally gapped line arresters (EGLAs). An illustrative lightning performance study will be presented to demonstrate how this stress–strength approach can be used to estimate failure probabilities and support practical asset management decisions for line arresters, where direct monitoring is not feasible and probabilistic assessment becomes essential.

How to compute reliability — Stress vs. Strength

The reliability of a surge arrester is best understood through the stress–strength interference model, a foundational concept in engineering reliability theory. In this framework, reliability is defined as the probability that the applied stresses throughout service life remain below the arrester's capability, as determined by standardized type tests, design margins, and material properties.

For surge arresters, electrical stress—including lightning surges, switching transients, and temporary overvoltages—is typically quantifiable and can be modeled as an annual distribution of stress events. These stress distributions can be compared directly to the arrester's known electrical strength, such as energy absorption capacity (Wth/Qth), charge withstand (Qrs), and TOV performance. This allows for a probabilistic estimation of the annual probability of failure, which is the most meaningful reliability metric for arresters under real service conditions.

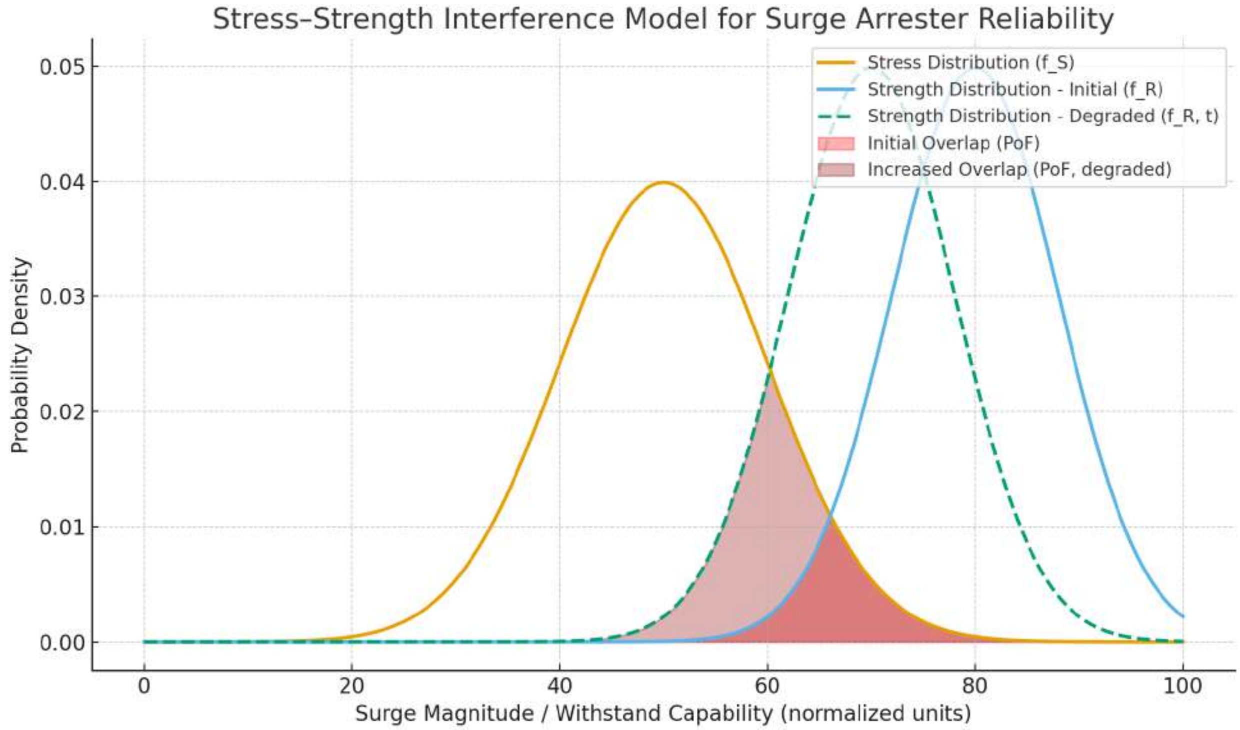


Figure 1. Theoretical mathematical illustration of the stress-strength overlap

However, electrical stress is only one dimension of the problem. In practice, surge arresters are subject to a range of mechanical and environmental stresses that influence long-term performance and failure risk. These may not always lend themselves to statistical modeling in the same way as electrical stress, but they must be acknowledged within a comprehensive reliability framework. They contribute to latent degradation, increase the likelihood of failure under marginal electrical events, and can, in some cases, be the primary cause of failure themselves.

Therefore, while the probabilistic comparison of electrical stress and strength forms the core of arrester reliability analysis, a complete engineering assessment must consider the combined effect of multiple stress domains. The interaction of these stresses over time defines the actual risk profile of the arrester in service.

In the following sections, this framework will be applied specifically to line surge arresters (LSAs), with a focus on Externally Gapped Line Arresters (EGLAs), where mechanical and environmental stress can be managed by design, but the risk associated with critical lightning strokes remains inherently difficult to predict and requires special attention.

What Are the Types of Stresses Seen by Surge Arresters

Surge arresters are subjected to a variety of stresses throughout their service life. These stresses can be broadly categorized into **electrical**, **mechanical**, and **environmental** stress. A comprehensive understanding of these stress types is essential for assessing reliability based on a stress–strength interference model.

Electrical Stress

Electrical stress is the primary category of stress encountered by surge arresters and arises from various types of overvoltages present in power systems.

- **Lightning Surges**
  These result from direct or indirect lightning strikes to overhead lines, towers, or nearby ground. They exhibit very fast front rise times (1–10 µs), high peak currents (typically 5–200 kA), and short durations (e.g., 8/20 µs waveform). The severity of lightning stress differs significantly between station-class arresters (which mostly face attenuated surges from incoming lines) and line surge arresters (which may experience direct strikes with high energy input). Lightning surges are typically addressed by verifying compliance with energy absorption capabilities (Qth) and charge withstand (Qrs) values as per IEC 60099-4, 60099-8, and upcoming IEC/IEEE 60099-11.

- **Switching Surges**
  Generated during operations such as capacitor bank energization, transformer energization, circuit breaker operations, and fault clearing. These surges have slower fronts and longer durations (typically 30–500 µs), and are particularly relevant in high-voltage substations. Switching surges are not relevant for line surge arresters intended solely for lightning protection, and are not applicable for externally gapped line arresters (EGLA), which are not energized. Switching surges are typically addressed by verifying compliance with energy absorption capabilities (Wth) and charge withstand (Qrs) values as per IEC 60099-4, and upcoming IEC/IEEE 60099-11.

- **Temporary Overvoltages (TOVs)**
  TOVs arise from system disturbances such as ground faults, load rejection, or ferroresonance. These overvoltages have power-frequency characteristics (50/60 Hz) and can last from a few milliseconds up to several seconds. While surge arresters are not designed to mitigate TOVs, they must be dimensioned to withstand and dissipate the resulting thermal stress. TOVs do not always have 50/60 Hz characteristics — those rich in harmonics especially—can reduce MOV resistance and cause cumulative heating [1]. TOV dimensioning is essential for gapless arresters but is irrelevant for EGLAs, which remain non-conductive under such conditions. TOVs are typically addressed by verifying compliance with the operating duty test (Ur) and TOV tests (with/without prior duty) as per IEC 60099-4, and upcoming IEC/IEEE 60099-11.

Mechanical Stress

Mechanical stresses result from both transient and sustained mechanical loads acting on the arrester structure, its mounting hardware, and housing materials.

- **Short-Term Loads**
  Include seismic events, wind gusts, and short-circuit-induced forces. These can apply sudden bending or torsional stresses and are typically addressed by verifying compliance with **Specified Short-Term Load (SSL)** values as per IEC 60099-4.

- **Long-Term Loads / Fatigue**
  Arise from the continuous mechanical load of conductors (cable or busbar weight), snow/ice accumulation, and gravitational stresses. These contribute to slow degradation through fatigue of core materials or seals and are verified via **Specified Long-Term Load (SLL)** tests as per IEC 60099-4.

- **Vibration Effects**
  Occur in environments with rail traffic, mechanical switching, or wind-induced vibrations. For EGLA applications, it is typically addressed by verifying compliance as per IEC 60099-8, and upcoming IEC/IEEE 60099-11.

Environmental Stress

Environmental stresses accelerate arrester degradation through external exposure. While difficult to quantify probabilistically, they remain critical in reliability assessments.

- **Moisture** (rain, fog, snow, condensation) can lead to surface leakage currents, especially when combined with contaminants. Moisture ingress through failed seals can trigger internal discharges and thermal ageing.

- **Pollution and Contamination** (e.g., industrial dust, salt fog, desert sand) can create conductive surface films that enable dry-band arcing, tracking, and erosion of the housing surface.

- **Temperature Extremes** affect both mechanical and electrical performance. High temperatures increase leakage current and power losses, while low temperatures can embrittle housings and seals. Thermal cycling accelerates material fatigue.

- **UV Radiation and Solar Heating** can degrade polymeric housings over time by breaking down surface hydrophobicity, leading to erosion and cracking.

- **Wildlife** such as birds and rodents can physically damage equipment (e.g., nests, droppings, chewed cables) and introduce unexpected contamination or mechanical failure modes.

Integrating Condition-Based Indicators into the Stress–Strength Reliability Framework

The annual probability of failure for surge arresters can be estimated using a stress–strength interference model, where the statistical distribution of applied stresses—primarily from lightning impulses, switching surges, and temporary overvoltages (TOVs)—is compared against the arrester's design strength (energy capability, TOV withstand). This approach yields a baseline failure probability that assumes the arrester remains in its original condition throughout its life.

However, in real-world conditions, arrester strength is not static. It can degrade over time due to cumulative thermal ageing, environmental exposure, mechanical fatigue, or sealing failure. Therefore, to refine the reliability estimate, the baseline stress–strength model can be dynamically updated using condition-based indicators—the most practical and widely accepted of which is leakage current monitoring.

This method, partially formalized in IEC 60099-5, is often based on the third-harmonic analysis, which estimates the resistive component of the arrester's leakage current—a key indicator of MOV degradation. Other analysis of current components, such as the total peak, can be a key indicator of moisture ingress and external pollution and contamination.

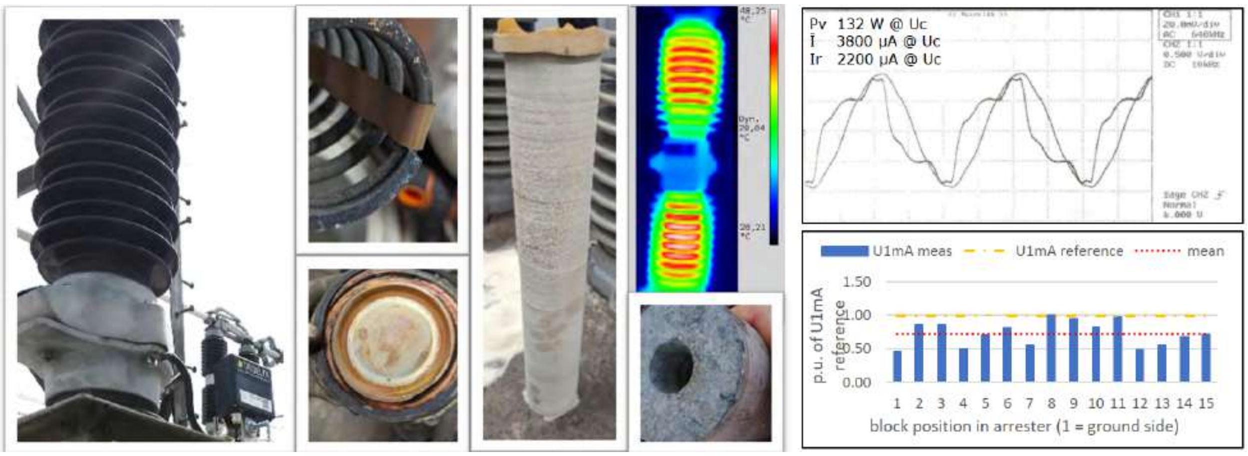
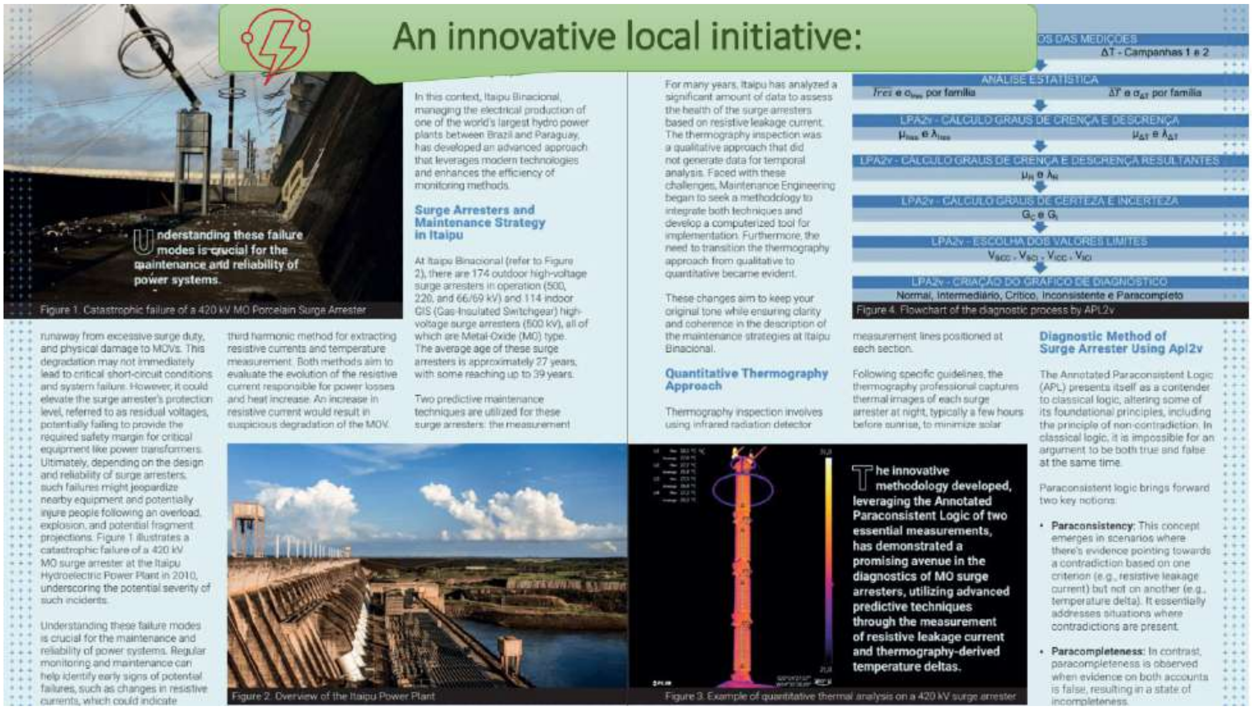


Figure 2. Example of critical surge arrester conditions which has been revealed by the use of advanced monitoring solutions [2]

An increase in resistive current leads to higher power losses, which in turn cause a rise in operating temperature. As a result, thermal imaging is commonly used in the industry as a complementary diagnostic tool, either to confirm elevated leakage current measurements or as a stand-alone alternative when electrical diagnostics are not available.

Modern approaches to surge arrester diagnostics are increasingly moving toward proactive and precise condition-based monitoring, using a combination of third-harmonic leakage current analysis and infrared thermography. These methods allow asset owners to detect early signs of arrester degradation—such as increased resistive current due to moisture ingress or thermal ageing—long before visible damage or failure occurs. Projects in large-scale networks have shown the value of systematically tracking these indicators to support informed replacement decisions, improve fleet-wide reliability, and avoid critical equipment damage. We fully support such methodologies and believe that they represent a valuable evolution in arrester asset management, especially when pursued through cooperation between manufacturers and end users, rather than relying solely on factory-based specifications or batch testing.



An innovative local initiative:

> Understanding these failure modes is crucial for the maintenance and reliability of power systems.

Figure 1. Catastrophic failure of a 420 kV MO Porcelain Surge Arrester

runaway from excessive surge duty, and physical damage to MOVs. This degradation may not immediately lead to critical short-circuit conditions and system failure. However, it could elevate the surge arrester's protection level, referred to as residual voltages, potentially failing to provide the required safety margin for critical equipment like power transformers. Ultimately, depending on the design and reliability of surge arresters, such failures might jeopardize nearby equipment and potentially injure people following an overload, explosion, and potential fragment projections. Figure 1 illustrates a catastrophic failure of a 420 kV MO surge arrester at the Itaipu Hydroelectric Power Plant in 2010, underscoring the potential severity of such incidents.

Understanding these failure modes is crucial for the maintenance and reliability of power systems. Regular monitoring and maintenance can help identify early signs of potential failures, such as changes in resistive currents, which could indicate

third harmonic method for extracting resistive currents and temperature measurement. Both methods aim to evaluate the evolution of the resistive current responsible for power losses and heat increase. An increase in resistive current would result in suspicious degradation of the MOV.

Figure 2. Overview of the Itaipu Power Plant

In this context, Itaipu Binacional, managing the electrical production of one of the world's largest hydro power plants between Brazil and Paraguay, has developed an advanced approach that leverages modern technologies and enhances the efficiency of monitoring methods.

Surge Arresters and Maintenance Strategy in Itaipu

At Itaipu Binacional (refer to Figure 2), there are 174 outdoor high-voltage surge arresters in operation (500, 220, and 66/69 kV) and 114 indoor GIS (Gas-Insulated Switchgear) high-voltage surge arresters (500 kV), all of which are Metal-Oxide (MO) type. The average age of these surge arresters is approximately 27 years, with some reaching up to 39 years.

Two predictive maintenance techniques are utilized for these surge arresters: the measurement

For many years, Itaipu has analyzed a significant amount of data to assess the health of the surge arresters based on resistive leakage current. The thermography inspection was a qualitative approach that did not generate data for temporal analysis. Faced with these challenges, Maintenance Engineering began to seek a methodology to integrate both techniques and develop a computerized tool for implementation. Furthermore, the need to transition the thermography approach from qualitative to quantitative became evident.

These changes aim to keep your original tone while ensuring clarity and coherence in the description of the maintenance strategies at Itaipu Binacional.

Quantitative Thermography Approach

Thermography inspection involves using infrared radiation detector

OS DAS MEDIÇÕES
ΔT - Campanhas 1 e 2
ANALISE ESTATISTICA
$\overline{Ires}$ e σ_{Ires} por familia
$\overline{\Delta T}$ e $\sigma_{\Delta T}$ por familia
LPA2v - CALCULO GRAUS DE CRENÇA E DESCRENÇA
μ_{Ires} e λ_{Ires}
$\mu_{\Delta T}$ e $\lambda_{\Delta T}$
LPA2v - CALCULO GRAUS DE CRENÇA E DESCRENÇA RESULTANTES
μ_R e λ_R
LPA2v - CALCULO GRAUS DE CERTEZA E INCERTEZA
G_C e G_I
LPA2v - ESCOLHA DOS VALORES LIMITES
V_{SCC} - V_{SCI} - V_{ICC} - V_{ICI}
LPA2v - CRIAÇÃO DO GRAFICO DE DIAGNOSTICO
Normal, Intermediário, Critico, Inconsistente e Paracompleto

Figure 4. Flowchart of the diagnostic process by APL2v

measurement lines positioned at each section.

Following specific guidelines, the thermography professional captures thermal images of each surge arrester at night, typically a few hours before sunrise, to minimize solar

> The innovative methodology developed, leveraging the Annotated Paraconsistent Logic of two essential measurements, has demonstrated a promising avenue in the diagnostics of MO surge arresters, utilizing advanced predictive techniques through the measurement of resistive leakage current and thermography-derived temperature deltas.

Figure 3. Example of quantitative thermal analysis on a 420 kV surge arrester

Diagnostic Method of Surge Arrester Using Apl2v

The Annotated Paraconsistent Logic (APL) presents itself as a contender to classical logic, altering some of its foundational principles, including the principle of non-contradiction. In classical logic, it is impossible for an argument to be both true and false at the same time.

Paraconsistent logic brings forward two key notions:

- **Paraconsistency:** This concept emerges in scenarios where there's evidence pointing towards a contradiction based on one criterion (e.g., resistive leakage current) but not on another (e.g., temperature delta). It essentially addresses situations where contradictions are present.
- **Paracompleteness:** In contrast, paracompleteness is observed when evidence on both accounts is false, resulting in a state of incompleteness.

Figure 3. Example of local initiative developed by Itaipu Binacional combining third harmonic method and thermal imaging to offer a state-of-the-art platform for asset managers

That said, it is important to recognize that these monitoring techniques are only applicable to station-class, gapless metal-oxide arresters, typically installed in substations to protect high-value equipment like power transformers. In contrast, line surge arresters (LSAs)—and in particular externally gapped line arresters (EGLAs)—do not conduct under normal operating conditions and therefore do not exhibit measurable leakage current. For these devices, condition-based diagnostics are not practical or meaningful. Given their large numbers and distributed nature, LSA failures are less critical and can be tolerated for a time until located and replaced. In such cases, the baseline reliability model based on stress–strength interference remains the most appropriate method for evaluating performance. The distinction between critical, monitored assets in substations and non-critical, probabilistically assessed assets on overhead lines is therefore essential in building an effective surge arrester asset management strategy.

Design Issues and Manufacturing Flaws: A Critical Dimension of Surge Arrester Reliability

In addition to operational stresses, a surge arrester's reliability is deeply influenced by design integrity and manufacturing quality. While this topic is often sensitive to address, it is a necessary part of any honest and technical discussion on long-term performance. As an independent consultant, it is clear that variability exists across the industry—in design philosophies, production standards, quality assurance procedures, and sourcing strategies. Acknowledging this reality is not about criticizing individual companies, but rather about understanding the full chain of reliability and the importance of transparency, standardization, and vigilance.

To structure this discussion, a surge arrester may be conceptually divided into three core elements: the MOV blocks, the arrester design, and the final assembly. Each of these contributes to overall performance, and weaknesses in any part can undermine the arrester's reliability—even if other components are of high quality.

1. The MOV Block – The Heart of the Arrester

Metal-oxide varistors (MOVs) are the core energy-absorbing elements of the surge arrester. The manufacturing of MOVs is a specialized process requiring controlled sintering conditions, stable material compositions, and consistent coating procedures. While some arrester manufacturers produce their own MOVs, many rely on third-party suppliers. This is not inherently problematic, but it places the burden of responsibility on the arrester manufacturer to ensure proper sourcing and stable long-term performance.
There is currently no IEC standard dedicated specifically to MOV blocks, which means quality assurance relies on internal specifications and incoming inspections. Defects in MOVs—such as inconsistencies in the coating or changes in electrical properties over time—can severely compromise performance. This makes the MOV supply chain a critical risk factor.

Figure 4. MOV Block Failure Probably Due to Internal Stress from Non-Uniform Sintering. Source TenneT Netherlands.

2. The Arrester Design – Integration and Encapsulation

Once MOVs are procured, they must be integrated into an arrester design—stacked, secured, encapsulated, and sealed. Common designs include molded polymer types, hollow-core housing designs, and other variations. The arrester design plays a fundamental role in determining how well the MOVs are protected from environmental and mechanical stresses.

It is important to note that a well-performing MOV does not guarantee a well-performing arrester. Design flaws—such as insufficient sealing or inappropriate mechanical interfaces—can lead to premature failure. A recent study from China [4] highlighted that high current impulse test results may not correlate well between MOVs, sectional units, and complete arresters, demonstrating that arrester performance is not purely a function of MOV quality, but also of design and materials used in encapsulation and assembly.

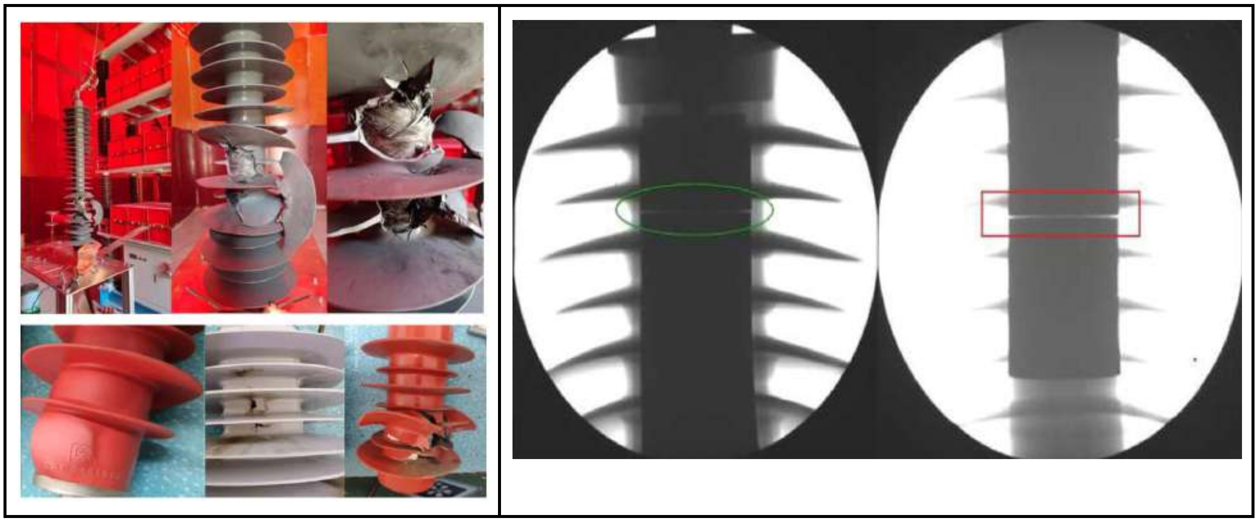
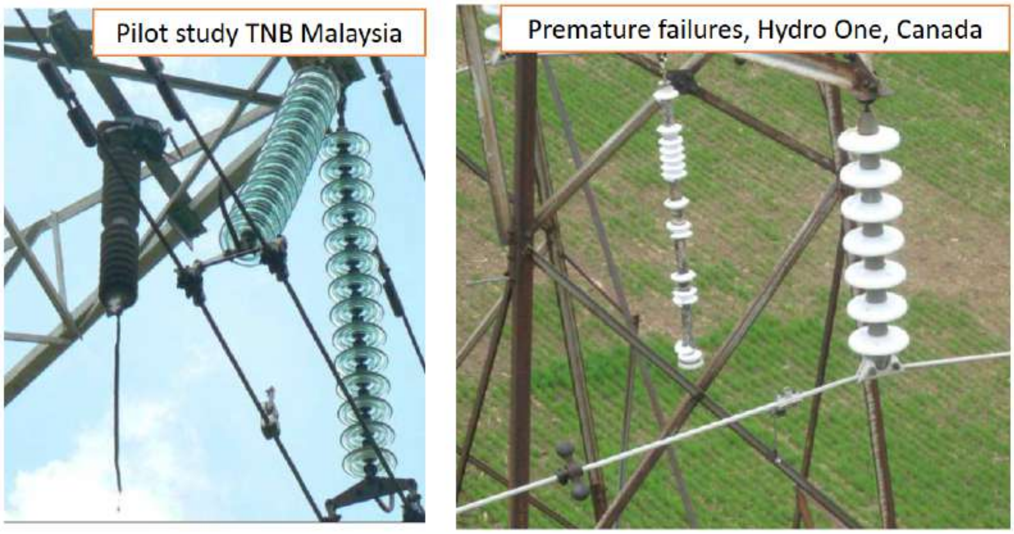


Figure 5. Example of failed arrester units (prorated sections) after a high current impulse test. Source State Grid China / CEPRI

3. Final Assembly – From Design to Application

The final arrester product must not only be functionally sound, but also suitable for the intended installation environment. This includes hardware interfaces, mounting brackets, leads, and coordination with system-specific parameters. For example, non-gapped line arresters (NGLAs) are often adapted from standard station-class designs. While the internal components may be robust, they are sometimes installed on overhead lines with poor-quality clamping systems or mechanically weak lead connections, which introduce new failure risks. In such cases, the MOVs and design may be technically correct, but the final product is unfit for the application—compromising reliability.

Figures 6. Damage to Overhead Conductor Due to Pressure Relief Discharge from Faulted Line Arrester (Ganzhou, China, 2017)



Pilot study TNB Malaysia

Premature failures, Hydro One, Canada

Figures 7. Examples of reported NGLA failures [5]

Distribution vs. Station-Class Arresters – A Divergence in Quality Culture

A clear divide exists in the industry between distribution-class and station-class arresters. Distribution-class arresters are often treated as commodity products, heavily driven by cost pressure. In this market segment, quality-related factors such as design verification, production control, and type testing are frequently overlooked in favor of extremely low prices. Failures are common and often go uninvestigated, under the assumption that the arrester “did its job”—as if it were a disposable fuse.

In contrast, high-voltage station-class arresters are considered critical protection assets. Utilities operating these arresters demand comprehensive qualification, including rigorous type tests, factory audits, and long-term performance data. This culture of quality control and engineering oversight results in arresters that often remain in service for 30–40 years or more, with minimal failure rates.

Ultimately, reliability cannot be guaranteed by MOV quality alone. It must be built into every stage of the product—from MOV sourcing and surge arrester design to assembly and application-specific integration. Furthermore, industry standards such as IEC and IEEE provide essential requirements and guidance, but they evolve slowly and are not always sufficient to prevent low-quality products from reaching the market. This is why constant vigilance, informed end users, and cooperation between manufacturers and utilities are critical to ensure that arrester reliability meets the demands of modern power systems.

The Importance of Being Proactive in Quality Assurance and Control

Many of the design issues and manufacturing flaws discussed earlier should not occur—if appropriate Quality Assurance (QA) and Quality Control (QC) systems are in place and actively applied. In the context of high-voltage equipment, where reliability is paramount, being proactive rather than reactive in quality management is not optional—it is a necessity. While international standards such as IEC and IEEE provide a foundation, they are not exhaustive. The reality of industrial practice shows that standards alone are not enough. One principle must remain at the core of any responsible QA/QC strategy: do not simply trust—verify. This is a fundamental rule across all industries that support critical and sensitive infrastructure, and it must apply equally to power system components.

Quality Assurance involves systematic planning, process definition, risk assessment, documentation, and preventive controls to ensure that products are designed and manufactured in accordance with defined requirements. Quality Control, by contrast, is the operational side: the inspection, testing, and verification of materials, components, and finished products to detect deviations and confirm compliance with technical specifications. Among these two pillars, Quality Control plays a particularly critical role in line surge arrester (LSA) projects, which often involve large volumes of equipment—far more than typical substation applications.

When dealing with hundreds or thousands of LSAs, ensuring consistent quality across all units becomes both a technical and logistical challenge. It is the responsibility of the end user, depending on the project’s scope, criticality, and budget, to implement appropriate control measures. This includes incoming inspections, oversight of key manufacturing steps, and potentially the use of additional sample testing, even if not required by IEC 60099-4 for surge arresters. (As a point of reflection: why are such procedures mandatory for insulators, but not for arresters?) It also means a thorough review of routine test records, strict acceptance testing to match project specifications, and full traceability to ensure that the same materials and processes used in type testing are applied in regular production.

Ultimately, catastrophic failures are avoidable, but only if QA and QC are treated not as paperwork obligations, but as active engineering tools for risk mitigation. Reliability starts long before energization—it starts at the factory gate, and only strong verification processes can keep it there.

Application of the Reliability Framework to Line Surge Arresters

The concept of reliability as an annual probability of failure becomes particularly insightful when applied to line surge arresters (LSAs). These devices are widely deployed on overhead lines to mitigate lightning-related outages, but due to their distributed nature and the large quantities involved in typical projects, they require a probabilistic and scalable approach to assess performance. This section focuses specifically on Externally Gapped Line Arresters (EGLAs) and provides a concrete methodology to estimate their reliability under actual site-specific service conditions, using the stress–strength interference model introduced earlier.

Before proceeding, it is useful to highlight a key distinction between EGLAs and Non-Gapped Line Arresters (NGLAs) in the context of reliability. NGLAs are continuously connected to the phase voltage and are therefore exposed to continuous electrical stress, including Temporary Overvoltages (TOVs) and switching surges. In contrast, EGLAs are not exposed to such stresses because their air gap is designed to withstand both TOVs and switching surges under worst-case conditions. EGLAs remain non-conductive except during lightning overvoltages. This distinction is crucial, as it simplifies the reliability model: for EGLAs, only lightning-related stresses are relevant to failure analysis in regard to electrical stresses.

In this application of the reliability framework, mechanical and environmental stresses are not included in the probabilistic model. This is because, as discussed earlier, these stresses can be effectively managed through proper design and quality assurance practices. Nevertheless, it is worth noting that some environmental factors remain important. Wildlife interaction is a real risk in certain regions and should be considered during the planning stage. UV radiation, temperature extremes, and pollution or contamination can all be mitigated through robust design and appropriate material testing. The risk of moisture ingress is more nuanced. While the industry could benefit from advancing test standards—similar to those developed for composite insulators—EGLAs offer a key advantage over NGLAs: because EGLAs are not continuously energized, there is significantly less risk of internal partial discharges or flashover due to trapped moisture. While moisture ingress cannot be fully ruled out, EGLA designs generally provide higher confidence in minimizing this failure mode.

Modeling Reliability for EGLAs: Stress vs. Strength

The methodology for assessing EGLA reliability begins by identifying the key stress parameter: the charge (Q) that flows through the arrester (SVU – Series Varistor Unit) when a lightning stroke triggers operation. This charge distribution depends on multiple factors, including:

- The ground flash density (GFD or Ng) at the site, typically expressed in flashes/km²/year, which should be derived from LLS-based historical lightning data,

- The peak current stroke distribution, preferably obtained from reliable sources such as CIGRÉ TB 839,

- The stroke attraction model, usually based on the Electro-Geometric Model (EGM), which estimates the likelihood of stroke interception by the line,
- The geometry of the line, which directly influences the proportion of backflashovers versus shielding failures. When lightning strikes phase conductors directly (shielding failure), the charge through the EGLA is significantly higher than in a backflashover scenario.

The stroke attraction model is particularly sensitive to the geometry and shielding design of the transmission line, including tower height, conductor configuration, and shield wire placement. These parameters define how likely a given lightning stroke is to strike the protected phase or bypass the line altogether.

Dedicated tools for lightning performance studies—such as EMTP, PSCAD, or specialized software like SIGMA SLP—can then be used to simulate EGLA behavior under each relevant lightning event. From these simulations, the charge (Q) delivered to the arrester can be extracted for each stroke scenario, forming the stress distribution required for the reliability analysis.

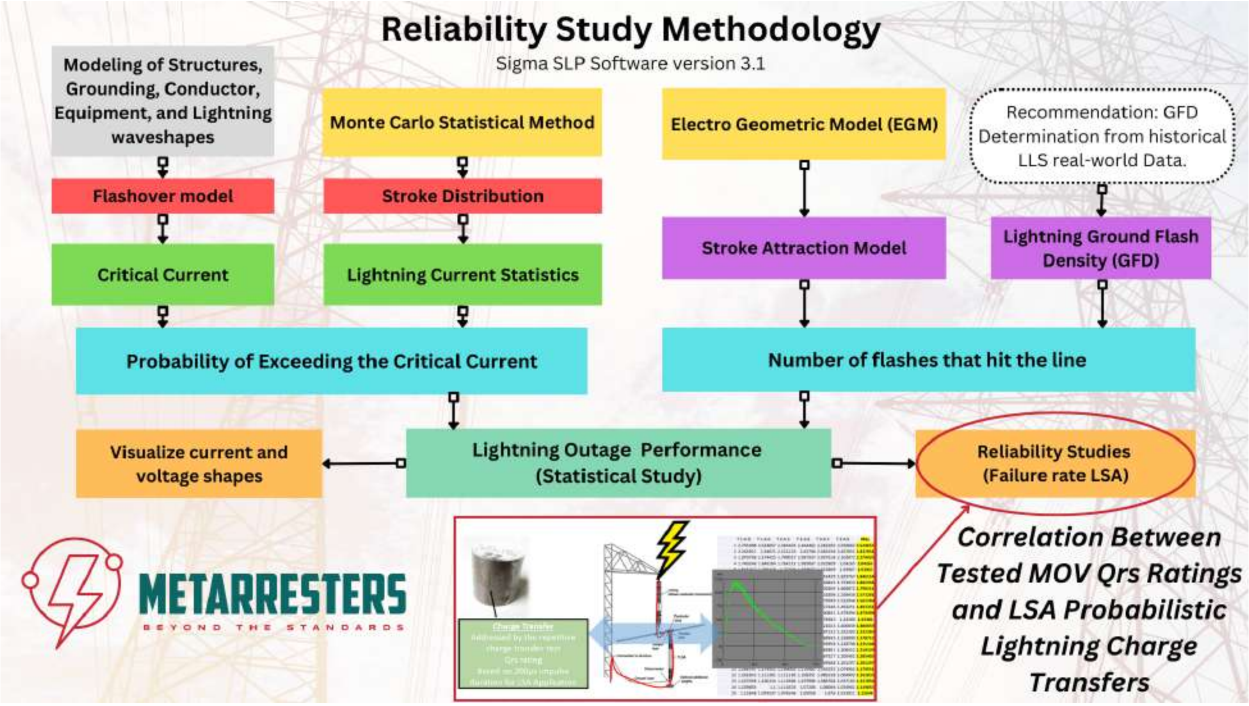


Figure 8. Methodology used for the reliability analysis using Sigma SLP version 3.1 to compute the probability of lightning charge through LSA exceeding the nominal Qrs (C) ratings.

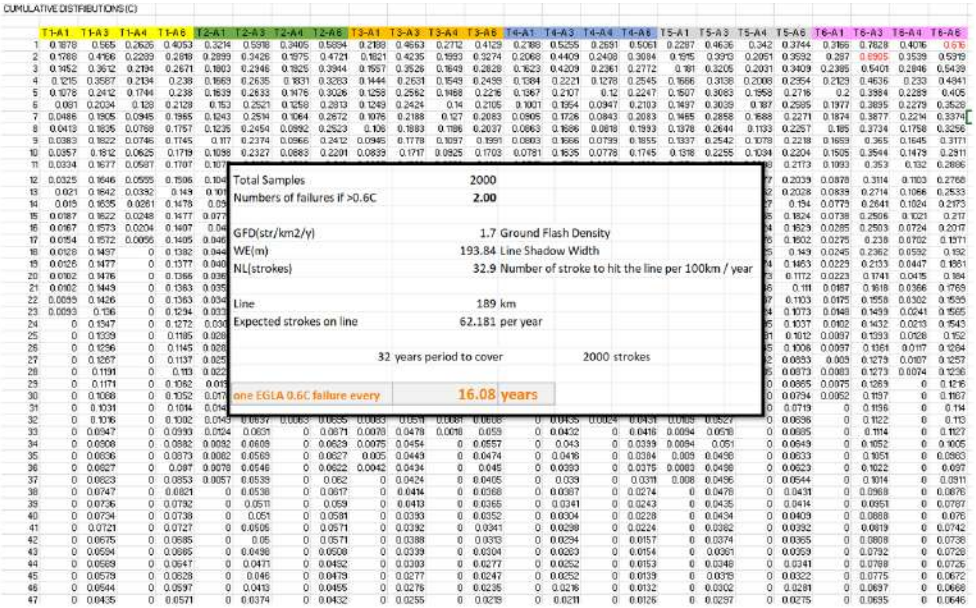
Comparing Stress and Strength

The strength of the EGLA is represented by its Qrs rating, or repetitive charge transfer capability, as defined in IEC 60099-8 (and the upcoming IEC/IEEE 60099-11). This value indicates the maximum charge the EGLA can safely absorb multiple times without degradation over its service life. By comparing the distribution of simulated lightning-induced charges (Qstress) with the EGLA's Qrs capability (Qstrength), we can calculate the overlap—that is, the probability that a given lightning stroke will produce a charge exceeding the EGLA's design rating.

This overlap defines the probability of failure per lightning event, but it does not yet reflect the time-based reliability of the arresters. To convert this into an annual probability of failure per EGLA, we first estimate the total number of critical lightning events expected along the line over a given period (based on a SIGMA SLP study), using site-specific parameters such as ground flash density (GFD), peak current stroke distribution, line geometry, and an Electro-Geometric Model (EGM).

In the example presented, this engineering prediction is computed using 2,000 lightning stroke samples that strike the line section under consideration. The number of simulated events exceeding the Qrs threshold is then divided by the number of years to obtain a fleet-level failure probability. This result is further divided by the total number of EGLAs installed (the fleet size), providing a per-unit annual probability of failure.

This fleet-based approach offers a scalable and meaningful reliability metric for asset managers and system planners operating under real-world service conditions.



CUMULATIVE DISTRIBUTIONS (C)

Total Samples	2000	
Numbers of failures if >0.6C	**2.00**	
GFD(str/km2/y)	1.7	Ground Flash Density
WE(m)	193.84	Line Shadow Width
NL(strokes)	32.9	Number of stroke to hit the line per 100km / year
Line	189	km
Expected strokes on line	62.181	per year

32 years period to cover   2000 strokes

one EGLA 0.6C failure every 16.08 years

Figure 9. Example of reliability study results using Sigma SLP version 3.1

Number of event simulated along the line section = **2000 samples** (representing ~32 years)

Qrs capability (Qstrength) of the EGLA = **0.6 C (200μs impulse duration)**

Ground Flash Density (GFD or Ng) = **1.7 flashes/km²/year**

Number of strokes to hit the line per 100 km / year = **32.9**

Number of simulated charges (Qstress) exceeding 0.6 C = **2**

Assuming an EGLA fleet of **1000 units :**

λ_fleet = 2 failures / 32 years = 0.0625 failures/year (fleet-level)

λ_unit = 0.0625 / 1000 = 6.25×10^{-5} per unit per year

Clarifying the Use of Charge Ratings in Reliability Assessment

In some system studies and reliability assessments, the term thermal energy (denoted *Wth* or *Qth*) is sometimes referenced to estimate the capability of surge arresters to withstand electrical stress. While this approach may appear technically valid, it is in fact misleading—especially in the context of lightning performance and externally gapped line arresters (EGLAs). The *Qth* or *Wth* test (which applies only to NGLA) is designed to evaluate thermal stability, not statistical endurance or repetitive discharge capability. Specifically, it involves the injection of two consecutive impulses, allowing the MOV blocks to partially cool between applications, followed by the application of the rated voltage and the continuous operating voltage. The purpose of this test is to confirm that the arrester remains thermally stable under worst-case temporary overvoltage conditions, not to verify its ability to repeatedly handle charge under lightning conditions.

As described in the upcoming IEC/IEEE 60099-11 standard, the thermal charge *Qth* is not equivalent to the Qrs rating, which is the correct reference when comparing stress (from lightning studies) to strength (arrester capability). In fact, since *Qth* includes two impulses, its value is approximately twice the Qrs, and therefore cannot be used as a direct indicator of repetitive energy withstand. Any attempt to assess the reliability of EGLAs based on Qth values would significantly overestimate their durability under realistic field conditions.

To ensure accurate reliability predictions, it is essential to base all stress–strength comparisons on the arrester's Qrs rating—the repetitive charge transfer rating, which quantifies the maximum charge that can safely pass through the arrester without degradation, under well-defined test conditions. According to IEC 60099-8 and the upcoming IEC/IEEE 60099-11, this test must be conducted using an impulse of 200–230 μs duration, which reflects the typical waveshape of lightning-induced discharges on overhead lines. However, many users and even manufacturers still reference Qrs values based on a 2 ms impulse, which originates from station-class arrester testing (IEC 60099-4) and is appropriate for switching surges, not lightning events. It is well established that the Qrs value drops by approximately 50% when moving from 2 ms to 200 μs impulses. Using the wrong impulse duration in stress–strength comparisons introduces a substantial bias, potentially underestimating the real probability of failure.

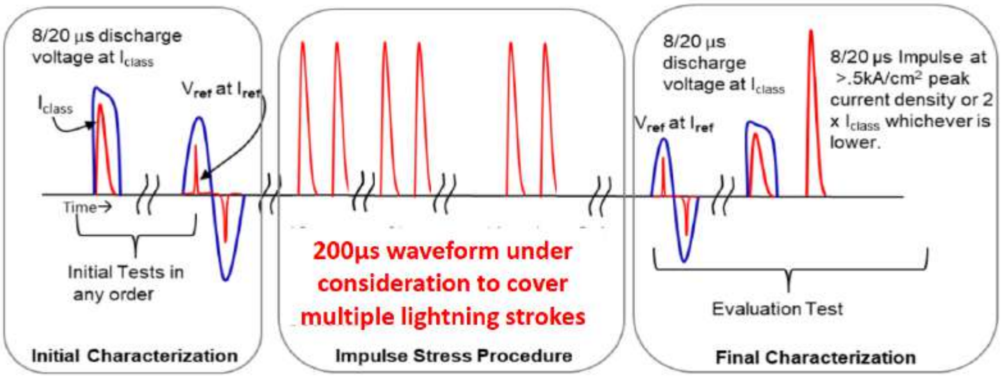


Figure 10. Type (Design) Test procedure of the Qrs rating (IEEE C62.11 equivalent to IEC)

Therefore, when computing the annual probability of failure of line surge arresters under actual service conditions, the Qrs rating used must match the impulse duration range of the discharge current waveform extracted from lightning performance studies. Only then can the statistical interference model accurately reflect the real operational risk.

Statistical Interpretation of Qrs: From IEC Testing to Field Reliability

The Qrs value published by manufacturers is typically derived from a statistical test—not a single impulse event. According to IEC 60099-4 (Clause 8.5) and IEC 60099-8 (Clause 8.6), ten MOV samples are subjected to twenty long-duration impulses each (2 impulses per sequence, 10 sequences), with full thermal recovery between sequences. This means Qrs reflects the repetitive charge transfer capability under controlled conditions—not an absolute limit, but one that accounts for material variability and test reproducibility. Thus, Qrs is inherently probabilistic: it ensures that a surge arrester built with comparable MOVs will meet or exceed this charge transfer level under repeated duty, within an acceptable failure rate.

In system studies and arrester dimensioning for typical applications (e.g., substations), generous safety margins are typically applied to account for expected stress. IEC standards further require a 10% margin between the tested value and the specified Qrs rating, providing additional confidence in the test results and published ratings. Furthermore, in practice, the failure resistance of MOV blocks follows a statistical distribution—some may withstand 15% more, others even 30% more than the nominal rating.

Yet the reality, as always, is more nuanced. What the IEC Qrs test actually verifies is:

- Setup: 10 MOV discs × 20 long-duration impulses each

- Criterion: ≤ 1 failure among the first 10 discs; or ≤ 2 failures in 20 discs if extended

- Pass meaning: Based on binomial statistics, the true per-disc failure probability at this stress level is ≤ ~0.56% (with ~95% confidence)

However, in service, the "weakest-link" effect must be considered—only one block needs to fail for the entire arrester to be compromised. Also, timing matters: a failure during the first high-current impulse is far more critical than one occurring after multiple repetitions.

In substation studies, we typically do not focus on the probability of exceeding Qrs, as lightning energy is rarely so severe. However, in lightning performance studies, especially for line surge arresters, the probabilistic nature of Qrs becomes central, as it is not feasible to design for the most extreme strokes without considering the probability of their occurrence.

Conclusion

This paper has proposed a structured and probabilistic framework to evaluate the reliability of Externally Gapped Line Arresters (EGLAs) under real-world service conditions. By applying the stress–strength interference model, we shift from traditional deterministic or lifespan-based approaches to a data-driven methodology grounded in system studies, site-specific lightning parameters, and the inherent electrical strength of surge arresters as defined by their Qrs ratings.

The methodology allows for a scalable and quantitative estimation of failure probability, offering valuable insights for asset managers and system planners who must deploy and maintain large populations of line surge arresters across extensive networks.

Beyond modeling, this paper also draws attention to real-world factors influencing arrester performance — including design issues, manufacturing variability, and quality assurance practices. In an industry where surge arresters are expected to perform silently but critically for decades, it is imperative to adopt a proactive stance: one that combines robust simulation methods, clear performance metrics like Qrs, and a culture of verification rather than blind trust.

As lightning performance becomes an increasingly important factor in grid resilience, especially in regions with high ground flash densities and growing reliance on overhead infrastructure, this approach provides a sound and adaptable tool for modern engineering practice. Further refinement of standards, more detailed test protocols, and deeper integration with field monitoring systems (if applicable) will only enhance the reliability and transparency of surge protection strategies in high-voltage and medium-voltage power systems.

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