XI WORKSPOT- 11th International Workshop on Power Transformers, Transmission and Distribution Equipment, Substations, Materials and Emerging Technologies

RIO DE JANEIRO, RJ – NOVEMBER, 25 - 27, 2024

A2 – TRANSFORMADORES E REATORES DE POTÊNCIA
TP 3: CONFIABILIDADE E DESEMPENHO EM CAMPO DE TRANSFORMADORES

Strategies for Preventing Incipient Failures in HV Bushings in Renewable Energy Conversion

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ABSTRACT

One of the greatest challenges in energy generation is ensuring that assets are always available, exhibit minimal failure rates, and maintain maximum operational output. Power transformers are among the most critical assets in wind farms, as they are particularly vulnerable due to being the connection points to Brazil's National Interconnected System (*SIN*).
It is widely known that the performance of power transformers used with renewable energy sources—due to the effects of harmonics, system transients, and power inverters—differs from that of transformers used in traditional generation, transmission, and distribution grids. Although these transformers have evolved over hundreds of years to become reliable in conventional applications, ensuring they serve reliably for forty years in renewable energy applications presents a completely different challenge.
Capacitive bushings, components of these transformers, demand close attention due to their failure rates—they account for 15.6% of failures, according to 2015 statistics from Cigré WG A2.37.
To mitigate risks associated with failures in power transformer bushings, the CPFL approach has involved the use of real-time monitoring tools and inferences. These tools are designed to preempt incipient failures by monitoring operational behavior. Through continuous online measurement, data is relayed to our Asset Monitoring Center (*CMA*). Here, any emerging risk of potential failure is identified using the potential failure curve (*PF*), which, if detected, can pose a significant threat—potentially leading to total or catastrophic loss.
This scenario necessitates a Business Impact Analysis (BIA) under ISO 31000 Risk Management and ISO55000 Asset Management standards, as well as increasing both operational costs and security risks.
The monitoring tool installed on high-voltage bushings senses and records several parameters including tangent delta, leakage current, and capacitance. This is part of an integrated asset management system that employs predictive techniques to preemptively address incipient failures. The data collected provides real-time insights into the behavior of capacitive bushings, enabling timely interventions through a Predictive Maintenance Plan. This not only prevents total asset loss but also optimizes maintenance strategies.
Moreover, the tool includes prognostic capabilities that predict future issues based on the progression of measurements over time. This early detection of problems in their incipient phase allows our asset management system to tailor interventions to the specific needs of wind farms in Brazil. The benefits

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of online monitoring include reduced risk exposure, enhanced operational health data, lower unexpected costs, and improved asset availability.
Each aspect of online monitoring is underscored by real-world cases that demonstrate its impact on the management processes of power transformers and wind farms. This technology significantly boosts productivity indicators and enhances the overall operational reliability of the company.
From these implementations, we have developed criteria for mapping operational risk management, which has resulted in cost savings, risk mitigation, and a more predictive approach to asset lifecycle management.

KEYWORDS

High Voltage Capacitive Bushings; Asset Management; Operational Risk; Real-time monitoring; Predictive maintenance; Power transformers; Wind farms

1 INTRODUCTION

In our pursuit of operational excellence, the company has strategically invested in asset monitoring, placing particular emphasis on the power transformers critical to our business. We utilize real-time capacitive bushing sensing technology to assess insulation conditions by monitoring tangent delta, capacitance, and leakage current for each phase of these transformers. Currently, nearly 70% of all bushings are monitored through our web platform.
Operational Risk Management has identified these assets as particularly significant due to their impact on business risk. Their availability is directly linked to the company's strategic management KPIs and other key performance indicators. Maintaining continuous availability and optimal conditions of these assets is essential for maximizing power delivery to the electrical system, thereby enhancing production and profitability.
To support these objectives, our corporate policy is grounded in asset management principles that drive strategic decision-making. Ongoing risk assessments within the system help identify failure modes, critical impact points, and the probabilities of their occurrence. These assessments are crucial not only for transmission lines, wind turbines, and substations but also for power transformers. As the most critical elements in energy dispatch, power transformers aggregate the output from various machines and deliver it at the appropriate voltage to the transmission network.

2 APPLICATION CONTEXT

Within the scope of assets evaluated by the Operational Risk Management area and overseen by the Asset Monitoring Center (CMA), power transformers stand out as critical assets requiring focused attention on risk and potential failures. For each component of these assets, we have developed a classification of suitable sensing technologies, tailored according to their power and voltage levels. This approach ensures that each transformer is monitored in a category appropriate to its risk profile. By standardizing these criteria across the company, we leverage new technologies and best practices to enhance monitoring and operational analysis throughout the transformer's lifecycle. This method aligns with the Business Impact Analysis (BIA) principles outlined in the company's Operational Risk Management framework, as illustrated in Figure 1.
Moreover, the operational risk associated with transformers is particularly linked to the reliability of capacitive bushings, which are critical insulating components. According to statistics from CIGRÉ Working Group A2.37 [01], capacitive bushings account for 17,16% (*13,99 (HV) + 2,8 (MV) + 0,37 (LV)*) of transformer failures, focusing solely on catastrophic failures that result in seven or more days of downtime.
This percentage likely increases when less severe incidents are included. Figure 2 presents data that corroborate these statistics.

Figure 1 - Table of Monitoring Levels Adopted in the Company

Monitoring Standard for Power Transformers Wind / Photovoltaic / Hydroelectric				
Criteria	**Class**	**Monitoring**	**New**	**In Operation**
Operating Range	**Criticality**		**IEDs / Function**	**IEDs / Function**
V < 34,5 kV VA ≤ 5 MVA	Type 0	Minimum	Temperature Moisture	Temperature Moisture (On demand)
34,5 ≤ V ≤ 138 kV 5 < VA ≤ 20 MVA	Type 1	Very Low	Temperature Voltage Regulation Moisture + Gas (H2)	Temperature Voltage Regulation Moisture + Gas H2 (On demand)
V ≥ 69 kV 20 < VA ≤ 30 MVA	Type 2	Low	Temperature Voltage Regulation Moisture + Single Gas OLTC Oscillography Bushings (Cap+Tg)	Temperature Voltage Regulation Moisture + Single Gas OLTC Oscillography Bushings (Cap+Tg)
V ≥ 69 kV 30 < VA ≤ 50 MVA	Type 3	Medium	Temperature Voltage Regulation Moisture + 3 Gases OLTC Oscillography Bushings (Cap+Tg)	Temperature Voltage Regulation Moisture + 3 Gases OLTC Oscillography Bushings (Cap+Tg)
V ≥ 69 kV 50 < VA ≤ 75 MVA	Type 4	Moderate	Temperature Voltage Regulation Moisture + 5 Gases OLTC Oscillography Bushings (Cap+Tg / (P.D. - On Demand))	Temperature Voltage Regulation Moisture + 5 Gases OLTC Oscillography Bushings (Cap+Tg / (P.D. - On Demand))
V ≥ 69 kV VA > 75 MVA	Type 5	High	Temperature Voltage Regulation Moisture + 9 gases OLTC Oscillography + Vibro-Acoustic Bushings (Cap+Tg / (P.D. - On Demand))	Temperature Voltage Regulation Moisture + 7 or 9 gases OLTC Oscillography + Vibro-Acoustic Bushings (Cap+Tg / (P.D. - On Demand))

The failure of a bushing can significantly disrupt energy flow, directly causing revenue loss due to halted generation, material damage to transformers and other substation components, and increasing the risk of injuries—from minor to severe—to nearby employees. Additionally, such failures often lead to fines and harm to the company's reputation. According to traditional maintenance guidelines set forth in IEEE Standard C57.19.100-1995, offline tests for capacitance and tangent delta (insulation indices) are recommended at intervals of 3 to 6 years [02]. However, the unique characteristics of renewable energy power plants may render these traditional maintenance philosophies less effective.

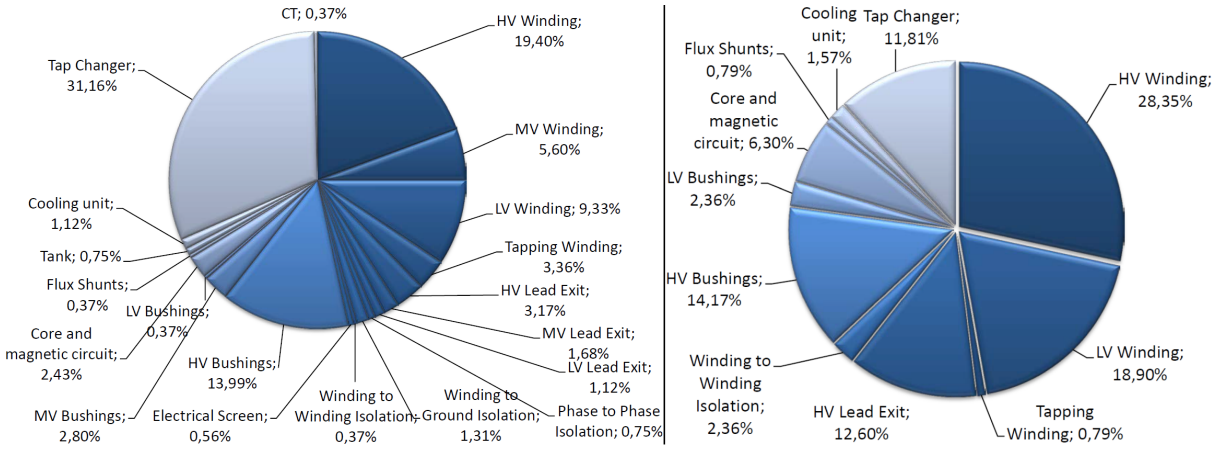


Figure 2 - On the left, failure location analysis, substation transformers, U ≥ 100 kV - 536 failures. On the right, failure location analysis, generator step-up transformers, U ≥100 kV, 127 failures [01]

Under such conditions, real-time monitoring diagnostics provide considerable benefits by accounting for operational behaviors and real-time electrical quantities affecting power plants. In scenarios with elevated systemic harmonic indices, it is prudent to conduct power quality measurement campaigns to characterize these conditions. When necessary, installing harmonic filters on substation buses can mitigate these effects. These measures address the operational challenges faced by capacitive bushings

due to the varied loads imposed by the system, particularly with the diversification of solar, wind, and other generation sources interconnected to the Brazil's National Interconnected System (SIN).

2.1 CONDITION AND RISK-BASED MAINTENANCE

The team of experts at the Asset Monitoring Center, in collaboration with web platform management and a third-party asset management company, has been concentrating on improving transformer management and mitigating inherent operational risks. This initiative aligns with the principles of World Class Maintenance (WCM), and the results have been promising. Within the WCM framework, the SAMI pyramid serves as a model highlighting key tools for maintenance management. As illustrated in Figure 3, one of the crucial strategies endorsed is Condition-Based Maintenance (CBM).

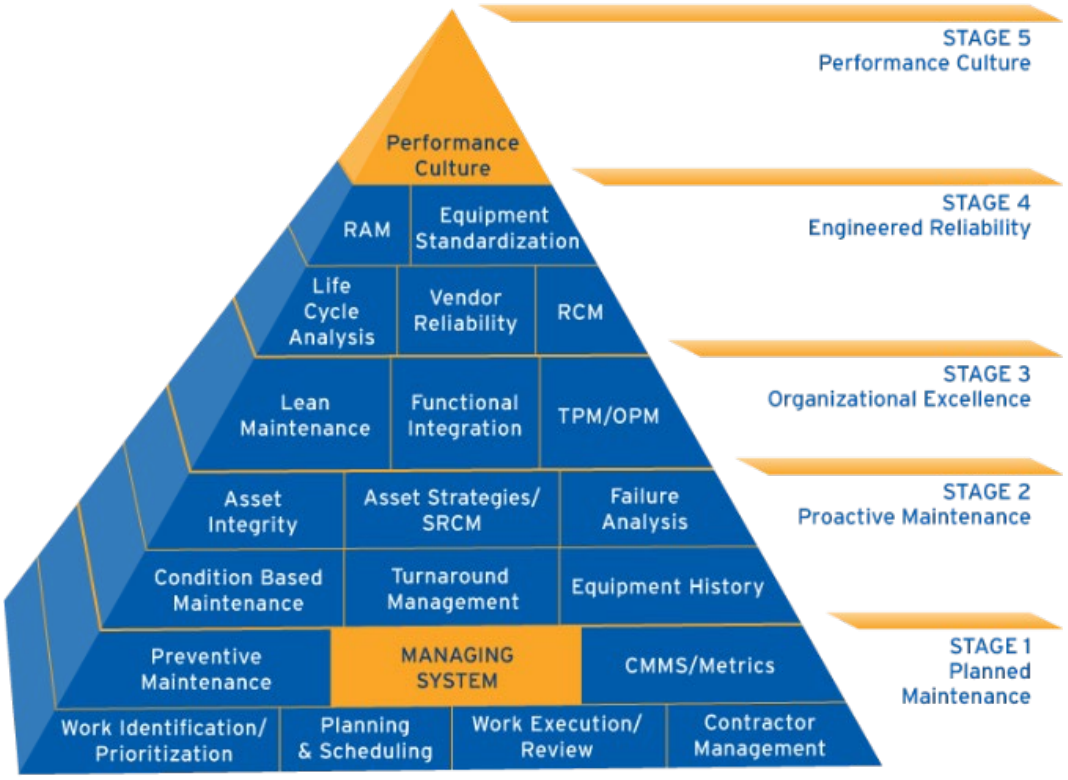


Figure 3 - WCM Pyramid (SAMI Pyramid Model) with processes and tools within asset management policy [03]

Pengxiang [04] characterizes Condition-Based Maintenance (CBM) as an advanced maintenance management approach that incorporates not only the current operational status but also evolving scenarios for informed decision-making. In this context, online monitoring tools have been employed for real-time condition monitoring of capacitive bushings. These systems are designed to assess the present state and predict potential failures by analyzing measurement trends over time. The ability to detect issues at their earliest stages has facilitated a shift in maintenance strategies from preventive to real-time predictive maintenance, significantly enhancing the technical management of assets.

3 ONLINE MONITORING OF CAPACITIVE BUSHINGS

Leveraging market experience and advanced instrumentation, the CPFL team implemented online monitoring using the vector sum technique of leakage currents to determine the capacitance and power factor (tangent delta) of bushings. These parameters are crucial for accurately assessing the insulation condition of the equipment. This technique is based on the characteristic phases of the three leakage currents, which are typically offset from each other by approximately 120 degrees and are similar in

magnitude. Consequently, the vector sum of these currents results in a value significantly lower than that of any individual leakage current.

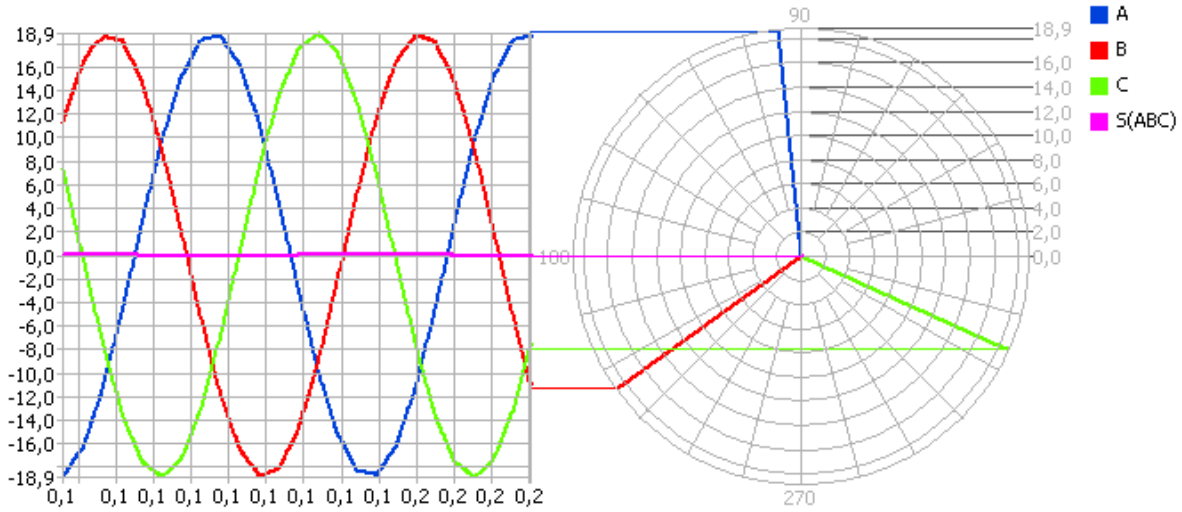


Figure 4 – Time and Phasor Representations of Bushing Leakage Currents in a Normal Operating System.

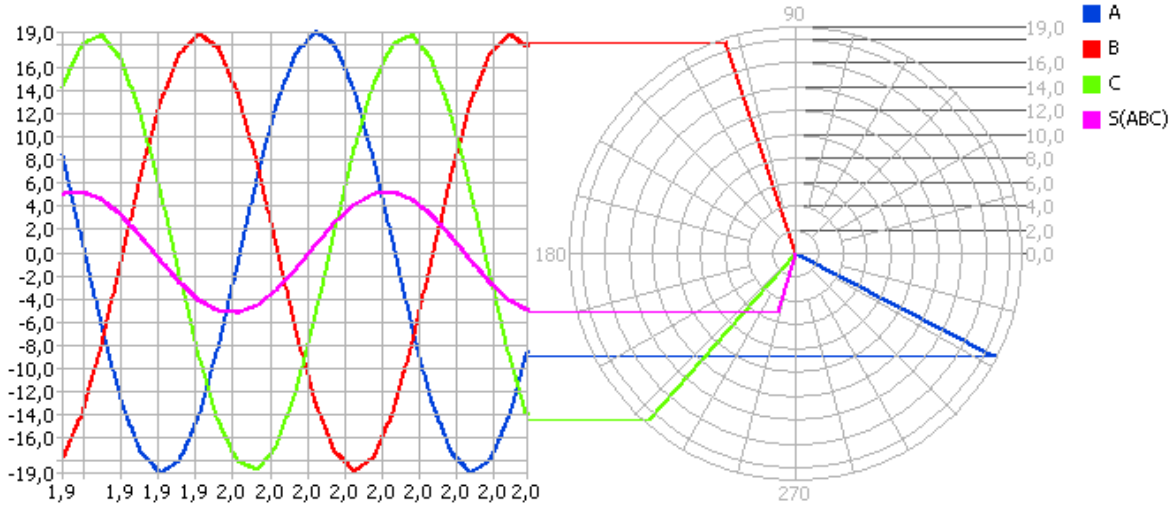


Figure 5 – Time and Phasor Representations of Bushing Leakage Currents Showing a Significant Increase in Dielectric Power Losses (Resistive Current Only)

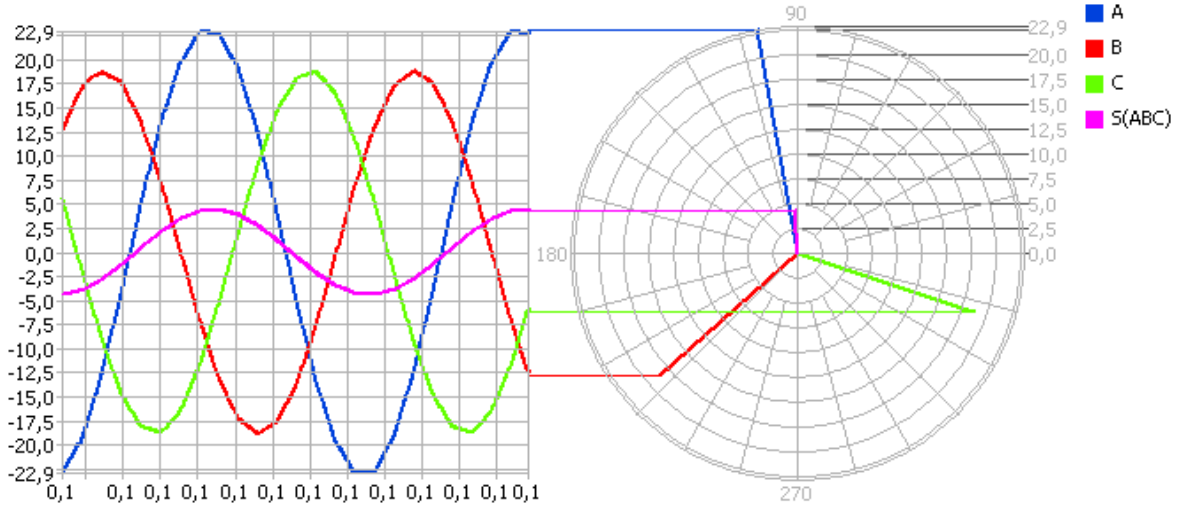


Figure 6 – Time and Phasor Representations of Bushing Leakage Currents Showing a Significant Increase in Capacitance Only (Loss of Capacitive Layers).

Figures 4, 5, and 6 illustrate significant changes in the characteristics of the A-phase bushing. By comparing variations in these vectors, changes in the bushing's impedance can be detected. This method enables continuous monitoring of both capacitance and insulation tangent delta. According to studies conducted in 2022 [05][06][07], this online monitoring technique has proven to be more efficient than traditional offline methods in detecting condition changes.

4 SYSTEMIC EFFECTS ON THE MONITORING TOOL

Within CPFL's assets, nearly all high-voltage bushings above 138 kV are under surveillance, with about 70% benefiting from predictive online monitoring. This includes installations at wind and small hydro power plants. The monitoring system is based on an initial learning period during which it observes the electrical system's behavior to establish a reference database. This reference allows for the detection of angular and amplitude variations, providing early indications of developing faults. In power systems—particularly within the hydro generation sector of the transmission network—the pattern of measurement variation tends to be minimal, indicating stable network behavior, as shown in Figure 7.

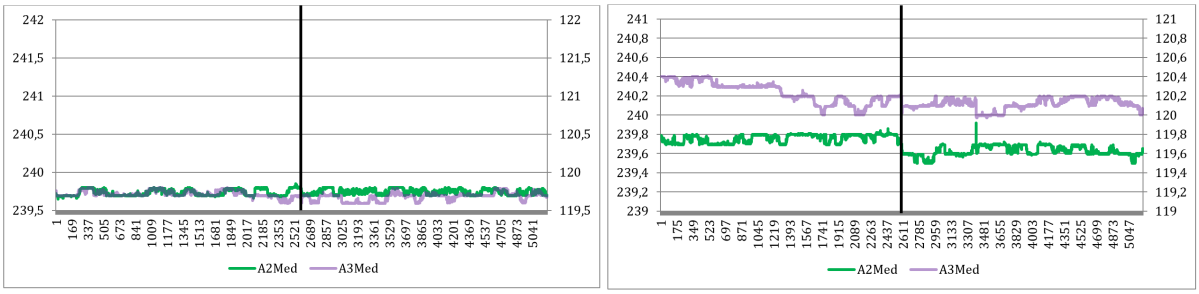


Figure 7 - Normal angle measurements from A2Med (Phase A to Phase B) and A3Med (Phase A to Phase C) exhibit typical, small oscillations.

According to IEEE standard C57.19.100-1995 and IEC 60137:2008, typical indicators for bushing health include:

- High capacitance: an increase of 2 to 3%.
- Very high capacitance: an increase of 5%.
- High tangent delta: an increase of 100% (or 0.7% in absolute value).
- Very high tangent delta: an increase of 200% (or 1.05% in absolute value).

However, during periods of change in the transformer's loading profile, abrupt variations in these metrics have been detected, with measurements significantly exceeding these guidelines

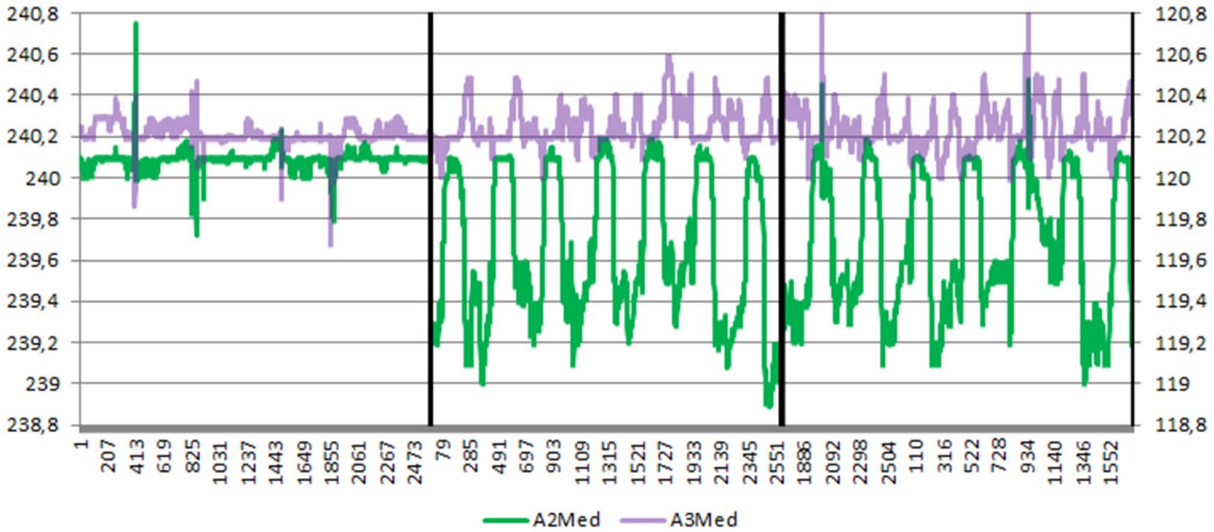


Figure 8 – Observed Effects of the Electrical Phenomenon, Particularly Noted in One of the Company's Plants

As show in Figure 8, during the learning phase, the reference bank records angular variations on the left side, while the two right side documents phenomena causing variations of up to 2°, which trigger the monitoring alarms. Despite these alerts, further analysis often reveals that these are merely systemic variations that do not lead to faults in the bushings. Consequently, such phenomena have occasionally misled online detection techniques, resulting in unnecessary concerns and distortions in asset management strategies.

5 DEVELOPMENT OF SPECIFIC SOLUTION

In response to the need for more precise asset management and diagnostics, the bushing monitoring software was upgraded to enhance field measurement analysis and incorporate noise filters. Preliminary analysis confirmed the following:

- Proper installation of monitors
- No defects in physical connections
- No imminent risk of insulation failure

However, further data collection on the specific operational characteristics of the generation system was necessary to address recurring alarms and systemic conditions. A case study was conducted at one of the company's substations, which consistently exhibited high and very high alarms for tangent delta (dissipation factor). Figure 9 shows the abnormal behavior of the angles between phases of leakage current. This substation, serving as a comparative measurement point between wind and hydro sources, displayed more pronounced issues in the company's wind sources.

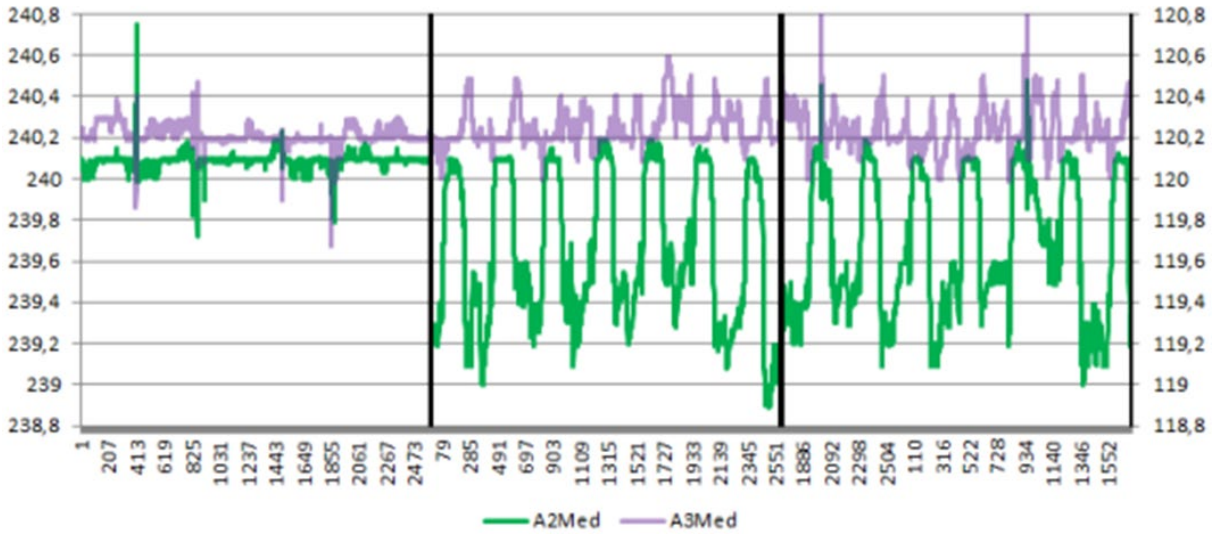


Figure 9 – Visualization of the representativeness of the selected case, showing measurements from the bushing monitor at the wind power source.

During a seven-day observation period, the angle AB exhibited atypical variations of approximately 1°, which is unusual for the operational conditions of the three-phase setup. Initial data collection included monitoring system variables like bus voltage and considering potential causes such as noise, atypical harmonics, and load variations—factors that could alter the dielectric properties of the bushings.

Subsequently, the vendor updated the monitoring system's firmware, incorporating a new filter module designed to reduce the sensitivity of tangent delta alarms. This new methodology increased the data density in both the reference and measurement banks, showing promising results as indicated in Figures 10 and 11. However, a full evaluation required observing the system through two distinct seasons.

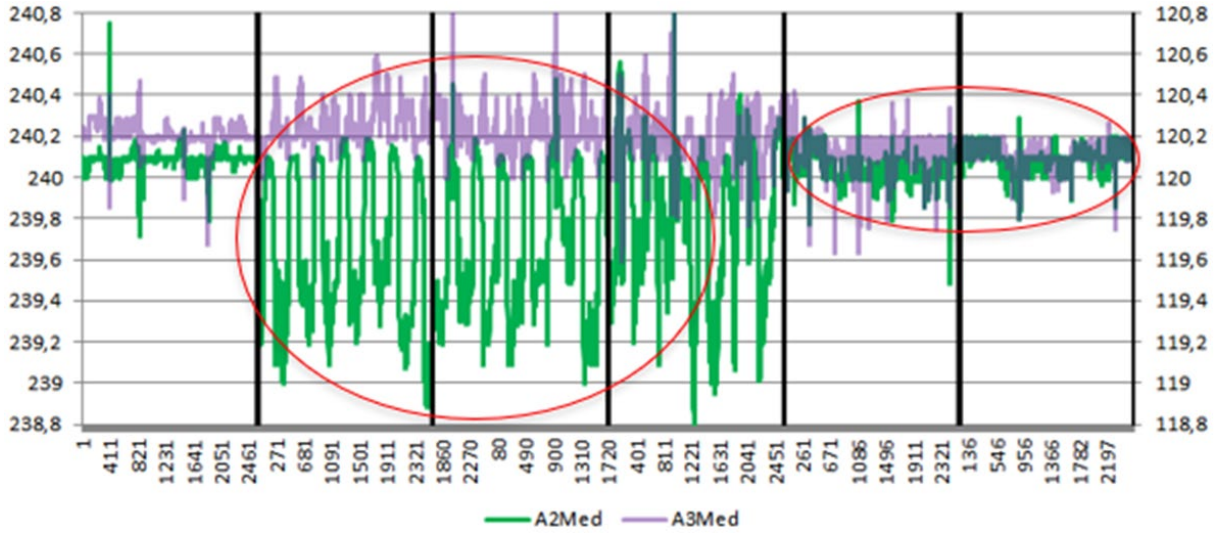


Figure 10 – Updated Reference Data Showing Increased Information and Reduced Oscillations

An important development was the adoption of the Hodrick-Prescott (HP) filter, which differentiates long-term trends from short-term noise more effectively than other methods. The HP filter removes short-term oscillations, focusing on the long-term trend of the data series. It offers high processing speed, low computational cost, and excellent efficacy in highlighting characteristics in electrical signals. Post-processing the HP-filtered data involves reducing the series to discrete points, which are then used to determine the operational state of the monitored object.

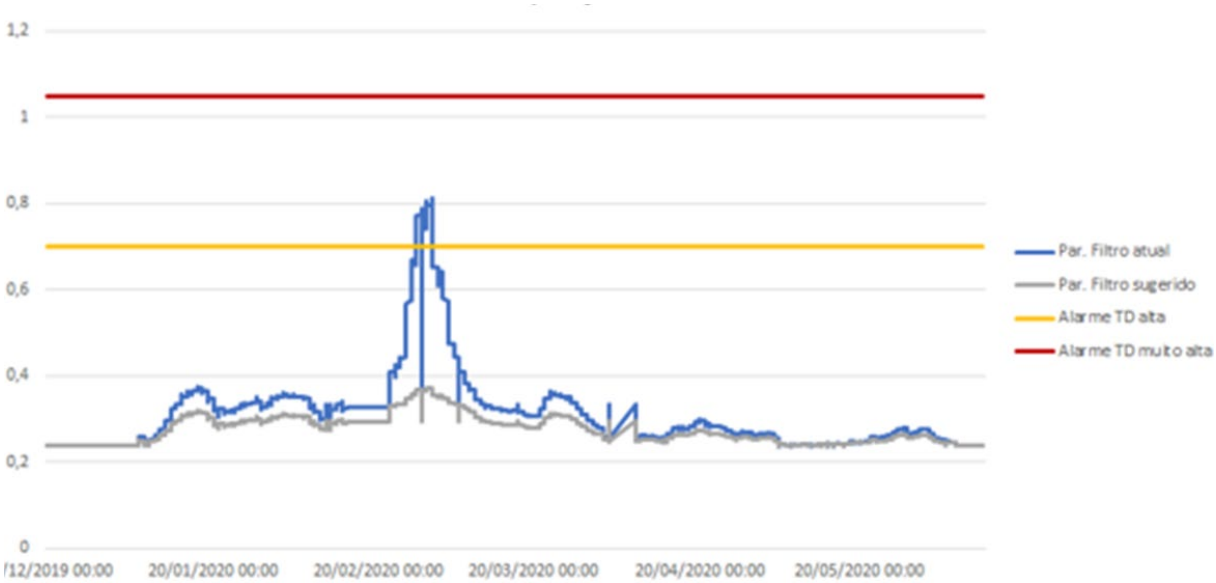


Figure 11 – Enhanced Sensitivity of Tangent Delta Alarms Using the New Experimental Active Filter

With the implementation of the new monitoring philosophy and enhanced robustness in measurement analysis, a consistent symmetric oscillatory behavior around the mean value was observed. This uniformity, with minimal variation between components, suggests no degradation in the condenser bushings. The figure 12 illustrates the behavior of phase angles, notably the oscillatory pattern of angle A2 (highlighted in green). Initially symmetric, this pattern becomes markedly asymmetric as "high wind" conditions commence, showing predominant negative oscillations.

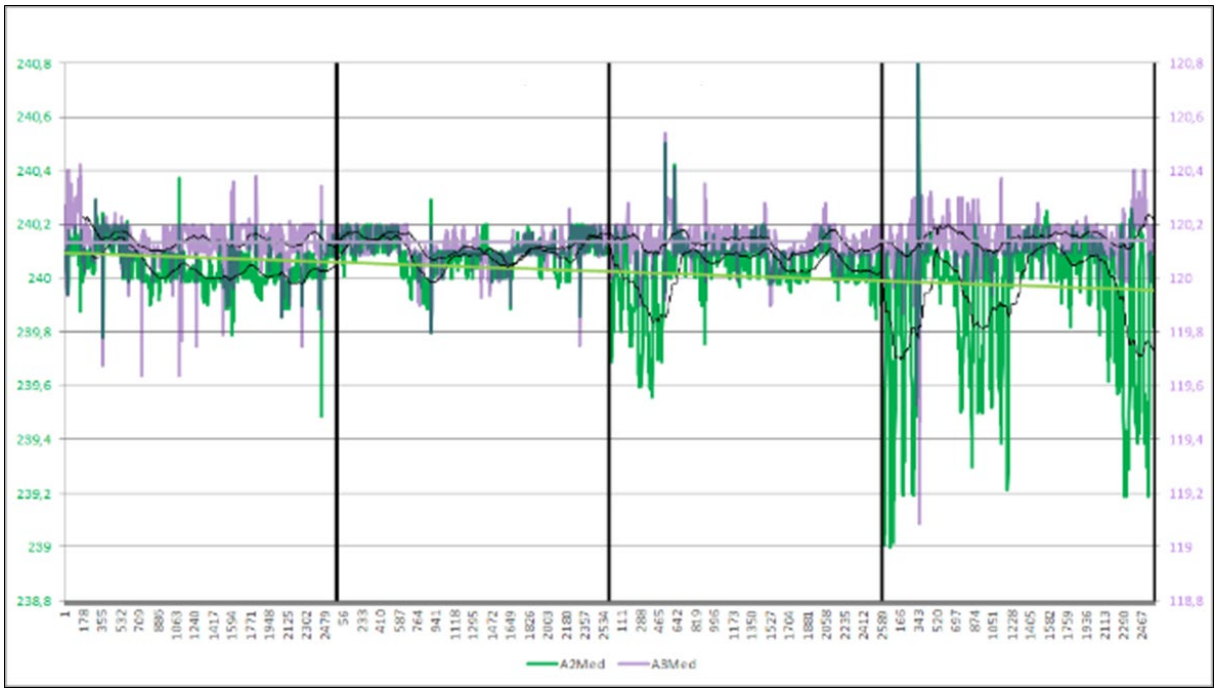


Figure 12 – Comparative Evolution of Angles AB and AC

This emerging asymmetry intensifies during peak generation periods of the wind source, suggesting a systemic causal relationship. Typically, natural oscillations should exhibit a normal or random distribution, but the observed biased behavior—predominantly in the direction of decreasing angle—points to a specific systemic influence.

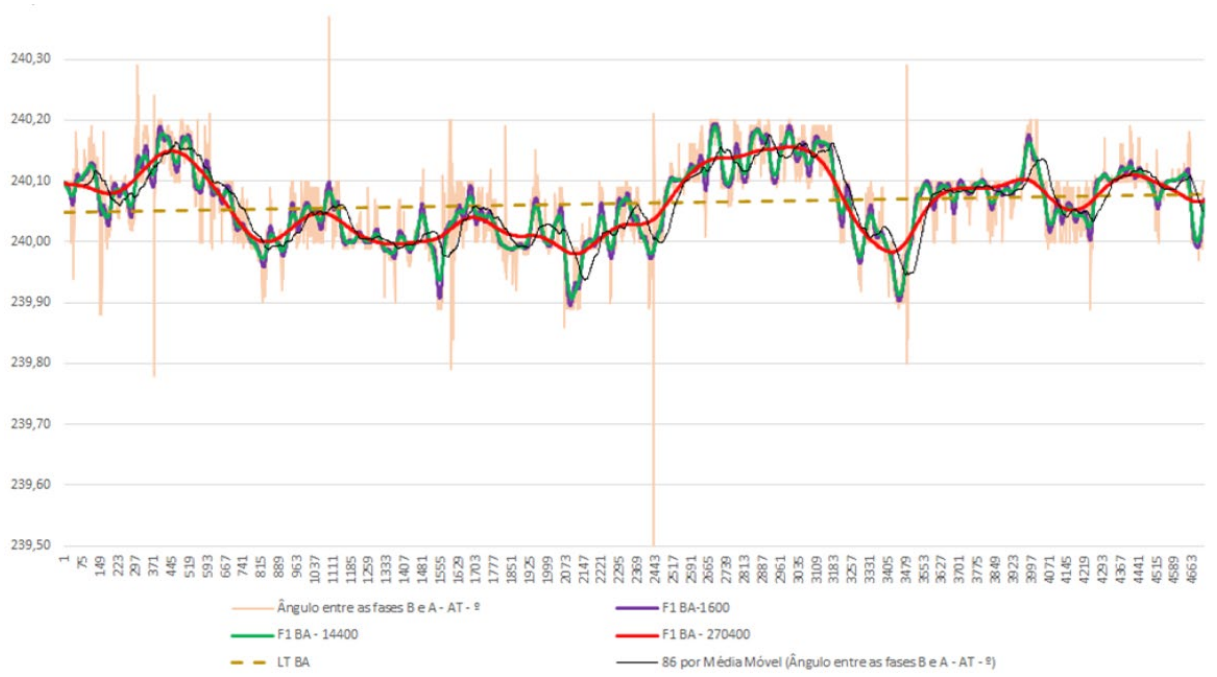


Figure 13 – Development and Application of the Specialized Filter

In Figure 13, we can see the result of the correctly implemented and active HP filter. The final lambda factor is represented by the red line, and the original leakage current curve is shown in pink. The purple, green, and red curves depict various outcomes of the decomposition process for different lambda values, as noted in the legend. The black line represents a moving average filter, and the dashed line shows linear regression analysis.

It is noted that there is no time shift in the analysis, which is a significant positive characteristic of this class of filters.

6 CHANGE IN MANAGEMENT PHILOSOPHY

In light of the successful integration of the new filter—which accurately reflects the insulation health of bushings under specific operational conditions in Brazil, especially in wind power scenarios and applicable to hydroelectric plants—several strategic decisions have been implemented:

- The corporate online monitoring platform is now the official tool for assessing the operational risk of high-voltage (HV) bushings.
- A revised schedule for offline interventions has been established, updating previous maintenance policies.
- All additional policies derived from the use of the new filter will adhere to the normative guidelines issued by the Asset Monitoring Center (CMA) for the monitoring and sensing of key assets.

These strategic updates are anticipated to yield significant long-term operational and financial benefits:

- Enhanced generation availability, ensuring that substations are always ready for energy export, aligning with the company's performance indicators.
- Improved reliability and availability of power transformers through effective risk mitigation.
- Reduction in operational expenditure (OPEX) by transitioning from periodic preventive maintenance routines to continuous online monitoring.
- Potential renegotiation of the company's insurance policies based on the reduced risk profile.

7 CONCLUSIONS

The adoption of online monitoring for high-voltage bushings has markedly enhanced our approach to operational risk management and asset reliability. By enabling real-time tracking of critical parameters, the system provides early warnings of potential issues, facilitating timely and proactive maintenance interventions. This strategic capability significantly minimizes downtime and curtails the likelihood of catastrophic failures, thereby bolstering asset reliability and reducing maintenance expenses.

Furthermore, the insights garnered from the online monitoring system have been instrumental in refining maintenance strategies. This optimization not only fosters further cost reductions but also elevates asset performance. Overall, the shift to online monitoring for high-voltage bushings represents a prudent investment for the company, securing the continued availability and reliability of our power transformer assets and underscoring a commitment to operational excellence and sustainability.

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