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Performance of Surge Arc Suppressors for Effective Lightning Mitigation

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Introduction

The landscape of surge protection devices in power systems has witnessed significant technological advancements over the years. As we examine the evolution of the different technologies, we find that the transition from gapped to non-gapped types, and back to gapped, offers valuable insights.

In a world increasingly reliant on stable and secure electrical supply, the role of Line Surge Arresters on overhead lines has never been more critical. This paper aims to explore the performance characteristics of the Surge Arc Suppressor (SAS) devices, as an alternative of conventional Metal-Oxide types, particularly focusing on their efficacy and reliability in various operational conditions. Targeting industry professionals, manufacturers, and power utilities, the paper endeavors to serve as a comprehensive guide for making informed decisions in the field of surge protection.

Drawing from empirical data, real-world case studies, and a thorough review of existing literature, this paper aims to provide actionable insights that can be directly applied to the selection and operation of Surge Arc Suppressor devices. By understanding the past, we can better prepare for the challenges and opportunities that lie ahead.

Historical Concept – The study of history helps us anticipate the future

Evolution from Silicon Carbide (SiC) Arresters to Metal-Oxide Surge Arresters (MOSA)- fear of past demons

In 1990, the predominant sentiment among arrester manufacturers was largely dismissive of silicon carbide gapped arresters (SiC gapped); which was entirely justified given their technical limitations and the introduction of Metal-Oxide Varistors (MOV) technology.

SiC gapped arresters were criticized for their instability and degradation over time, which adversely affected their sparkover characteristics. Consequently, even promoting MOV gapped arresters faced significant challenges, as the presence of a gap was generally equated with inferior performance.

Nevertheless, the industry witnessed a remarkable enhancement in residual voltage voltage (protection level) associated with MOV gapped arresters. This advancement faced criticism primarily from manufacturers who were focused on producing non-gapped MOV products (dominant design).

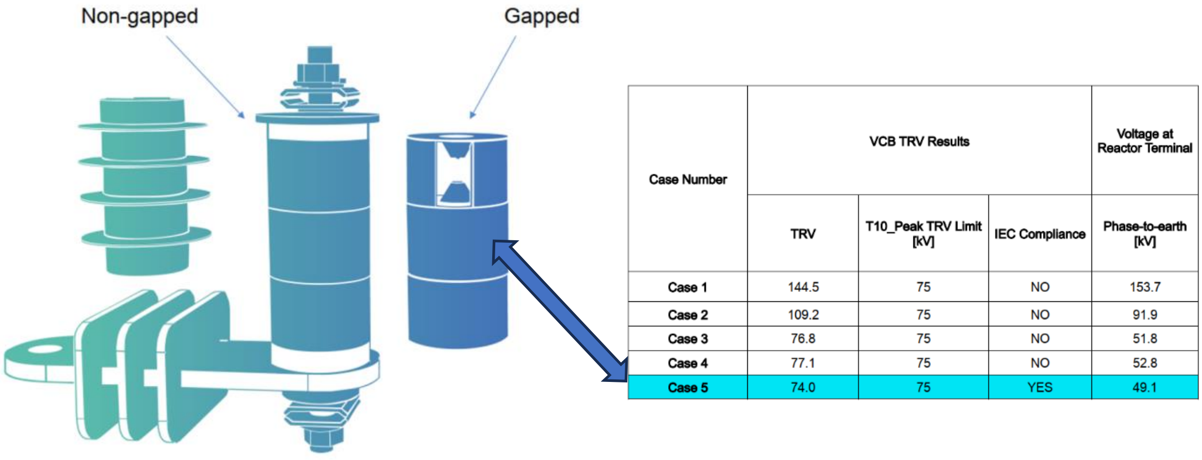
Typically, utilities seeking lower residual voltages opted for the gapped arresters. For applications in delta circuits for instance, the gapped MOV's higher TOV represented a distinct advantage.

The introduction of gapped MOV technology by one manufacturer in the US created significant opposition from other manufacturers, who were concurrently promoting non-gapped MOV technology. Various experts involved in international committees and working groups were highly skeptical of this "gapped” technology. They later conceded that their initial perception—that gapped MOV was an approach to mask inferior blocks—was unfounded. In fact, high-quality MOV blocks were consistently employed in the technology.

A proposed standard, IEC 60099-6, aimed to regulate this emerging gapped MOV arrester technology. The publication of the standard was delayed for years, primarily due to certain experts who exerted considerable efforts to obstruct its release. Currently, both IEC 60099-6 standard accommodates gapped MOV products while IEEE C62.11 accommodate both gapped and non-gapped MOV products.

In the contemporary U.S. market, this type of arrester has gained substantial traction, especially for riser pole applications. Market share estimates suggest that it accounts for approximately 5 to 10% of distribution arrester sales in the United States.

Recent trends indicate a resurgence of interest in gapped arresters within the MV industry. Companies emphasize their enhanced reliability on Distribution System, while others showcase their superior protective performance in Resistor-Capacitor (RC) Snubbers.



Case Number	VCB TRV Results			Voltage at Reactor Terminal
	TRV	T10_Peak TRV Limit [kV]	IEC Compliance	Phase-to-earth [kV]
Case 1	144.5	75	NO	153.7
Case 2	109.2	75	NO	91.9
Case 3	76.8	75	NO	51.8
Case 4	77.1	75	NO	52.8
Case 5	74.0	75	YES	49.1

Figure 1. Source: Optimizing Application of MV Surge Arresters in Resistor-Capacitor (RC) Snubbers – Tim Rastall & Kerim Ozer – INMR Congress Berlin 2022

Adoption of Series-Gap Technologies: EGLA and Gapped MV Types – the fight of series gaps

Looking closely at the history of Line Surge Arresters (LSAs) and the introduction of Externally Gapped Line Arresters (EGLAs), initially developed in Japan, it's intriguing to observe that technology adoption isn't merely a matter of rational assessment of its performance.

EGLAs have been gaining recognition in Japan since the 1980s. By 1988, Japan had nearly 4,500 EGLA units in active service, and it ceased the use of Non-Gapped Line Arresters (NGLAs) due to clear technical advantages. Nevertheless, it took decades for other countries to begin understanding and adopting the technology.

The first IEC standard 60099-8, pertaining to EGLA applications, was only released in 2012. Manufacturer and user experience has long served as a hindrance to effective, widespread adoption. Many manufacturers initially saw no reason to invest, given the uneven market distribution.

Today, EGLAs are dominant in numerous countries and have become the sole authorized technology for protecting overhead lines. Some manufacturers, historically opposed to EGLAs, have even launched their inaugural EGLA portfolios. Others have been compelled to comply with user requirements to meet technical specifications.

Our industry has experienced two major disruptions: the adoption of EGLA (IEC 60099-8) and Gapped MV types (IEC 60099-6). **Both technologies feature series gaps and have faced resistance from the traditionally conservative "Antigap" sector.**

All these developments confirm a universal principle that applies as much to the human sciences as to technology: Any innovation, invention, change, or revolution passes through three stages in collective consciousness—

1. It's ridiculous
2. It's dangerous
3. It's obvious; and eventually, everyone adopts it.

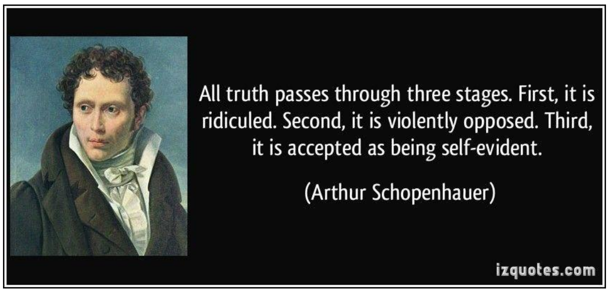


Figure 2. Quote from Schopenhauer – izquotes.com

Industry Challenged and Limitations of Conventional MOSA Technology

Criticism and Limitations of Existing Standards – focus on MV LSA

Within the electricity distribution network, surge arresters play a crucial role, significantly enhancing the system's reliability and operational stability. Medium-Voltage Surge Arresters cover a broad spectrum of applications, and specialized designs are employed to meet specific requirements.

Here is an overview of the various applications for medium-voltage surge arresters:

- Pole-mounted transformers & transition points (riser-pole)
- Line surge arresters (EGLA & NGLA)
- MV transformers
- MV switchgears

- Industrial applications (motors, generators, furnaces, etc.)
- Capacitor banks (high energy)
- Battery storage
- Cable sheaths (SVL)
- Coil & line traps
- Renewable energies (solar, wind turbines)
- Separable arresters (plug-in types)

One critical application involves the use of riser-pole arresters, where overhead distribution lines transition to underground systems. Another significant market segment is the **utilization of distribution-class surge arresters to mitigate lightning-induced outages on medium-voltage lines**, offering both gapped and non-gapped solutions.

These devices are governed by international standards such as IEEE C62.11 and IEC 60099-4. They are designed and tested to withstand the most extreme conditions. However, this article aims to explore some of the limitations encountered when these arresters are deployed outdoors on a large scale and are exposed to extreme weather and atmospheric conditions.

Criticism and Limitations of Existing Standards – focus on MV LSA

Metal Oxide Surge Arresters (MOSAs) have been employed in the electricity supply industry for over 40 years. State-of-the-art designs and applications offer higher reliability when designed, manufactured, and tested in accordance with international standards. This text is not intended as a critique of the technology; rather, it aims to highlight specific areas for improvement that could enhance reliability in particular applications and voltage ranges. Globally, there are numerous instances of MOSAs that have operated reliably for more than four decades.

This discussion will not delve into criticisms of manufacturers who do not comply with international standards or address the issue of subpar equipment that is, unfortunately, frequently installed in electrical grids, often due to budgetary constraints and short-term planning.

Reports of Surge Arrester failures are uncommon. The CIGRE Working Group A3.39 [1] faces challenges in locating users willing to share information on this topic. As a result, we must rely on failure statistics from independent testing laboratories, which have been providing insightful findings.

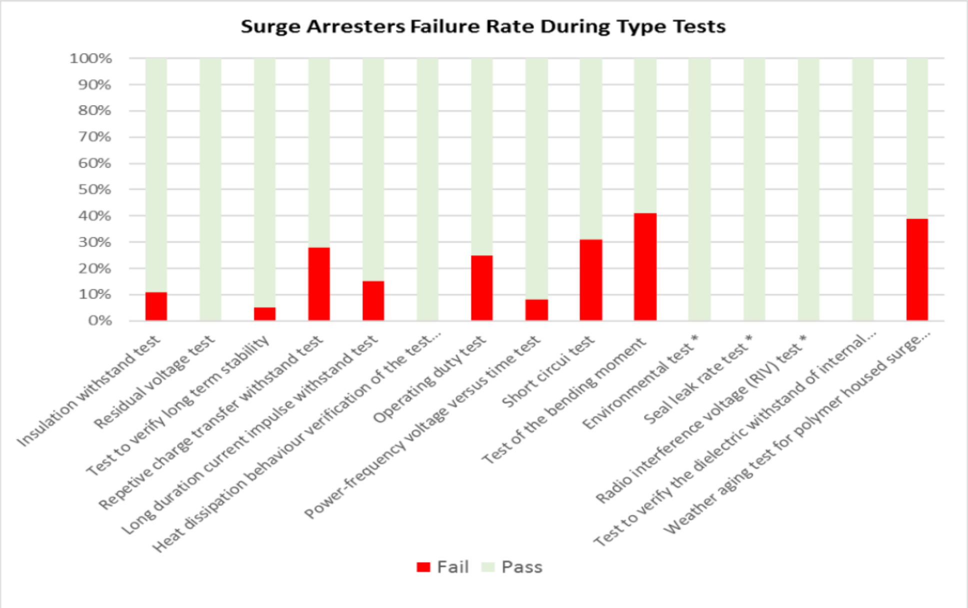


Figure 3. Surge Arresters Failure Rate during Type Tests – Statistics CESI test lab [1]

From these results of Figure 3, we can extrapolate specific insights. The analysis presented here is theoretical and establishes a correlation between the most common types of distribution arrester failures and their prevalent causes, as indicated by the aforementioned results. It is important to note that this analysis is subject to criticism, given that the statistics do not differentiate between Medium Voltage (MV) and High Voltage (HV) applications.

- The primary cause of failure across all types of surge arresters is **moisture ingress**, which ranks as the foremost cause. This is predominantly verified through **bending moment** tests that include thermal conditioning and water immersion.
- Distribution Class Arresters are particularly vulnerable due to the use of less expensive polymer materials, a compromise to remain competitive in a highly aggressive market. When subjected to constant electrical stress, these low-cost polymers often fail to pass the **Weather Aging Test**, making this the second leading cause of failure.
- A variety of designs for Distribution Arresters are available in the market, each with its own set of challenges regarding short-circuit performance. Whether it is cage design, wrap design, cast resin, or winding filament, manufacturers face the complex task of balancing lightness with robustness.

The two other recurring causes of failure are charge transfer (Qrs) and thermal charge (Qth). These issues are predominantly associated with MOV block manufacturers. As is the case with surge arresters, various quality levels of MOV blocks are available on the market.

Nevertheless, it is possible to access randomly reports and statistics from the field through publications papers and single sources as shows in the Figure 4 [2].

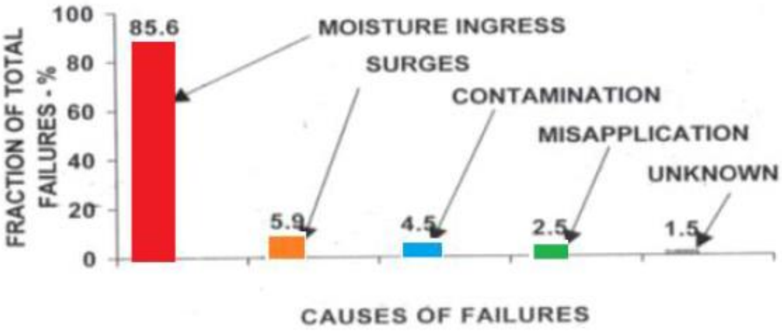


Figure 4. Statistics of Failures in South Africa on Distribution Class Arresters [2]

Most surge arresters that adhere to industry standards and incorporate the latest methods and technologies typically deliver excellent performance. However, it is evident from these reports and feedback from practical experience that a recurrent issue exists with distribution surge arresters. What's more, every professional in this industry is confronted with feedback that leaves much to be desired. In many cases, the information provided remains confidential and is not intended for the general public.

The IEEE Guide (Std 1410-2010) for Improving the Lightning Performance of Electric Power Overhead Distribution Lines provides average failure rate data for Heavy Duty Arresters (Standard Distribution Class DH as per IEC) with a 40mm MOV diameter. According to this guide, the failure rate per Direct Stroke on an unshielded line ranges from 12% to 33%. While these figures are open to interpretation and further verification, it is clear that conventional distribution surge arresters (either HD or DH) are susceptible to lightning strikes on unshielded lines. This statistic represents a universal truth connected to lightning exposure and does not account for failures related to design or manufacturing processes.

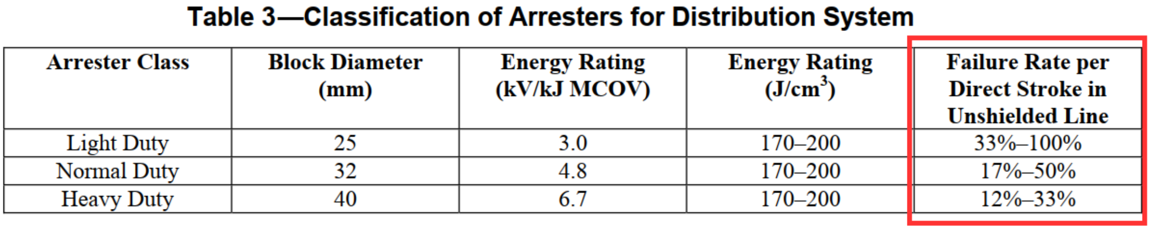


Table 3—Classification of Arresters for Distribution System

Arrester Class	Block Diameter (mm)	Energy Rating (kV/kJ MCOV)	Energy Rating (J/cm^3)	Failure Rate per Direct Stroke in Unshielded Line
Light Duty	25	3.0	170–200	33%–100%
Normal Duty	32	4.8	170–200	17%–50%
Heavy Duty	40	6.7	170–200	12%–33%

Figure 5 IEEE 1410 Guide . 7.3.2 Arrester energy absorption capability

As per the IEEE guide, the failure rate estimates presented in Table 3 apply to three-phase plus neutral lines without overhead ground wires, and assume that arresters are installed on all poles and for each phase.

Identified Weakness of MO LSAs on MV lines

MO LSAs have been reliably used on transmission lines for years, yet their deployment on distribution lines has been less frequent. The reasons for this limited uptake are multi-fold:

Cost Implications: Distribution line outages usually have less financial impact than those on transmission lines, thus reducing the urgency to adopt MO LSAs in such settings.

Initial Investment: The high costs associated with MO LSAs often make them less appealing, especially when manufacturers fail to provide compelling reasons for the investment.

Lightning Charge Transfer: Distribution lines are often not shielded, resulting in a higher anticipated transfer of lightning charge, exceeding the standard Qrs ratings of MO LSAs.

Temporary Overvoltage Stress: In certain systems, high levels of temporary overvoltage (TOV) can occur, surpassing the voltage thresholds that MO LSAs can handle.

Reliability Concerns: Failures related to sealing issues such as moisture infiltration have been reported in MO LSAs, posing questions about their long-term reliability.

Given these limitations, SAS or CLGs have emerged as a compelling alternative technology, offering solutions where MO LSAs may fall short.

Working Principles of Surge Arc Suppressors (SAS)

Overview of SAS Technology

Both SAS and Metal Oxide Line Surge Arresters (MO LSAs) are designed to mitigate the impact of lightning on electrical power systems. Typically, they are positioned alongside the insulation of overhead towers. Despite serving a similar purpose, important distinctions exist between these two technologies that can influence decision-making.

Although not universally recognized, SAS devices, also known as Current Limiting Gaps (CLGs), are often employed to mitigate lightning-induced interruptions in distribution networks [8]. It's noteworthy that the Japanese electrical infrastructure incorporates SAS technology even in transmission lines up to a 154kV system. Formally outlined in the CIGRE Technical Brochure 855 released in 2021, SAS devices are categorized as a subtype of Line Surge Arresters. However, their technological framework diverges significantly from the conventional Metal-Oxide Line Surge Arresters (MO LSA) predominantly deployed in transmission systems. Unlike resistor valve types of arresters composed of Silicon Carbide elements and series gaps, SAS are not intended to safeguard high-value equipment within substations, such as power transformers. Instead, they employ an avant-garde design incorporating one or more arc quenching chambers, providing follow current quenching capabilities. This feature has been rigorously assessed and corroborated, much like Externally Gapped Line Arresters (EGLA). Originating in the 1990s, SAS have progressively garnered global recognition, largely attributable to their favorable lifecycle expenditures and resilience against high charge transfer ratings in unshielded overhead lines. Presently, SAS have ascended as a compelling alternative for distribution grids globally, presenting an efficacious strategy for diminishing lightning-associated disruptions on medium and high-voltage lines."

To grasp how SAS function, we should explore their key features. Central to the SAS is what's called an arc quenching chamber. This chamber helps to put out the electrical arc formed between two contact points. It allows the electric current to move through it, reducing the arc's energy until it goes out. Unlike components in circuit breakers that actively work to stop the arc using materials like SF6 gas or vacuum, these chambers passively put out arcs through their design.

SAS devices come in different forms, including:

Multi-Chamber Models: These kinds split the electrical arc into smaller parts, eventually putting them out.
Single-Chamber Models: In this design, the chamber uses two holes to direct the arc onto specific points on an insulator, where it is then extinguished.

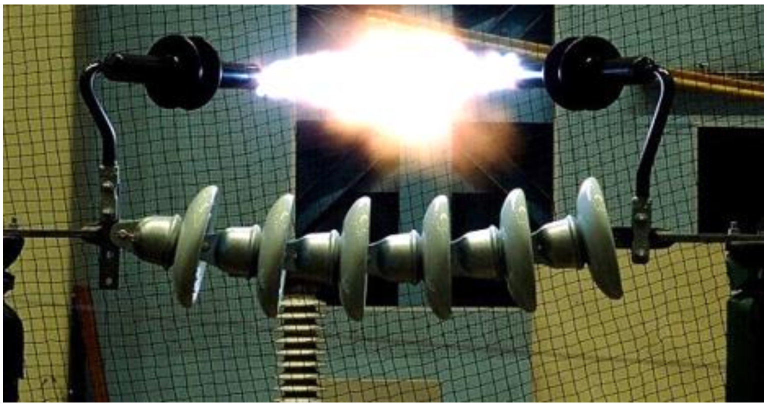


Figure 6. Single-Chamber Model (2 bodies)
Source: CRIEPI Report Japan [3]

Figure 7. Multi-Chamber Model
Source: Sreamer Electric AG [5]

Technical limitations

SAS devices are effective at preventing power failures caused by lightning. However, it's vital to understand their limits, especially concerning fault currents. We need to look carefully at system settings before using SAS on any line.

All SAS devices are tested to interrupt the follow currents within a very short time (less than half a cycle), avoiding the need for circuit breaker operations and further outages due to lightning. Typically, they can handle currents up to 10 kA depending on the design. But they also have limitations in how many operations they can handle and how much follow current they can interrupt. Therefore, SAS devices are most useful where expected fault currents are within these limits.

The highest possible fault current is affected by how close the SAS device is to a power transformer. The nearer it is, the stronger the current will be. So, it's important to keep a minimum distance between the SAS and the transformer to make sure the device works within its limits.

Advantages of SAS Over MO LSA

SAS offers several advantages over MO LSA:

- **Attractive Life-Cycle Costs:** Compared to DH Class surge arresters, SAS presents more favorable life-cycle costs. It should be noted that costs are a complex subject, subject to fluctuations due to market and economic conditions.

- **Exceptional Charge Transfer Capability:** SAS boasts a charge transfer capability significantly above all other surge arrester classes. This gives SAS a distinct advantage in applications that are unshielded or have challenging grounding conditions and high soil resistivity.

Disadvantages of SAS Over MO LSA

However, like any technology in the industry, SAS has its disadvantages when compared to MO LSA:

- **Non-Linear Voltage-Current Characteristics:** SAS lacks the non-linear Voltage-Current characteristics provided by MO resistors. This results in an unstable residual voltage and high follow currents in the kA range.

- **Limited Lifetime:** The lifespan of SAS is determined by the number of operations. The performance of follow current interruption degrades due to the cumulative effect of the current density of each operation.

A Life-Cycle Costs Approach Featuring Failure Rate Analysis

MO LSA manufacturers often criticize SAS for diverging from established technology and for perceived unreliability. To counter this criticism, we propose conducting an analysis based on tangible data related to lightning stroke distribution. This analysis uses simulation software (Sigma SLP) to compare the Failure Rate of MO LSA and SAS, considering factors such as charge transfer stress from lightning strokes and frequency of sparkover occurrences for SAS. Although comments and suggestions are provided at the end, failures resulting from design issues, manufacturing flaws, or quality topics are not considered in this analysis due to the limited information available.

Failure rate for MO LSA

The concept of "Failure Rate" for MO LSA arises from Reliability Studies. These studies involve statistical analyses of failures, taking into account a specific model used for Lightning Performance. Factors such as stroke distribution and Ground Flash Density significantly influence the results. From a system perspective, noteworthy differences exist between shielded and unshielded lines. To define the failure rate, we establish a correlation between the tested MOV "Qrs Repetitive Charge Transfer Ratings" (200µs) and the EGLA Statistical Lightning Charge Transfers computed by SIGMA SLP. It is assumed that any charge in coulombs exceeding the nominal Qrs rating of the MO LSA will result in a failure. IEC test protocols already include safety factors, and the impact of operations below the nominal Qrs on the life expectancy of MO LSA has not been extensively studied.

Failure rate for SAS

The concept of "Failure Rate" for SAS differs from that for MO LSA. High amplitude lightning strokes cannot damage SAS. However, exceeding a certain number of operations can result in failure.

System Parameters and Assumptions for the Case Study

- 100km 36kV unshielded distribution, single-circuit line
- Pole footing resistance is 20 Ohms, and soil resistivity is 800 Ohms per meter (average value)
- Devices (SAS or MO LSA) are installed on every pole and every phase, involving 1,714 units over the 100km line
- EGLAs are used to achieve equivalent behavior in spark-over operation (not 100% accurate but more realistic than using NGLAs)
- The SVU of the EGLA is a Distribution Class surge arrester (DH/HD) with a Qrs repetitive charge transfer of 0.4 Coulombs (200µs duration) – equivalent ~36mm MOV blocks
- The Qrs test already includes a safety margin (10%); therefore, the analysis considers any computed charge exceeding 0.4C as an EGLA failure
- In favor of MO LSA, a relatively mild stroke distribution (5 years of LLS data from the Southwest of Turkey) is considered, in contrast to conservative CIGRE models, which would involve a higher concentration of high-amplitude lightning strokes
- A Ground Flash Density (GFD) of 4 flashes/100km/year is considered
- Simulation is performed using Sigma SLP software
- Computed charges in Sigma SLP are considered with a 200µs duration
- SAS devices cannot fail due to excessive charge transfer value; nevertheless, for the analysis, they are considered as failure-free up to 5 operations
- A period of 35 years is studied, computing 1,000 samples and resulting in a relatively realistic timeframe for the life expectancy of such electrical devices
- In favor of MO LSA, a constant rate of 5 SAS failures per year was considered. This represents potential follow currents exceeding the maximum interruption current capability of SAS devices, as well as a non-homogeneous distribution of lightning strokes along the line (75% only).
- A deeper study could analyze the evolution of failure rates beyond 35 years for SAS devices

Note: SIGMA SLP is an object-oriented software package designed for the computation of transmission and distribution line lightning performance. In short, it calculates the number of outages to expect based on configurable system parameters and lightning activities.

Results of the case study

all operation	241	145	343	303	186	472	334	195	549	339	202	541	301	185	452	243	141	337
above 0.4C	30	13	19	48	29	43	44	23	35	52	25	44	56	28	44	32	12	26
	Tower 2			Tower 3			Tower 4			Tower 5			Tower 6			Tower 7		
samples sorted by max. charge	T 2-A 1	T 2-A 2	T 2-A 3	T 3-A 1	T 3-A 2	T 3-A 3	T 4-A 1	T 4-A 2	T 4-A 3	T 5-A 1	T 5-A 2	T 5-A 3	T 6-A 1	T 6-A 2	T 6-A 3	T 7-A 1	T 7-A 2	T 7-A 3
1	2.47	2.11	2.39	2.32	1.90	2.23	1.34	1.26	1.46	2.20	1.95	2.14	2.90	2.54	2.79	1.46	1.30	1.47
2	1.70	1.36	1.63	2.04	1.90	2.06	1.14	0.92	1.34	1.99	1.83	1.98	1.83	1.73	1.73	0.92	0.84	1.07
3	1.31	0.82	0.89	1.60	1.54	1.62	1.03	0.89	0.99	1.45	1.30	1.37	1.72	1.62	1.70	0.70	0.67	0.97
4	1.12	0.74	0.88	1.38	1.30	1.37	1.00	0.88	0.99	1.17	1.01	1.34	1.63	1.46	1.65	0.68	0.67	0.90
5	0.89	0.70	0.81	1.33	1.25	1.32	0.99	0.77	0.95	1.13	0.99	1.10	1.63	1.45	1.54	0.58	0.54	0.86
6	0.79	0.69	0.76	1.21	0.97	1.16	0.93	0.76	0.94	0.89	0.71	1.08	1.56	1.40	1.46	0.58	0.54	0.80
7	0.78	0.65	0.75	1.13	0.94	1.09	0.93	0.73	0.80	0.83	0.60	1.07	1.28	1.21	1.22	0.56	0.52	0.79
8	0.76	0.57	0.70	1.09	0.94	0.91	0.90	0.72	0.78	0.78	0.60	0.77	1.18	1.00	1.10	0.56	0.49	0.75
9	0.72	0.55	0.69	1.03	0.86	0.90	0.84	0.67	0.73	0.74	0.59	0.67	1.04	0.84	0.99	0.55	0.49	0.62
10	0.70	0.54	0.63	1.02	0.83	0.89	0.84	0.66	0.72	0.68	0.57	0.65	1.03	0.81	0.97	0.53	0.49	0.59
11	0.70	0.50	0.61	0.98	0.83	0.88	0.80	0.66	0.69	0.65	0.56	0.62	1.00	0.81	0.96	0.53	0.48	0.58
12	0.68	0.48	0.55	0.95	0.78	0.88	0.80	0.62	0.68	0.62	0.52	0.61	0.94	0.80	0.95	0.52	0.47	0.56
13	0.65	0.45	0.54	0.94	0.78	0.79	0.79	0.62	0.67	0.59	0.50	0.59	0.85	0.78	0.88	0.52	0.40	0.56
14	0.65	0.40	0.50	0.92	0.70	0.79	0.78	0.56	0.65	0.59	0.48	0.54	0.81	0.71	0.88	0.52	0.37	0.56
15	0.64	0.39	0.49	0.89	0.66	0.75	0.76	0.49	0.62	0.59	0.48	0.54	0.77	0.69	0.87	0.51	0.34	0.55
16	0.62	0.39	0.49	0.87	0.66	0.74	0.76	0.48	0.60	0.59	0.48	0.53	0.75	0.65	0.85	0.51	0.31	0.53
17	0.59	0.37	0.47	0.86	0.65	0.71	0.75	0.48	0.57	0.58	0.48	0.52	0.75	0.61	0.82	0.51	0.30	0.50
18	0.55	0.37	0.42	0.80	0.56	0.68	0.74	0.47	0.56	0.58	0.47	0.52	0.73	0.57	0.81	0.50	0.30	0.50
19	0.53	0.35	0.41	0.80	0.55	0.66	0.73	0.46	0.55	0.56	0.46	0.52	0.72	0.57	0.80	0.50	0.30	0.50
20	0.53	0.35	0.40	0.78	0.54	0.61	0.71	0.42	0.55	0.56	0.44	0.51	0.65	0.55	0.78	0.49	0.29	0.46
21	0.51	0.34	0.38	0.78	0.52	0.60	0.71	0.42	0.54	0.56	0.43	0.49	0.64	0.55	0.78	0.47	0.29	0.46
22	0.51	0.33	0.38	0.73	0.51	0.59	0.63	0.41	0.52	0.55	0.43	0.48	0.61	0.50	0.74	0.47	0.29	0.44
23	0.51	0.31	0.38	0.71	0.49	0.59	0.61	0.40	0.52	0.55	0.43	0.48	0.59	0.47	0.70	0.46	0.27	0.43
24	0.50	0.29	0.38	0.70	0.47	0.58	0.56	0.38	0.48	0.55	0.42	0.48	0.57	0.47	0.65	0.45	0.26	0.43
25	0.48	0.28	0.37	0.68	0.44	0.58	0.56	0.33	0.46	0.54	0.41	0.47	0.57	0.44	0.61	0.45	0.26	0.42
26	0.48	0.27	0.36	0.67	0.44	0.56	0.55	0.33	0.45	0.53	0.38	0.47	0.57	0.43	0.60	0.44	0.26	0.40
27	0.46	0.26	0.36	0.65	0.43	0.53	0.54	0.31	0.45	0.52	0.37	0.46	0.56	0.42	0.57	0.43	0.24	0.39
28	0.44	0.26	0.35	0.62	0.43	0.51	0.54	0.31	0.44	0.52	0.35	0.46	0.55	0.41	0.55	0.43	0.24	0.38
29	0.41	0.24	0.35	0.60	0.41	0.49	0.52	0.30	0.42	0.52	0.35	0.46	0.55	0.40	0.52	0.43	0.24	0.36
30	0.40	0.23	0.35	0.59	0.40	0.48	0.49	0.29	0.42	0.50	0.34	0.45	0.55	0.38	0.51	0.42	0.24	0.36
31	0.39	0.22	0.35	0.58	0.39	0.48	0.48	0.28	0.41	0.50	0.32	0.45	0.52	0.35	0.50	0.41	0.23	0.35
32	0.39	0.21	0.35	0.57	0.38	0.47	0.46	0.28	0.41	0.50	0.30	0.45	0.52	0.34	0.49	0.40	0.23	0.35
33	0.38	0.21	0.35	0.57	0.36	0.47	0.46	0.26	0.40	0.50	0.29	0.45	0.51	0.34	0.48	0.38	0.23	0.35
34	0.38	0.20	0.34	0.56	0.36	0.46	0.45	0.26	0.40	0.49	0.28	0.44	0.51	0.33	0.48	0.38	0.22	0.35
35	0.38	0.20	0.34	0.55	0.35	0.46	0.44	0.25	0.40	0.47	0.28	0.44	0.51	0.33	0.47	0.38	0.22	0.34
36	0.38	0.20	0.34	0.53	0.34	0.45	0.43	0.25	0.39	0.47	0.27	0.44	0.50	0.32	0.47	0.37	0.22	0.34
37	0.38	0.20	0.34	0.47	0.34	0.45	0.43	0.24	0.39	0.47	0.27	0.43	0.49	0.32	0.47	0.36	0.21	0.34
38	0.38	0.20	0.33	0.47	0.33	0.44	0.43	0.24	0.39	0.46	0.25	0.43	0.48	0.32	0.45	0.36	0.21	0.33
39	0.37	0.19	0.33	0.47	0.32	0.44	0.42	0.23	0.39	0.46	0.25	0.42	0.47	0.31	0.44	0.36	0.21	0.33
40	0.37	0.19	0.32	0.47	0.32	0.43	0.42	0.23	0.38	0.45	0.25	0.42	0.47	0.31	0.44	0.35	0.21	0.33
41	0.37	0.18	0.32	0.46	0.30	0.42	0.42	0.23	0.38	0.45	0.25	0.41	0.47	0.30	0.42	0.35	0.21	0.33
42	0.36	0.18	0.32	0.45	0.29	0.41	0.41	0.23	0.38	0.45	0.24	0.41	0.47	0.28	0.42	0.35	0.21	0.33
43	0.36	0.18	0.32	0.44	0.29	0.40	0.41	0.23	0.37	0.45	0.24	0.41	0.47	0.25	0.41	0.34	0.21	0.33
44	0.36	0.18	0.32	0.44	0.27	0.38	0.40	0.23	0.37	0.44	0.24	0.40	0.46	0.25	0.40	0.34	0.21	0.33
45	0.36	0.17	0.32	0.44	0.27	0.37	0.40	0.22	0.36	0.44	0.23	0.39	0.46	0.25	0.40	0.34	0.20	0.32
46	0.35	0.16	0.31	0.42	0.26	0.37	0.39	0.22	0.36	0.44	0.22	0.37	0.46	0.24	0.39	0.34	0.20	0.32
47	0.35	0.16	0.31	0.41	0.26	0.36	0.38	0.22	0.36	0.43	0.22	0.36	0.45	0.24	0.39	0.34	0.20	0.32
48	0.35	0.16	0.30	0.41	0.25	0.36	0.38	0.21	0.35	0.43	0.21	0.36	0.45	0.23	0.37	0.34	0.20	0.32
49	0.35	0.16	0.29	0.40	0.25	0.35	0.38	0.21	0.35	0.43	0.21	0.35	0.45	0.23	0.37	0.34	0.19	0.31
50	0.35	0.15	0.29	0.39	0.24	0.35	0.37	0.21	0.35	0.43	0.21	0.35	0.45	0.22	0.36	0.33	0.19	0.31
51	0.34	0.15	0.28	0.38	0.23	0.35	0.37	0.20	0.35	0.41	0.20	0.35	0.44	0.22	0.36	0.33	0.18	0.30
52	0.34	0.15	0.28	0.38	0.22	0.35	0.37	0.20	0.35	0.41	0.20	0.35	0.43	0.22	0.36	0.32	0.18	0.30
53	0.34	0.15	0.28	0.38	0.21	0.34	0.36	0.20	0.34	0.39	0.20	0.34	0.43	0.22	0.35	0.32	0.18	0.30
54	0.34	0.15	0.28	0.38	0.21	0.34	0.36	0.20	0.34	0.39	0.20	0.34	0.42	0.22	0.35	0.31	0.18	0.30
55	0.34	0.15	0.27	0.38	0.20	0.34	0.36	0.20	0.33	0.39	0.20	0.33	0.41	0.21	0.35	0.31	0.17	0.30
56	0.33	0.15	0.27	0.38	0.20	0.34	0.35	0.19	0.33	0.39	0.19	0.33	0.40	0.21	0.35	0.31	0.16	0.30

Figure 8. Charge transfer through MO LSA resulting from 1000 lightning strokes samples following a tailored stroke distribution

Total Samples	**1000**	
Total Operations	**5509**	gap sparkover
Numbers of failures if >0.4C	**603**	

GFD(str/km2/y)	**4**	Ground Flash Density
WE(m)	**72.97**	Line Shadow Width
NL(Expected strokes on line)	**29.1**	per year (based on Line Shadow Width)
1000 samples represent	**34.36**	years
Line parameters		
Line	**100**	km
Average span	**0.175**	km
Number of Poles	**571**	
EGLA (MO LSA)		
damageable by lightning when charge exceeds 0.4C		
one EGLA failure every	**0.0570**	years
	20.80	days
in	**34.36**	years , **603** failures are expected
SAS		
cannot be damaged by lightning, but can be damaged by exceeding a certain number of operations		
Number of SAS on the line	**1714**	assuming installation on every pole and every phase
Guranteed numbers of operations	**5**	(safety factor since test reports show higher numbers)
Expected operations per SAS after 34.36 years	**3.21**	considering homogeneous dsitribution along the line
Aggravating factors (worst case)	**4.28**	not homogeneous, only 75%

Table 1. Detailed results of the lightning simulations

Preliminary Conclusion

- Over a span of approximately 35 years, around **600 MO LSA units** would fail due to excessive charge transfer from high-amplitude lightning strokes. This constitutes 35% of the total installed units.

- In contrast, SAS would theoretically experience zero failures attributable to lightning. However, an estimated **175 SAS failures** could occur, assuming a constant failure rate of 5 failures per year. This worst-case scenario represents potential follow currents exceeding the maximum interruption current capability when SAS units are installed near transformers or due to other unforeseen factors.

- Interestingly, it is not solely the lightning statistics that should be scrutinized when comparing the lifetime performance of MO LSA and SAS integrations. The topic is more complex.

- While MO LSA failures can be significantly reduced using larger MOV blocks (SL type, approximately 48mm or more), this approach entails a higher capital investment compared to distribution class units. It is worth noting that MO LSA manufacturers have not optimized their portfolio for applications requiring high charge transfer ratings.

- Given that no current data provides a comprehensive performance overview over a 35-year period—especially for the MO LSA or SAS designs used today in distribution networks—additional considerations are crucial:

    - **Gapped vs. Non-Gapped:** This remains a pressing issue that continues to stir debate within the industry. The continuous voltage on NGLA impacts life expectancy, a factor not adequately addressed by international standards for large-scale, mass-produced projects.
    - **Comprehensive Studies: These** are essential to align Qrs charge transfer ratings with lightning parameters, particularly when used on unshielded lines.
    - **Future Standards for SAS:** Manufacturers must reliably guarantee a minimum number of operations to ascertain effective life-cycle costs.

Global Market Overview

Current Market Landscape

As a specialized application for distribution overhead lines and higher voltages, the market for SAS technology is discrete but relatively well-established. Globally, the number of SAS units is estimated to be around 3 million, primarily deployed on networks with voltages up to 77kV, although some applications do extend beyond this range. The utilization of SAS devices has gained increasing significance in distribution networks, especially as MO LSA manufacturers have been unable to fully satisfy all market demands.

For over 25 years, SAS technology has been globally deployed to improve lightning performance on overloaded lines:

- In Japan, more than 120,000 units have been installed on networks up to 77kV since 1994. It is noteworthy that Japan also employs this technology on its 154kV networks.

- In the CIS countries, including Russia and Kazakhstan, approximately 2.5 million units have been in operation on networks up to 35kV since 1999. Additionally, some pilot projects have been conducted on high-voltage networks.

- The technology is gaining traction in China, with over 200,000 units installed to date on networks up to 35kV. The first installations in China date back to 2012.

- In other parts of the world, such as Vietnam and Indonesia, it is estimated that around 100,000 SAS units have been installed since 2012.

In summary, a rough estimation would indicate that nearly 3 million SAS units are currently in operation worldwide.

National Standard and Existing Specifications

SAS technology has, until now, remained relatively isolated on a geographical basis but is gradually gaining momentum. One key challenge impeding its international adoption is the absence of standardization according to IEC or IEEE international standards.

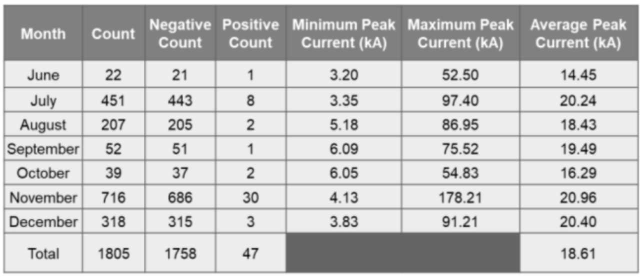
In China, standardization initiatives have been undertaken, most notably with the creation of the Chinese Society for Electrical Engineering (CSEE) standard T/CSEE 0082-2018. This standard delineates the general technical requirements for multi-chamber gap (MCG) lightning protection devices used in medium-voltage distribution lines. The implementation of this standard signifies China's commitment to ensuring the quality and safety of SAS technology, while also advocating for its extensive adoption across the nation's power distribution infrastructure.

In both Russia and Japan, SAS technology predominantly adheres to national specifications. As will be elaborated in the conclusion of this document, concerted efforts towards standardization are imperative for establishing an international standard that engages all stakeholders in the field.

Case Studies in Malaysia

Malaysia offers an insightful case study for the integration of SAS technology into power distribution networks [6]. Initially, MO LSAs were deployed on distribution lines in accordance with the IEEE 1410 Guide. However, multiple failures were reported, attributed to various factors such as grounding conditions, soil resistivity, and specific surge arrester requirements. These challenges prompted the Malaysian Distribution System Operator to explore alternative options, leading to the adoption of SASs as a more viable solution. Utilizing SAS technology has proven to be both reliable and effective, successfully addressing the unique difficulties inherent in Malaysia's power distribution infrastructure. This experience underscores the versatility and value of SASs, emphasizing their capability to satisfy diverse market needs and enhance the resilience of power distribution systems.

Malaysia's journey serves as a crucial case study for other nations contemplating the inclusion of SASs in their power distribution strategies. The experience warrants considerable attention from MO LSA manufacturers. It should be highlighted that there exists a legitimate need to assess certain technical characteristics of MO LSAs used in the network, including but not limited to technical specifications, design, and product quality (root cause analysis).



Month	Count	Negative Count	Positive Count	Minimum Peak Current (kA)	Maximum Peak Current (kA)	Average Peak Current (kA)
June	22	21	1	3.20	52.50	14.45
July	451	443	8	3.35	97.40	20.24
August	207	205	2	5.18	86.95	18.43
September	52	51	1	6.09	75.52	19.49
October	39	37	2	6.05	54.83	16.29
November	716	686	30	4.13	178.21	20.96
December	318	315	3	3.83	91.21	20.40
Total	1805	1758	47			18.61

Figure 9. Report Lightning near line of interest for case study in Malaysia

Figure 10. Installation of SAS by Malaysian DSO

Conclusions

In the realm of lightning performance on power systems, both MO LSA and SAS technologies offer distinct advantages and challenges over a projected lifespan of approximately 35 years covered in this paper. An extensive and thorough studies including other ageing factors and system constraints will be valuable but difficult with the available resources. MO LSAs are susceptible to failures due to high-amplitude lightning strokes, accounting for around 35% of total installed units with favorable conditions. In contrast, SAS technology demonstrates near-zero failures attributed to excessive charge transfer from lightning. It should be added that a CRIEPI report from 2009 reported 9 failures in Japan over a period of ~20 years for a total 115,900 SAS units.

The treatment given to SAS is not fair, and it is appropriate to approach the subject in a scientific and methodical manner. Despite their differing performance metrics, it's crucial to recognize that the issue is more nuanced than merely scrutinizing lightning statistics. MO LSA failures can be mitigated using larger MOV blocks, but this involves higher capital investment. On the other hand, SAS units offer high charge transfer ratings and an ergonomic design, facilitating integration and potentially promising lifecycle cost advantages. However, both technologies are subject to various complexities that are not yet fully described in this paper.

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