

Strategic Decision Support for Asset Management: Advancing Surge Arrester Diagnostics with Leakage Current and Infrared Methods

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Introduction: Status Quo Today

Surge arresters are crucial in safeguarding power systems, protecting electrical equipment against transient overvoltages by diverting excessive voltage to the ground. This prevents the voltage from traveling through the power system, where it could damage transformers, insulators, and other critical components. Despite their robust design, surge arresters can fail for various reasons, leading to serious implications for the reliability

and safety of power networks. Station Class Surge Arresters, especially those in generation power plants and sensitive substations, necessitate a heightened level of reliability to ensure the operation of these vital centers of electrical infrastructure.

One common failure mode is internal short-circuiting caused by internal degradation, wherein the surge arrester can no longer withstand the applied voltage. This deterioration may result from several factors such as moisture ingress, aging of Metal-Oxide Varistor (MOV), thermal



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Florent Giraudet is a renowned expert in surge arrester technology and lightning performance on power systems with over a decade of experience in the surge arrester industry, primarily with Siemens Germany. Specializing in the engineering and implementation of Line Surge Arresters and overhead lines applications, Florent has played a pivotal role in numerous large-scale projects, driving innovations in the protection of overhead lines from lightning-induced disturbances. Today, as an independent consultant, Florent leverages a comprehensive approach that spans the analysis of lightning data, through the strategic implementation of LSA solutions, to their ongoing monitoring, ensuring enhanced reliability and performance of power systems for clients worldwide. With an engineering degree in electrical engineering, Florent's technical expertise is matched by a deep commitment to advancing the field through knowledge-sharing and strategic guidance.

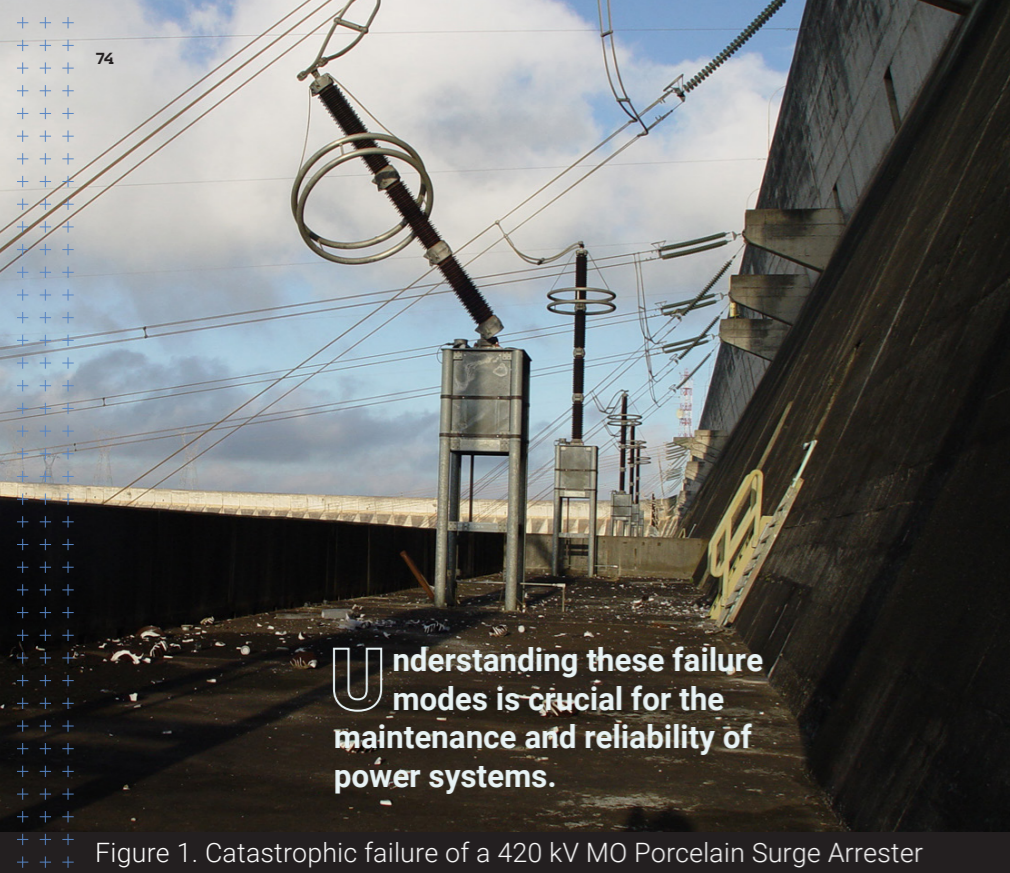


Figure 1. Catastrophic failure of a 420 kV MO Porcelain Surge Arrester

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

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 moisture ingress, MOV degradation, or other issues. To address these vulnerabilities, the power industry has developed dedicated monitoring solutions to assess the condition of the arrester's core: the MOV. Among available solutions and technologies on the market, two fundamental methods stand out: the

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

Caution is advised in this area, as individual solutions may have limitations, making it challenging for users to interpret the data accurately. Although the method of extracting resistive current based on the third-order harmonic is described in the IEC standard, the monitoring

of the third harmonic component of the leakage current to extract the resistive part (using an instrument based on the B2 method according to the IEC 60099-5 standard) and the thermography inspection (only for outdoor surge arresters). Both techniques are performed

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devices themselves are not subject to strict testing and constraints by standardization groups.

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

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semiannually and aim to cover the most common failure modes.

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

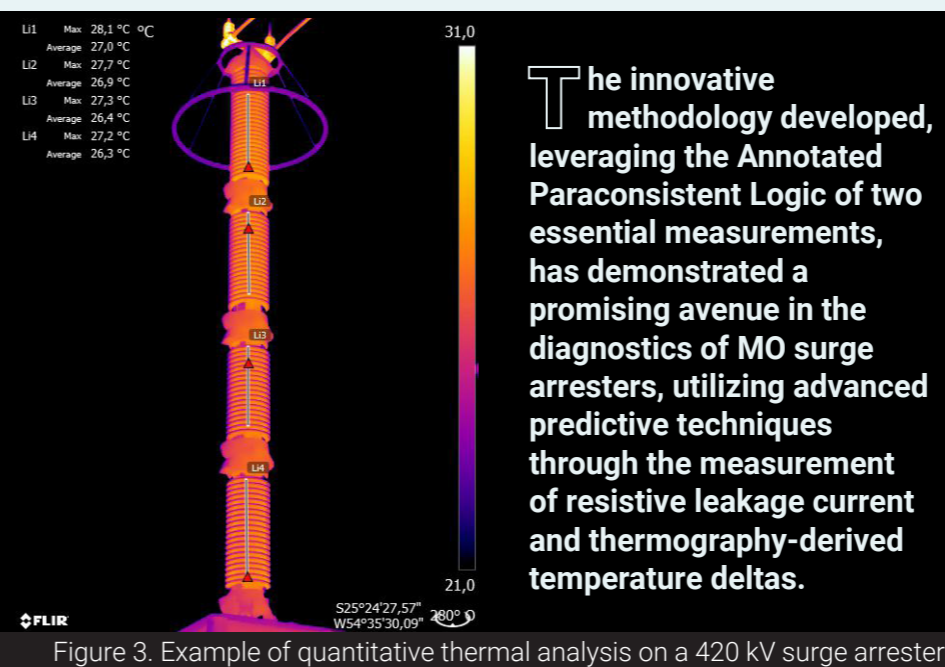


Figure 3. Example of quantitative thermal analysis on a 420 kV surge arrester

cameras to capture and analyze the thermal profile of an object. The quantitative approach includes measuring, for instance, the temperature difference (delta) across the body of the surge arrester. Figure 3 illustrates the thermal image of a 420 kV MO surge arrester, with



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.

radiation interference. Subsequently, these images are analyzed, and the temperature delta is determined by calculating the difference between the highest maximum temperature and the average of the average temperatures across the sections of the 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.

In summary, paraconsistent logic diverges from classical logic by accommodating contradictions and incomplete evidence. This flexibility makes it an invaluable framework for evaluating complex situations, such as surge arrester assessments.

The values of resistive current and temperature delta act as logical annotations. Based on these values, we can determine the degrees of belief (μ) and disbelief (λ) related to the proposition: 'The surge arrester is degraded.' The degree of belief quantifies the confidence in the surge arrester's degradation. Conversely, the degree of disbelief measures the level of skepticism regarding this assertion. Both degrees span from 0 to 1, within the realm of real numbers.

Utilizing the degrees of belief and disbelief, one can ascertain the degrees of certainty (G_c) and uncertainty (G_i), as delineated by equations (1) and (2), respectively.

$$G_i = \mu + \lambda - 1 \quad (1)$$

$$G_c = \mu - \lambda \quad (2)$$

A diagnostic method for surge arresters utilizing APL2v was developed and implemented computationally through a collaborative research and development (R&D) project between Itaipu Binacional and the Itaipu Technological Park Foundation (FPTI, from its Portuguese acronym). This collaboration resulted in the creation of a web application named Surge Arrester Diagnostic System (SDPR, from its Portuguese acronym).

The operational workflow of the tool, from the input of measurement data

to the final diagnosis, is depicted in a flowchart presented in Figure 4.

As illustrated in Figure 4, from the resistive leakage current and temperature delta data collected during campaigns 1 and 2 (which are any subsequent campaigns spaced six months apart), the mean and standard deviation for each family of surge arresters are calculated. It is crucial to note that prior research was conducted to determine the most suitable probability distribution model to represent the data, utilizing the Anderson-Darling test. The findings indicated that the Gaussian distribution was more representative for the majority of surge arrester families (those of the same manufacture, model, and year).

The degrees of belief (μ_{Ires} and $\mu_{\Delta T}$) for the data from campaign 2 are calculated through normalization from the mean and standard deviation (where I_{res} represents the resistive leakage current and ΔT the temperature delta from thermography inspection). On the other hand, the degrees of disbelief (λ_{Ires} and $\lambda_{\Delta T}$) are derived by comparatively evaluating the evolution of values from campaign 2 (current) in relation to campaign 1 (previous).

The resulting degrees of belief and disbelief (μ_R and λ_R) are determined by applying maximization and minimization functions, respectively. Finally, the degrees of certainty and uncertainty are calculated according to equations (1) and (2).

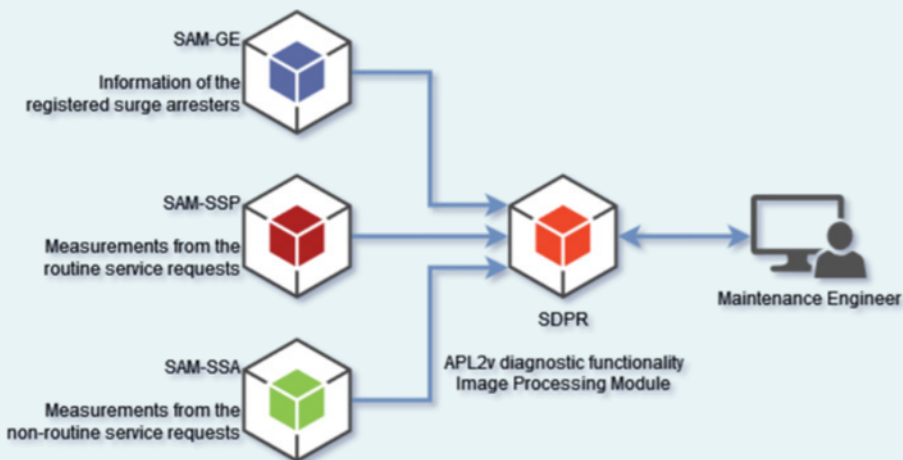


Figure 5. SDPR software architecture

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The SDPR integrates seamlessly with Itaipu's Maintenance Support Systems (SAM), as indicated by its Portuguese acronym. Below are the primary capabilities and features of the SDPR:

a) Access to Equipment

Management Data: Via SAM-GE, the SDPR accesses equipment management data, specifically retrieving details about registered surge arresters.

b) Service Request Records

Retrieval: The platform can access both routine (SAM-SSP) and non-routine (SAM-SSA) service request records. These records offer crucial insights for the diagnostic process.

c) Diagnostic Functionality for Surge Arresters

Utilizing the gathered data, the SDPR enables maintenance engineers to conduct diagnostic evaluations of surge arresters.

d) Thermographic Image Processing

The SDPR includes an image processing module that extracts temperature data from thermographic images of surge arresters, thus improving the accuracy of diagnostic analyses.

Figure 5 illustrates the software architecture of the SDPR.

Accurate temperature measurements are pivotal for the SDPR, serving as essential input data. This precision is attained through the meticulous analysis of thermal images from each campaign by professionals proficient in both the equipment and the principles of infrared thermography. However, this approach entails significant implications:

- The process demands a considerable allocation of man-hours.
- It relies on various proprietary software solutions.
- There is a potential risk of misinterpreting thermal images, contingent on the analyst's training and experience.

In response to these challenges, the Surge Arrester Detector (SAD)

was developed. This innovative component of the SDPR utilizes Artificial Intelligence (AI) to enhance efficiency and accuracy. Operating as a robust REST API, the SAD accepts thermal images, employs a trained AI model to identify surge arrester segments, extracts measurements, and then provides temperature data to the user. Figure 6 illustrates this process.

The AI model identifies surge arrester segments and extracts temperatures from the thermal data contained in the images. Specialized functions further refine this extraction process by filtering out background elements. Ultimately, the processed information is compiled into a report, and the image set is returned, each tagged with unique identifications in the metadata.

Key Outcomes: Next-Gen Diagnostics for Surge Arresters

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. This dual-measurement approach comprehensively addresses the most prevalent failure modes, providing a robust framework for navigating through complex diagnostic scenarios that may present undefined or contradictory evidence.

A standout feature of the Surge Arrester Diagnostic System (SDPR) is the incorporation of the Surge Arrester Detector (SAD) module. This module exemplifies technological ingenuity by identifying surge arresters within thermal images and autonomously extracting temperature data, thereby streamlining the diagnostic process and significantly reducing the workload for field technicians. This advancement not only enhances operational efficiency but also

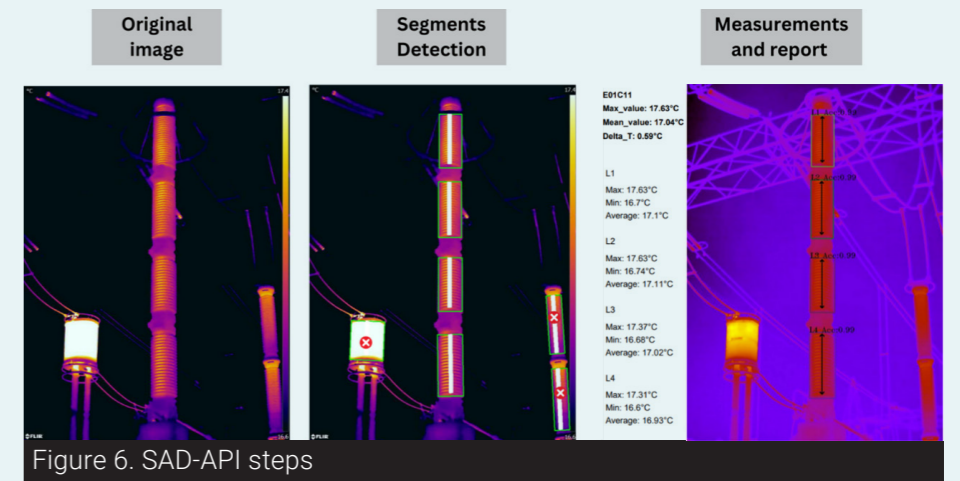


Figure 6. SAD-API steps

exemplifies the pivotal role of automation in field diagnostics.

Throughout its deployment, Itaipu's Maintenance Engineering team has successfully utilized the SDPR to perform a series of diagnostics, revealing no critical statuses across two successive campaigns. This observation was further corroborated by additional analyses, including online partial discharge measurements via high-frequency current transformers, which yielded no noteworthy findings. While Itaipu has yet to decommission any surge arresters solely based on SDPR indications, there is a proactive strategy to further investigate units with high SDPR scores, indicative of potential critical status, subsequent to their replacement. These examinations, slated for an independent high-voltage laboratory followed by meticulous internal inspections, are anticipated to be a cornerstone in a comprehensive long-term study aimed at validating the effectiveness and reliability of the APL2v-based diagnostic method.

This approach not only underscores Itaipu's commitment to pioneering in the realm of electrical infrastructure maintenance but also sets a benchmark for the industry, heralding a new era of precision, efficiency, and reliability in the diagnostic assessment of surge arresters. The potential findings from this long-term validation study are expected to contribute significantly to the field, offering a scientifically robust framework that could revolutionize asset management practices

across the power transmission and distribution sectors.

Future Improvements & Perspective

Itaipu is at the forefront of enhancing transmission system reliability and safety through an extensive program, replacing outdated MO porcelain surge arresters with modern polymeric ones equipped with monitoring devices. This upgrade facilitates the transition from manual to automated daily data collection of resistive leakage current, enabling deeper analytical insights and improving maintenance efficiency.

In a parallel stride towards innovation, Itaipu, in collaboration with the Itaipu Technological Park Foundation (FPTI), is pioneering the development of a cutting-edge system for the automatic, online acquisition of resistive leakage current data. This system is poised to seamlessly merge comprehensive monitoring data with vital SCADA information, offering a holistic view of surge arrester behavior over time.

Moreover, a partnership with a leading surge arrester manufacturer aims to test and refine an online monitoring device and its data management platform, aiming to improve analytical tools and provide actionable insights to the engineering team. These efforts underscore Itaipu's commitment to leveraging cutting-edge technology for superior system reliability and operational safety, setting new industry standards for infrastructure management.