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TRANSFORMER TECHNOLOGY MAG

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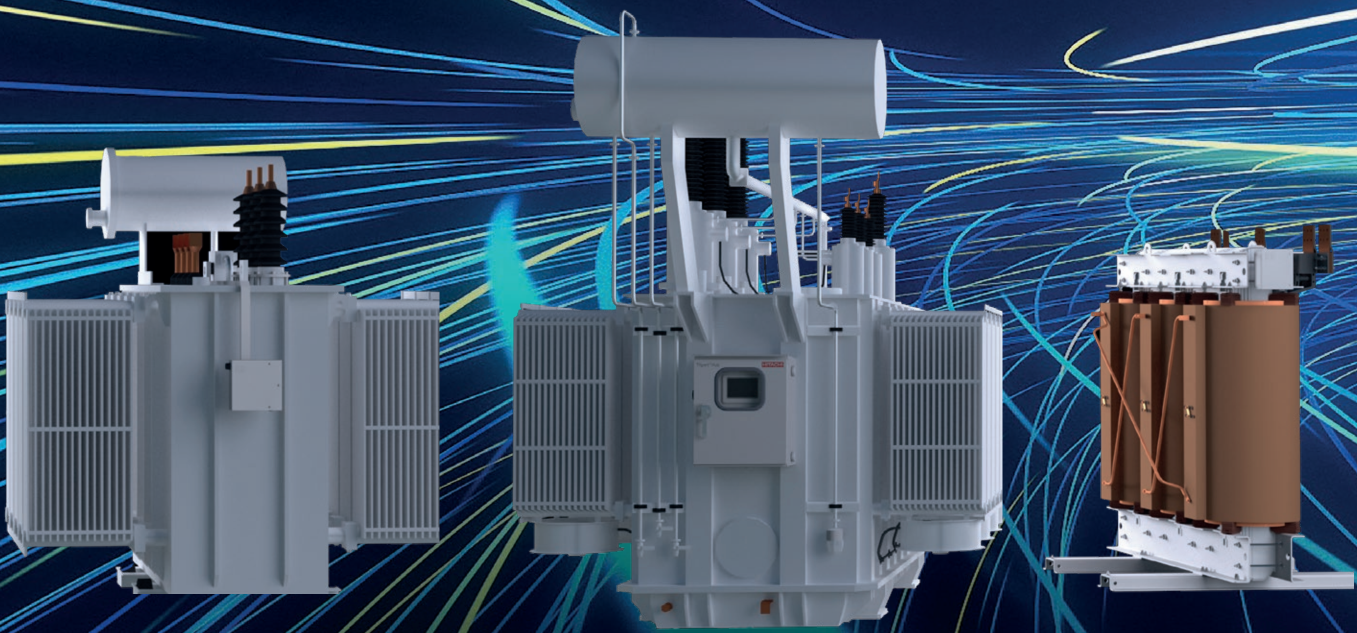
PST POWER SYSTEMS TECHNOLOGY



MONITORING & DIAGNOSTICS TECHNOLOGY, DATA SCIENCE & AI

Integration of DGA monitors to more comprehensive Transformer monitoring systems

AI-driven power transformer digital twins: **A SWOT analysis**

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

Laser focused on arcing faults

The InsuLogix® G2

The InsuLogix® G2 accurately measures low levels of acetylene, providing reliable detection of arcing faults in their early stages. The InsuLogix® G2 empowers transformer owners to take necessary actions to mitigate further damage to their transformers preventing costly unplanned outages.

Monitoring acetylene, along with hydrogen and moisture, provides you with the important actionable information needed to help protect your power transformer.

Some of the key features of the InsuLogix® G2 are:

- Laser technology - detects down to 0.5 ppm acetylene in oil
- Hydrogen detection for early fault awareness
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- Long life, low maintenance 10+ years

San QR code to learn more about the InsuLogix® G2 or visit: www.megger.com/G2

Megger's InsuLogix® G2 ... the unique solution for detecting potential dangers before they damage your transformer.

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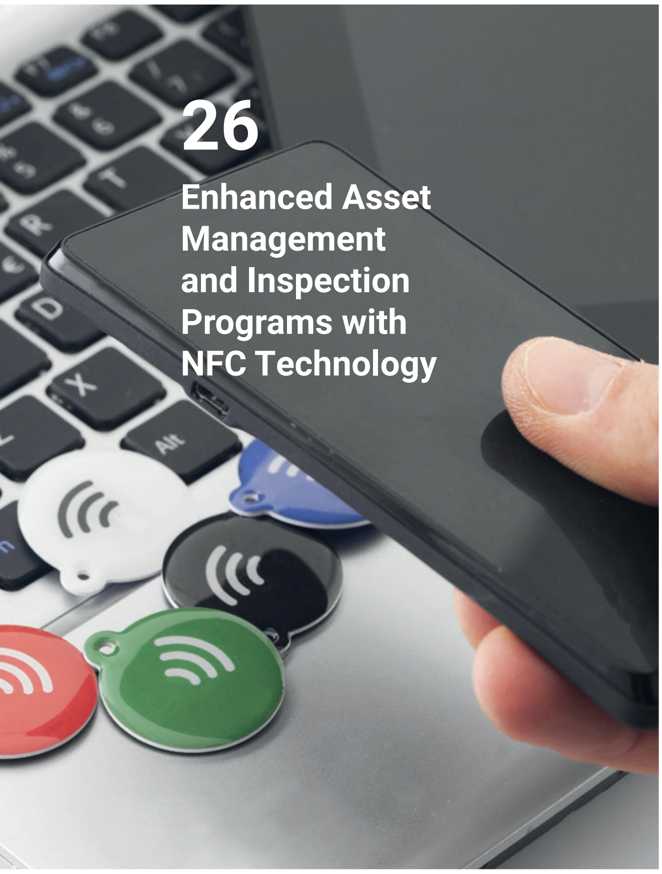

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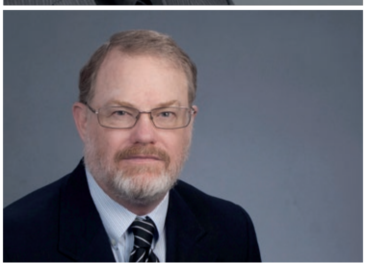

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POWER SYSTEMS TECHNOLOGY

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WiPS Women in Power Systems

ARE WOMEN IN POWER REALLY IN POWER?

The power systems industry is traditionally male dominated, with women making up around 22% of the workforce globally, and occupying only 12% of leadership positions, according to reputable sources. However, roughly 50% of energy consumers are women – all of us charging our phones, heating our apartments and much more.

Nowadays we see a truly commendable trend of women being in more and more positions of power in the power systems industry. However, a problem occurs when their titles are merely that - titles, and they do not hold any real executive power. How do we address this issue? This is the question we asked engineers, CEOs, team leaders from leading companies.

The road towards a more equal representation is long, but we want to be a part of the change by encouraging discussion and giving a platform to women's voices in the industry.

Support the voices of women in power systems - be the voice of women in power systems!

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COMING IN
WOMEN IN POWER SYSTEMS
SPRING 2024

Revolutionizing Power Sector Maintenance: The Shift from Reactive to Predictive Strategies

Predictive maintenance, preventative maintenance, and proactive maintenance are all important strategies in the maintenance of equipment and systems in various industries, including the power sector. I've spent many years of my career as the President of the Electric Power Reliability Alliance (EPRA) watching how the maintenance industry began to grasp with, and eventually champion, reliability of equipment, especially electrical assets.

Predictive maintenance involves using data and analytics to predict when equipment is likely to fail so that maintenance can be performed just in time. This approach helps to minimize downtime and reduce costs associated with unexpected failures. By monitoring the condition of equipment in real-time, predictive maintenance can identify potential issues before they cause a breakdown.

Preventative maintenance, on the other hand, is a scheduled maintenance approach that involves performing regular inspections, tests, and servicing of equipment to prevent failures from occurring. This approach is designed to help extend the lifespan of equipment and reduce the likelihood of unexpected breakdowns, however there are too many situations where preventative maintenance has led to unnecessary work being done and is typically based on manufacturer recommendations and industry best practices, rather than condition. Given the state of lead times for major assets, especially transformers, condition monitoring and predictive maintenance must become the standard, as opposed to time- based maintenance.
That increases the demand for monitoring and diagnostics.

Proactive maintenance takes preventative maintenance a step further by actively seeking out and addressing potential issues before they become problems. This approach involves analyzing data, conducting risk assessments, and implementing strategies to mitigate risks and improve the reliability of equipment.

Proactive maintenance aims to identify and address root causes of failures to prevent them from occurring in the future and both Machine Learning (ML) and Artificial Intelligence (AI) will play an increasing role since we know the advantages that AI and ML bring is the ability to analyze vast amounts of data in real-time, allowing for more accurate and timely detection of issues within the grid.

Why is this important and vastly better than scheduling maintenance based on time?

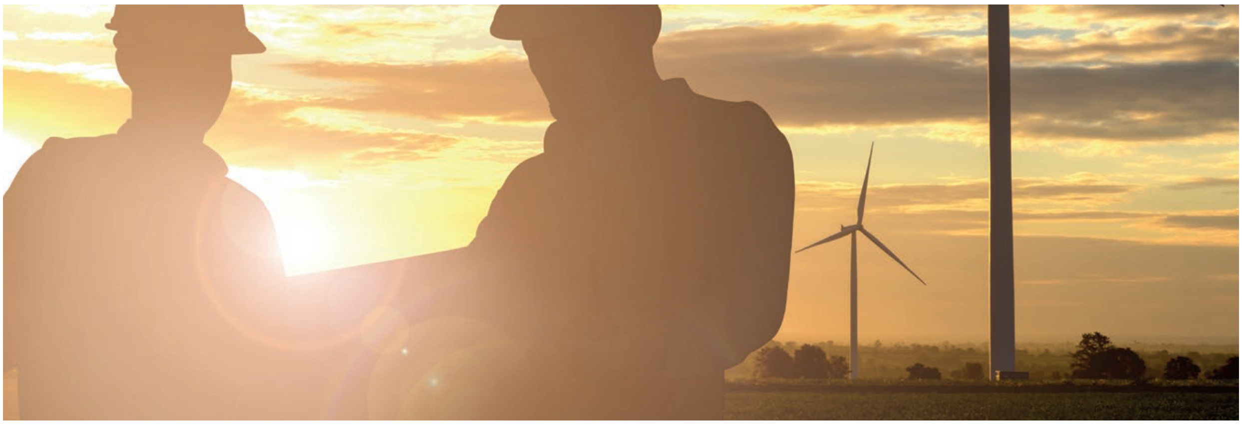


Photo: Shutterstock

By analyzing historical data on equipment performance and failure rates, AI algorithms can predict when a piece of equipment is likely to fail and alert operators to take preventative action. This can help reduce downtime and maintenance costs, as well as improve overall grid reliability.

> **By analyzing historical data on equipment performance and failure rates, AI algorithms can predict when a piece of equipment is likely to fail and alert operators to take preventative action.**

Additionally, AI and ML can be used for fault detection and classification. By analyzing data from sensors and other sources, AI algorithms can automatically detect when a fault occurs in the grid and classify the type of fault. This information can help operators quickly isolate the issue and take appropriate action to restore power to affected areas.

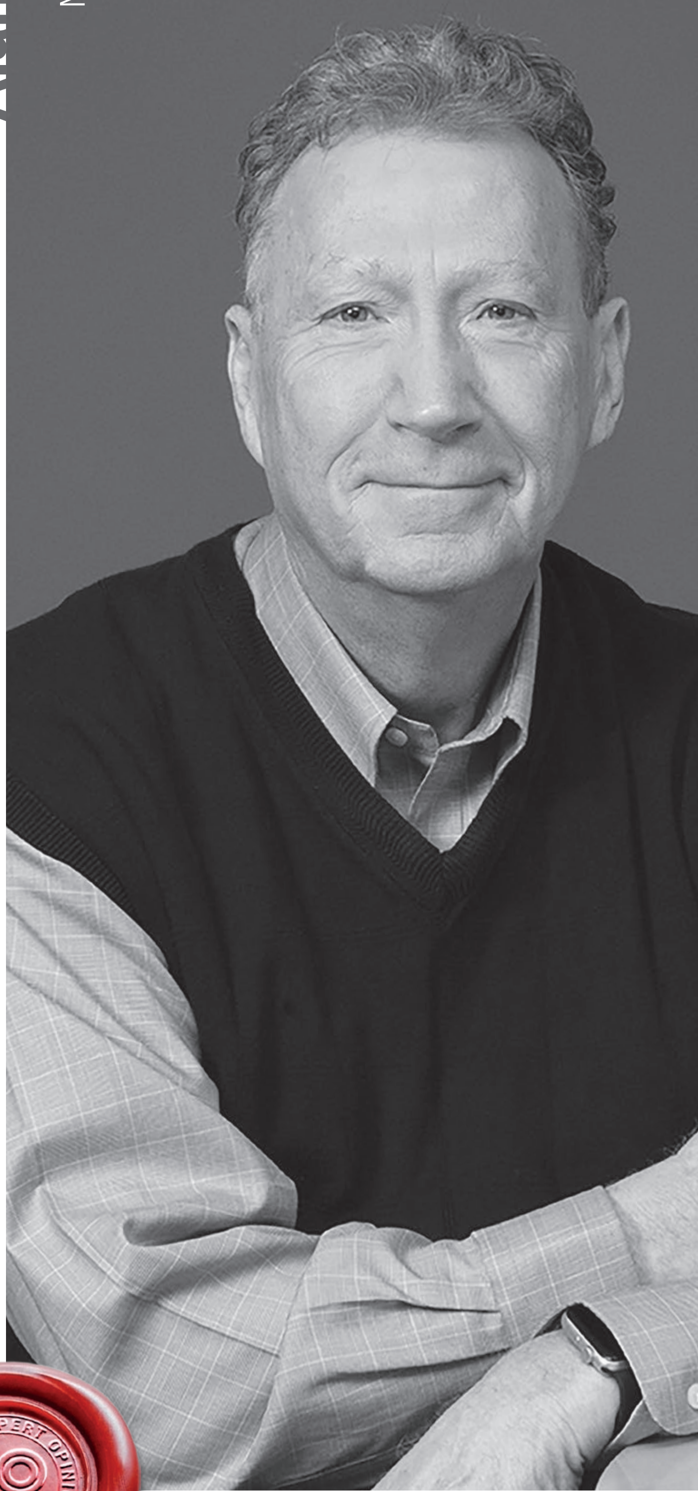
AI and ML technologies have the potential to revolutionize diagnostics in the electric grid by providing more accurate, timely, and cost-effective solutions. By leveraging these advanced technologies, utilities can improve grid reliability, reduce downtime, and ultimately provide a more efficient and resilient power system for customers.

Overall, the future of monitoring and diagnostics in the distribution system of the power sector is bright, with advancements in technology driving improvements in reliability, efficiency, and performance. By leveraging advanced sensors, artificial intelligence, remote monitoring and control systems, and proactive maintenance strategies, operators can ensure that the distribution system remains reliable and resilient in the face of evolving challenges and demands.

> **Overall, the future of monitoring and diagnostics in the distribution system of the power sector is bright, with advancements in technology driving improvements in reliability, efficiency, and performance.**

Alan M Ross
CRL, CMRP
Managing Editor
APC Media
Technical Director

Alan has decades of experience in the power systems industry and is one of the greatest reliability experts out there.



Detection of air leaks with total gas pressure

by **Senja Leivo**

Photo: Vaisala

Ambient air is the sole source of oxygen in transformers... Modern power transformers usually have sealed designs, and older ones are often upgraded with sealing systems to keep out oxygen and moisture, extending their lifespan.

Senja Leivo is the Senior Industry Expert at Vaisala and an active member of CIGRE working groups. Her professional focus is on condition monitoring of power transformers. With 20 years of experience, she is responsible for identifying the strategic trends and new monitoring needs within the industry, as well as bringing customers' voice close to the Vaisala's product development. Senja holds a Master of Science degree in Materials Engineering.

Why aging of the insulation system matters?

Transformers that employ cellulose based solid insulation are typically expected to function for decades under their nominal load and specified ambient temperature conditions. The aging of a transformer is influenced by its design, materials, contaminants within the insulation system, and operational conditions. The combination of water, oxygen, and acids within the solid insulation speeds up the aging process and degrades cellulose molecules, resulting in diminished mechanical strength and a consequently shorter lifespan for the transformer.

Under normal operating temperature in a water and oxygen free environment, ageing processes are almost nonexistent. However, making a transformer completely free of oxygen and moisture is not practical or affordable. It's been reported that if the oxygen level in the oil stays below 2000 ppm, the insulation system ages more than five times slower than in a free breathing transformer. It's important to know that aging isn't limited to cellulose; the insulation oil also undergoes aging, mainly through oxidation, which forms carboxylic acids that can speed up paper aging.

Ambient air – the sole source of oxygen and moisture

Ambient air is the sole source of oxygen in transformers. Simultaneously, the primary supply for water is atmosphere, where humidity levels consistently exceed those found within transformers. To tackle this, transformers use preservation systems like a rubber bag or nitrogen blanketing, creating a protective barrier between the insulation oil and the surrounding environment. Modern power transformers usually have sealed designs, and older ones are often upgraded with sealing systems to keep out oxygen and moisture, extending their lifespan. Air leaks, usually caused by gasket or rubber bag deterioration, have become a significant concern, especially when transformers operate at higher loads. The increasing use of sealed designs makes it crucial for asset managers to ensure that the transformer tanks remain airtight, requiring simple and straightforward methods to confirm their tightness.

Identifying the limits of traditional methods

Leaking happens over time and creates varying rates of air ingress. Traditionally, finding air leaks involved measuring oxygen and nitrogen in standard DGA oil samples. However, the risk of sample contamination with outside air has been a major challenge. When samples are taken at the transformer site, transported, and handled, they can pick up oxygen, leading to wrong data interpretation.

Online measurement of oxygen concentration in oil is a way to confirm air entry, but it won't detect slow air leaks when active oxidation processes are simultaneously consuming oxygen. Additionally, interpreting oxygen measurements requires an experienced DGA specialist. Even after more than six decades of using dissolved gas analysis in the industry, there is still no recognized standard or established common practice for interpretation of oxygen concentration.

Some DGA monitors include integrated oxygen measurement, and nitrogen levels are calculated based on those values. However, these calculations assume constant oxygen-nitrogen ratios in air-saturated oil, making them unsuitable in that respect for sealed transformers.

What really matters for asset maintenance teams?

Aging of insulation system is not just about what happens in the paper; it also involves the liquid. To understand the aging process, one can't rely solely on gas concentrations like O_2, CO_2, and CO. It's crucial to also consider oil quality parameters, such as acidity, and ageing markers like furans or methanol. Assessing the remaining life of solid insulation is a complex task that demands a higher level of expertise. Unlike transformer faults

Photo: Shutterstock

that may develop rapidly, oxidation is a slow process, usually taking years to show significant progress. Therefore, real-time gas monitoring isn't necessary for tracking oxidation, as it is for quickly evolving faults.

Ultimately, decision-makers in transformer maintenance do not need to know precise oxygen or nitrogen concentrations. What matters most is to know whether the insulation system of a sealed transformer is exposed to air, the source of oxygen. Based on that information, they can plan for repair of the sealing system, oil degassing or dry out and so forth.

Finding the solution – a step forward in air leak detection

A simpler way to spot air entry is by measuring the pressure of all gases dissolved in oil. Total gas pressure (TGP), which sums up the partial pressures of all these gases, is an uncomplicated and easy-to-understand parameter.

Once the gases are extracted by the DGA monitor, their pressure can be measured. The key fault gases—hydrogen, methane, acetylene, ethylene, ethane, carbon monoxide, and carbon dioxide—make up only a tiny fraction of the pressure where nitrogen and oxygen are dominant factors. Increase in TGP in a sealed transformer signals an air leak, without the need for specialized opinions or interpretations.

For new transformers, the pressure of dissolved gases should be very low due to degassing of oil during commissioning. In a sealed transformer, the pressure stays low. However, a noticeable increase in pressure indicates a potential issue. Even when oxygen sensors can't catch slow air leaks due to oxygen-consuming reactions, the TGP value remains reliable. This is because the proportion of nitrogen dominates and increases over time, as it is neither formed nor consumed in the transformer.

Leaking happens over time and creates varying rates of air ingress... Online measurement of oxygen concentration in oil is a way to confirm air entry, but it won't detect slow air leaks when active oxidation processes are simultaneously consuming oxygen.

Seal leaks aren't a simple yes or no situation—they develop gradually, leading to different rates of air entry over time. By measuring the pressure of dissolved gases, utilities can easily spot the entry of air if the TGP rises. A properly sealed transformer should maintain low gas pressure levels for its entire lifespan, well below atmospheric pressure 1000 hPa (14.5 psia). If the TGP value starts to rise, it's a clear sign that air is making its way in. This suggests an issue with the transformer's sealing system, whether it's related to materials or workmanship—especially if the increase follows maintenance work. If the data indicates a recent ingress of air marked by an increase in total gas pressure, maintenance teams can decide whether they need to inspect and repair the sealing system during the next service break. This ensures there's no further deterioration of the insulating paper due to oxygen.

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TGP measurement in practice

Properly membrane-sealed transformers in service typically have a pressure of dissolved gases ranging between 100 to 300 hPa (1.45-4.4 psia). Figure 1 illustrates the TGP measured using the Vaisala OPT100 online DGA monitor. It also displays as reference calculated partial pressures of oxygen and nitrogen at 50°C, based on gas concentrations determined by a laboratory from standard DGA oil samples with gas chromatography. The data is from a new transmission transformer with membrane sealing, with monitoring initiated a few weeks after the transformer commissioning.

Over 11 months, there was a 23 hPa (0.33 psi) increase in TGP, having respective increase in nitrogen (N_2) 1500 ppm and none detected in oxygen (O_2) in oil. The clear increase in nitrogen concentration without oxygen indicates an active ageing process consuming oxygen probably occurring. This highlights the sensitivity of pressure measurement to even minor air ingress. Additionally, the TGP measurement is inherently free from air contamination, a constant risk when using oil samples.

O_2/N_2 ratio, is it important?
IEEE standard C57.104-2019 includes O_2/N_2 ratios in its gas concentration tables (90th and 95th percentile), which are often called as typical values of fault gases. Does this imply a need to start calculating these ratios? No, it doesn't. The ratios were solely introduced to differentiate between different transformer designs in the database of 1.5 million DGA results, where the transformer design information was not available. To select relevant reference values for DGA data of a transformer, one only needs to know the design of their transformer in question. Sealed and nitrogen blanketed transformers fall under the column with O_2/N_2 ratio <0.2, while free-breathing transformers fall under >0.2.

Photo: Shutterstock

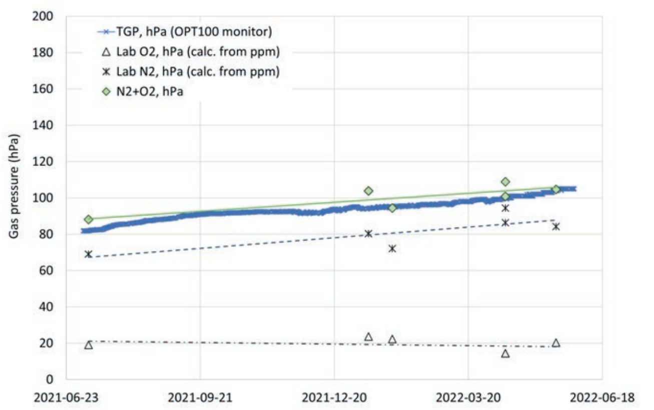

Figure 1
Total gas pressure (TGP) and calculated partial pressures of oxygen and nitrogen at 50°C with linear fitting.

Figure 2 presents real-time TGP readings measured from two sealed generation step-up (GSU) transformers. GSU1 maintains a consistently low TGP level in its initial two years. Right after commissioning, there's a release of gases into the oil due to air from the transportation phase, present in the oil-impregnated paper. This gradually moves to the bulk oil, causing a slight increase in TGP, which then stabilizes at a low level. The average annual increase in TGP after stabilization is only 7 hPa (0.1 psi), suggesting it would take with the same rate around 130 years to reach equilibrium with atmospheric pressure. In the real transformer application, achieving complete gas-tightness without any minimal air ingress through diffusion is not possible. However, the data indicates that GSU1 is well-sealed and doesn't require any actions in this respect.

The TGP data for sealed GSU2 after degassing presents a different scenario. Following degassing, there's a quick 30 hPa (0.43 psi) increase due to gas coming from the oil-impregnated paper. Unlike GSU1, this increase doesn't stabilize; instead, there's a steady rise at a significantly higher rate. Over the next two years, the rate of change is approximately 60 hPa/year (0.87 psi/a). If this rate continues, it will take roughly 15 years the oil to become saturated with air. It's apparent that more oxygen, and possibly moisture, is entering the transformer continuously, potentially reducing its lifetime. At this point, it becomes important to weigh the expected lifespan of the transformer against the costs of investigating and repairing the leakage or implementing other mitigation actions. Due to the nuanced nature of these decisions, it may not always be practical or economically relevant to attempt fixing the leakage.

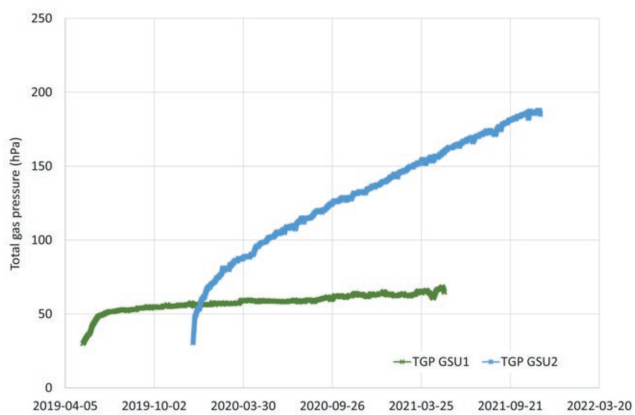

Figure 2
TGP data of two new power transformers right after transformer commissioning.

BREAKTHROUGH IN PROTECTION WHEN MONITORING BUSHINGS

The energy transition is a huge shift from fossil-based to fossil-free sources. This will mean moving to an energy system with electricity as the backbone that can handle a growing demand from industry, buildings and transportation. We estimate that by 2050 we will need four times the generation capacity and our electrical power systems will need to transfer three times more electrical energy than today.

Highlighting that today's energy system is deficient in security, equity and sustainability is not about blaming the old system – we recognize that each era has its own economic and social constraints and its own technological limits. Instead, we see these deficiencies as a recognition that the power system of tomorrow cannot be the same as today, they show our imperatives for shaping a power system that is fit for our future.

Highlighting that today's energy system is deficient in security, equity and sustainability is not about blaming the old system – we recognize that each era has its own economic and social constraints and its own technological limits.

We must **strengthen** the power system, making it more reliable and secure; **expand** it in both reach and scalability; and **evolve** it to be more sustainable and resilient.

Our role in this is critical, our purpose at Hitachi Energy is clear and crucial – to **advance a sustainable energy future for all**. This article will share how we combined our expertise in bushings and transformer monitoring to make the grid more resilient.

Transients affecting bushings equipped with monitoring equipment

High voltage capacitance graded bushings are critical components of power systems, and their failure can result in significant economic and safety consequences. According to CIGRE studies 5 to 50% transformer failures are bushing related, and this percentage increase when we look at shunt reactors failures1. A prominent failure mode is overstressing the bushing insulation, a phenomenon that often happens in combination with transients or very fast transients (VFT) in the grid.

Transients and very fast transients (VFT) are high frequency electrical disturbances that occur in power systems and can lead to the degradation of components such as bushings. The transient voltages are created in renewables applications and mostly from switching operations of breakers and disconnector operations in gas insulated switchgear (GIS) but also from harmonics generated by power electronics.

Transients and very fast transients (VFT) are high frequency electrical disturbances that occur in power systems and can lead to the degradation of components such as bushings.

For safe bushing operation, it is important that the main insulation is properly earthed. Most commonly this is done via a lid on the tap connecting the outermost conduction layer to the earthed flange. When exposed to transients, very fast transients or other high-frequency events, maintaining low impedance to earth is crucial. In cases with failures due to high impedance to earth, the failures occur in the tap region, cables connected to the tap or between the outmost layer and earth.

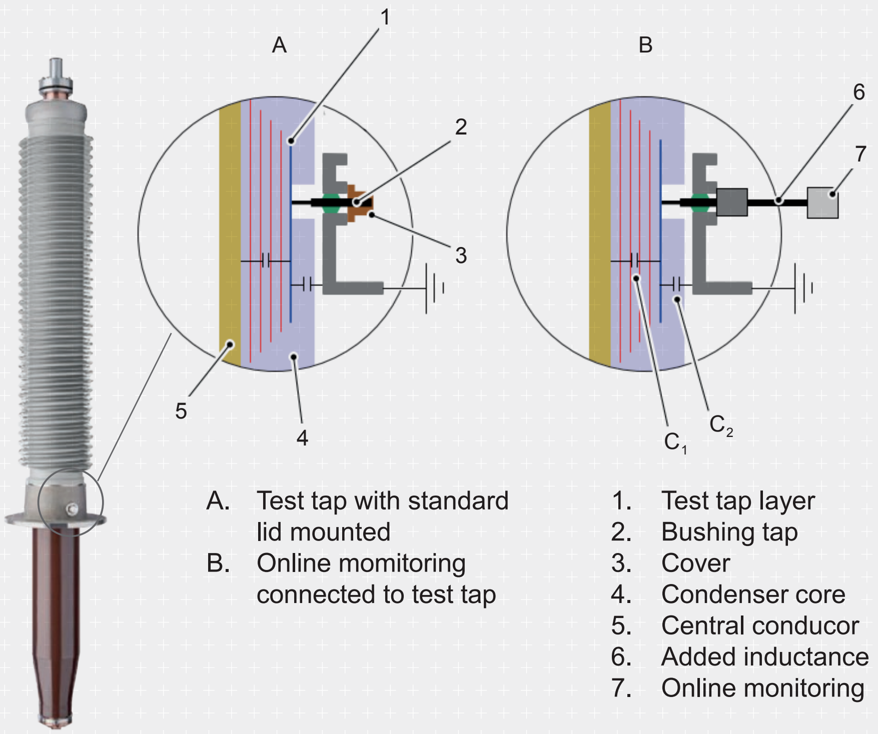

Figure 1
Principal design of a test tap. Earth connection is done via the lid (A) or via monitoring equipment (B).

Photo: Hitachi Energy

With increasing complexity in the grid, transformers are also used for improving power quality and network management, and today this means much greater connectivity and digitalization. Hitachi Energy strongly supports the adoption of high-quality monitoring equipment, including our TXpert Hub, to enhance the reliability of electrical systems and support our customers in their maintenance. However, it's important to acknowledge that most bushing monitoring systems require connection to the inner components of a capacitance graded bushing through the tap. When the earthing cover is removed from the tap, it exposes the latter to a new physical environment controlled by the monitoring equipment. The application, grid topology and impedance should be carefully evaluated when considering the implementation of any monitoring system.

Monitoring equipment is usually connected to the bushing tap to measure properties of the main insulation such as capacitance, C1, loss factor (tan δ) or partial discharge. This usually causes an increase in the total impedance of the tap, increasing the risk of failures in service. Our studies have shown that most current online monitoring solutions offered on the market have insufficient protection to safeguard the bushings from the added impedance to earth in combination with VFT.

To illustrate the importance to understand the bushing operational environment, our service teams have worked with several customers during failure investigations where bushing monitoring systems have been involved. Our teams have conducted field and laboratory measurements, and extensive simulations.

We discovered that in several cases, due to the station layout in combination with SF6 breakers (and in many cases GIS switchgear), the bushing was exposed to high frequency transients. Together with the customer it was concluded that this created voltage peaks in the test tap region much higher than the designed limits, with durations between ten to hundred nanoseconds, due to the added impedance of the bushing monitoring system.

To mitigate these issues, it is crucial to minimize the impedance between the test tap and the earthing point. This can be achieved by reducing the impedance of the cable or any attached measuring equipment. The most effective solution, offering the lowest impedance, is the lid specifically designed for the bushing. However, when additional monitoring equipment needs to be attached to the test tap, it is important to maintain control over the impedance to earth.

Figure 2
Picture of failed 400 kV RIP bushing installed on a shunt reactor with to high impedance to earth and exposed to VFT.and exposed to VFT.

Table 1 – Classes and shapes of overvoltages, standard voltage shapes and standard withstand voltage tests

Class	Low frequency		Transient		
	Continuous	Temporary	Slow-front	Fast-front	Very-fast-front
Voltage or over-voltage shapes	1/f; T_t	1/f; T_t	T_p; T_2	T_1; T_2	T_f; $1/f_1$; $1/f_2$
Range of voltage or over-voltage shapes	f = 50 Hz or 60 Hz $T_t \geq$ 3 600s	10 Hz < f < 500 Hz 0,02 s ≤ T_t ≤ 3 600 s	20 µs < T_p ≤ 5 000 µs T_2 ≤ 20 ms	0,1 µs < T_1 ≤ 20 µs T_2 ≤ 300 µs	T_f ≤ 100 ns 0,3 MHz < f_1 < 100 MHz 30 kHz < f_2 < 300 kHz
Standard voltage shapes	1/f; T_t f = 50 Hz or 60 Hz T_t [a]	1/f; T_t 48 Hz ≤ f ≤ 62 Hz T_t = 60 s	T_p; T_2 T_p = 250 µs T_2 = 2 500 µs	T_1; T_2 T_1 = 1,2 µs T_2 = 50 µs	[a]
Standard withstand voltage test	[a]	Short-duration power frequency test	Switching impulse test	Lightning impulse test	[a]

[a] To be specified by the relevant apparatus committees.

Figure 3
Table 1 from IEC 60071-1, no standard voltage shapes nor tests are defined for transients or very fast transients with rise times below 100 ns and ringing frequency above 0.3 MHz.

The Bushing Tap Protector

We have demonstrated that it is crucial to control the voltage carefully when the tap of a bushing is not solidly earthed to prevent the operating voltage or transient voltages from reaching dangerous levels. The acceptable voltage levels vary depending on the specific design of the bushing. While most monitoring systems incorporate voltage protection mechanisms, it is essential for the user to verify that the chosen scheme offers adequate long-term protection, having in mind also that in standards such as IEC there are no standardized tests for transients and very fast transients.

Our extensive studies and full-scale tests made on most devices available on the market, showed an inability to fulfill our requirements. Leading us to push the boundaries and develop a patented innovative solution. We call it the bushing tap protector (BTP).

Our extensive studies and full-scale tests made on most devices available on the market, showed an inability to fulfill our requirements. Leading us to push the boundaries and develop a patented innovative solution.

The main objective for the BTP is to reduce the impedance to earth during a transient event to protect the bushing. At the same time, it is does not affect signals of both high and low frequencies at voltage levels below 200 V as not to interfere with the monitoring systems. The BTP protection is fast enough to handle the fast rise times of VFT, 1-10 ns, as well as slower transients in the range of a few microseconds. It also needs to handle surge currents of up to 40 kA while limiting the transient pulses inside the test tap below the withstand level of the insulation. Different variants of the BTP exist to accommodate different tap designs but obtaining the same protection level.

Photo: Hitachi Energy, Shutterstock

The Bushing Tap Protector will be offered together with either Hitachi Energy Bushings or TXpert Hub monitoring systems.

TXpert Hub is the heart of Hitachi Energy's TXpert Ecosystem. It enables the user to take simple steps to digitalize a transformer; liquid filled or dry; new or retrofit; regardless of its brand.

TXpert Hub collects data from sensors, watches interdependencies, and trends their evolution based on configurable thresholds. It acts as the cyber secure bridge for communication going up from or down to the transformer, allowing safe and remote monitoring.

The new generation of TXpert Hub, powered by the latest CoreTec technology, has been built from the ground up to ease transformer digitalization, focusing on:

- Incorporating the operative experience from users of earlier versions of the system since 1991,
- The application of the latest technologies in communications and cyber security,
- Off-the-shelf retrofit solutions for dry, distribution and power transformers.

As a global leader in bushing and transformer digitalization, Hitachi Energy highly recommends the use of the tap protector, independent of the application or the site topology. The device will be showcased in May 2024 at CIWEME in Berlin and IEEE in Anaheim, to allow our customers and partners to see it and discuss pilot installations.

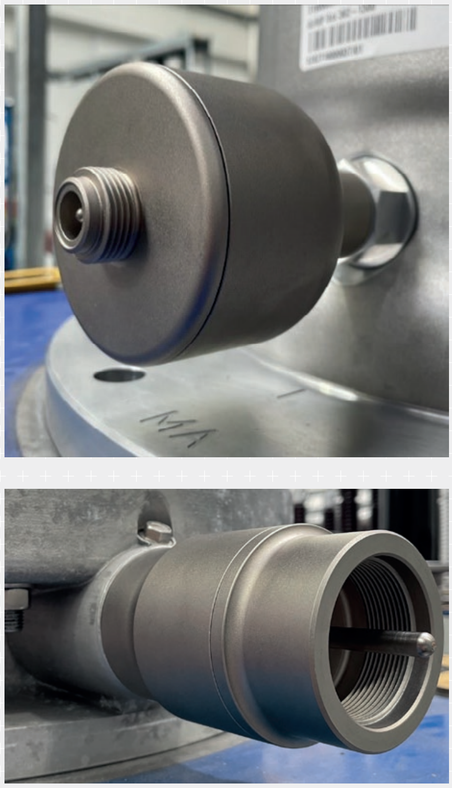

Figure 4
Pictures of two of the different designs of the BTP mounted on bushings.

Figure 5
TXpert Hub PT Basic+ includes bushing monitoring and will be offered with the Bushing Tap Protector

References
[1] CIGRE studies TB 755/2019
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Dr. **Henrik Löfås** is a Product Specialist for bushings at Hitachi Energy in Sweden and has 10 years of professional experience in the area, including design, R&D, engineering solutions and testing. He started as a scientist in the corporate research organization and later moved to the engineering. He has also been heavily involved in failure investigations and questions related to condition assessment of aged bushings. He is a member of the PT 36414 working group within IEC TC 36 as well as the newly initiated CIGRE WG A2.68. Henrik has a PhD and a M. Sc. degree both from Uppsala University, Sweden.

Lony Tehini is Hitachi Energy's Global Product Manager for transformer accessories. His experience in product management and sales over the last 10 years covers transformer conventional and digital components and services. He currently serves on the Canadian Electricity Advisory Council. Lony is a professional engineer with a degree in electrical engineering from McGill University.

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Enhanced Asset Management and Inspection Programs with NFC Technology

This article explores the transformational role of Near Field Communication (NFC) technology in advancing asset management and inspection processes. By leveraging NFC tags' enhanced security, efficiency, and seamless integration capabilities, companies can significantly improve their operations' safety, reliability, and cost-effectiveness. This article also outlines the superior features of NFC tags over traditional barcodes and QR codes, mainly focusing on their integration with IoT sensors to streamline operations and the substantial time and cost savings realized by businesses across industries.

Introduction
In the realm of data management and asset inspection, Near Field Communication (NFC) technology is transforming how companies approach their operations' safety, reliability, and efficiency. NFC tags, which allow wireless communication between a tag and an NFC-enabled device over a short distance, offer several advantages over traditional barcode and QR code systems. This article explores NFC tags' enhanced security, efficiency, and integration capabilities, particularly in inspection programs. It also examines how their linkage with IoT sensors streamlines operations, saving time and money for businesses across industries.

Enhanced Security Features of NFC Tags
NFC technology inherently possesses superior security features compared to barcodes and QR codes, primarily due to its short-range communication capability. This feature minimizes the risk of unauthorized scanning and data interception, a common vulnerability in barcode and QR code systems that can be scanned from a distance by any camera-equipped device. NFC tags can also be encrypted, adding a layer of security. This encryption ensures that even if data is intercepted, it remains indecipherable to unauthorized users. Moreover, NFC tags can be programmed to work only with specific devices or to trigger actions only after verifying the user's identity, thus providing a bespoke security solution that barcodes and QR codes cannot offer.

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Another significant advantage of NFC over its predecessors is its ability to facilitate two-way communication. This capability allows for dynamic interaction with the stored data, including updating and deleting, thereby enhancing the integrity and relevance of the information associated with each asset. In contrast, barcodes and QR codes are static, offering no such flexibility and necessitating the generation of new codes for updated information, which can lead to data management inefficiencies and inaccuracies.

Efficiency in Data Control and Management
NFC-based inspection programs significantly streamline the process of data control and management. The simplicity of tapping an NFC-enabled device to a tag for immediate data retrieval drastically reduces the time and effort required for asset inspection. This contrasts sharply with barcode and QR code systems, where aligning a scanner or camera can be cumbersome, especially in hard-to-reach or poorly lit conditions. NFC's ease of use accelerates the inspection process and minimizes the risk of human error, ensuring more accurate data collection.

NFC-based inspection programs significantly streamline the process of data control and management. The simplicity of tapping an NFC-enabled device to a tag for immediate data retrieval drastically reduces the time and effort required for asset inspection.

Furthermore, NFC tags can store a more comprehensive array of data types directly on the tag, from simple identification information to detailed inspection history. This capability allows immediate access to comprehensive asset data on-site without needing an internet connection to retrieve information from a central database. Such autonomy in data access enhances the efficiency of inspection processes, especially in remote or challenging environments where connectivity may be an issue.

Photo: Shutterstock

Seamless Integration with IoT Sensors
Integrating NFC technology with Internet of Things (IoT) sensors represents a leap forward in asset management and inspection programs. NFC provides a straightforward and user-friendly means to bridge physical assets with their digital twins in IoT ecosystems. By tapping an NFC-enabled device against a tag, data from IoT sensors—from temperature and pressure to location and movement—can be easily accessed, reviewed, and analyzed.

This integration facilitates real-time monitoring and predictive maintenance, as anomalies detected by IoT sensors can be immediately flagged and investigated. Such proactive approaches to maintenance prevent costly downtimes and extend the lifespan of assets, thereby saving companies significant resources in the long run.

Cost Savings and Operational Efficiency
Adopting NFC-based inspection and asset management programs yields considerable cost savings and operational efficiencies. The reduced time and labor involved in inspections, coupled with the enhanced accuracy of data collection, translate into direct cost savings for businesses. Moreover, the predictive maintenance facilitated by NFC and IoT integration minimizes unexpected breakdowns and the associated repair costs and operational disruptions.

In addition, the dynamic nature of NFC tags—allowing for on-the-fly updates and interactions—eliminates the need for physical replacement or reprinting that barcodes and QR codes require when information changes. This reduces material and operational costs and contributes to environmental sustainability efforts by minimizing waste.

The transformational impact of NFC technology on inspection programs and asset management underscores a pivotal shift towards more secure, efficient, and integrated operational frameworks. NFC tags outperform traditional barcode and QR code systems with superior security features. They also streamline data control and management processes, seamlessly integrate with IoT sensors, and drive considerable cost savings and operational efficiencies.

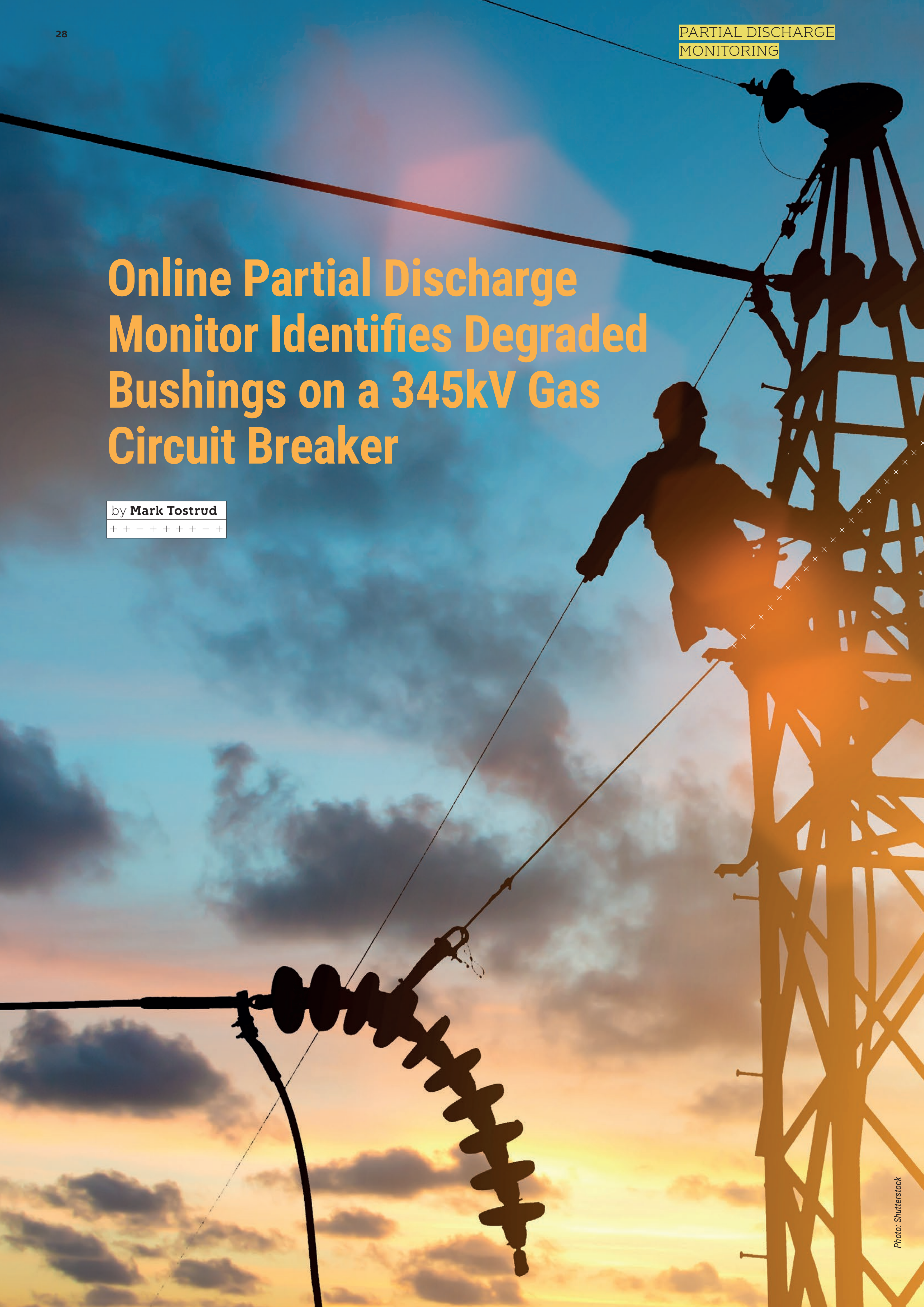
A critical advantage of NFC technology is its compatibility with various devices, including smartphones, specialized readers, and tablets. This versatility ensures that NFC-based solutions are accessible to a broad audience, facilitating widespread adoption across various industries. The ability to use NFC with everyday devices like smartphones dramatically lowers the barrier to entry, enabling more organizations to leverage this technology without significant upfront investment in specialized equipment.

Moreover, NFC technology presents an intrinsically safe solution for operations in hazardous environments. When used with specialized readers designed to meet intrinsic safety standards, NFC can safely operate in areas where explosive materials are present, reducing the risk of ignition. This feature is precious in industries such as oil and gas, chemical manufacturing, and mining, where safety is paramount.

Conclusion
NFC technology is a beacon of innovation in asset safety and reliability. Its encryption capabilities and short-range communication offer unmatched security, mitigating the risk of unauthorized access and data breaches. The ease with which NFC tags can be read by smartphones, specialized readers, and tablets enhances their practicality, ensuring that crucial asset information is always at the fingertips of those who need it. Furthermore, the compatibility of NFC with intrinsically safe readers opens new avenues for its application in hazardous environments, reinforcing its role as a versatile and secure solution. As companies continue to navigate the challenges of efficient asset management in an increasingly complex world, adopting NFC-based programs is not just a strategic advantage but a pathway to future-proofing operations, embracing sustainability, and achieving operational excellence.


Author:
Martin Robinson
Founder, Owner and CEO of IRISS Inc.

Martin Robinson is the founder, owner, and CEO of IRISS Inc., a leading manufacturer of infrared inspection windows. Robinson focuses on innovation and is a pioneer of Electrical Maintenance Safety Devices (EMSDs) that help protect technicians from harm while protecting their companies' bottom line. He holds several patents for condition-based maintenance devices and has designed multiple maintenance programs that include infrared, ultrasound, partial discharge testing, non-destructive testing (NDT) and energy management strategies. He holds a NEBOSH certificate in Occupational Safety and Health, an IAM Certificate in Asset Management, is a certified Level III Thermographer, a Certified Maintenance and Reliability Professional (CMRP) and a Certified Reliability Leader (CRL). He is a member of IEEE, NFPA and is a standing member on the technical committee CSA Z463 guidelines on maintenance of electrical systems.



Online Partial Discharge Monitor Identifies Degraded Bushings on a 345kV Gas Circuit Breaker

by **Mark Tostrud**

Photo: Shutterstock

One of the earliest indicators that high voltage electrical assets are beginning to degrade is the presence of partial discharges. IEC60270 defines partial discharge as a localized electrical discharge that only partially bridges the insulation between conductors, and which can or cannot occur adjacent to a conductor. Partial discharges can take several forms:

1. Void discharges occur in defects in the solid insulation. The discharges occur because the breakdown strength of the void is much lower than the breakdown strength of the solid insulation around it. Void discharges typically occur in cables, bushings, and transformers. Void discharges can be highly destructive to insulation and in time will typically result in complete failure of the insulation.
2. Surface discharges occur along the surface of insulation rather than in voids in the insulation. Repeated surface discharges will often result in surface tracking which is easily seen by the eye. Surface discharges can occur in air insulated switchgear, on the external weather sheds of insulators and bushings, and in motors and generators. Surface discharges can significantly increase in the presence of surface contamination, humidity, fog, and light rain.
3. Corona discharges occur when the air surrounding a conductor carrying high voltage becomes ionized allowing the charge to continuously bleed off the conductor into the air. Corona often radiates from sharp surfaces or irregularities on the surface of the conductor.
4. Arcing discharges are prolonged electrical discharges produced by the electrical breakdown of a gas. Plasma is an example produced when current flows through air, or any other normally non-conductive medium.

Mark Tostrud is the Technology Officer for Dynamic Ratings, Inc. located in Sussex, Wisconsin. He joined Dynamic Ratings in the fall of 2006 and has been instrumental in helping Dynamic Ratings customers incorporate online monitoring into their condition-based maintenance programs. Mark's goal is to improve the understanding of the technologies and analytics the monitors offer so customers can get the most out of their monitoring systems, improve their system performance and make better asset management decisions. Prior to his present position, Mark was a Construction & Maintenance Supervisor at We Energies. During his 19 years at We Energies, Mark lead the implementation of many of condition-based monitoring programs for substation equipment. Mark is a past officer of the Doble Oil Committee, and was an active member on various Doble Committees and Subcommittees including the Transformers, Insulating Materials, DGA of LTCs and others. Mark is a registered professional engineer in the State of Wisconsin.

Partial discharges (PDs) can pose a significant threat to high voltage electrical equipment. Partial Discharge is also typically the first indicator that an electrical asset is degrading. If left undetected or if corrective actions are not taken, partial discharges can lead to costly electrical failures. Thankfully, technologies exist which allow the detection of partial discharges in energized electrical equipment. PD cannot be measured directly, however, its energy by-products such as electrical transients, electromagnetic emissions, sound, light, and heat can be measured. Of these, the monitoring of electrical transients (i.e. electrical partial discharge monitoring) is the easiest and most cost effective to implement continuously online. Electrical partial discharge monitoring also offers the ability to utilize a single sensor for both bushing monitoring as well as online partial discharge monitoring.

As part of a comprehensive online monitoring program, an electrical utility installed key gas DGA, bushing and partial discharge monitoring on their generator step up transformers.

> **Partial Discharge is typically the first indicator that an electrical asset is degrading.**

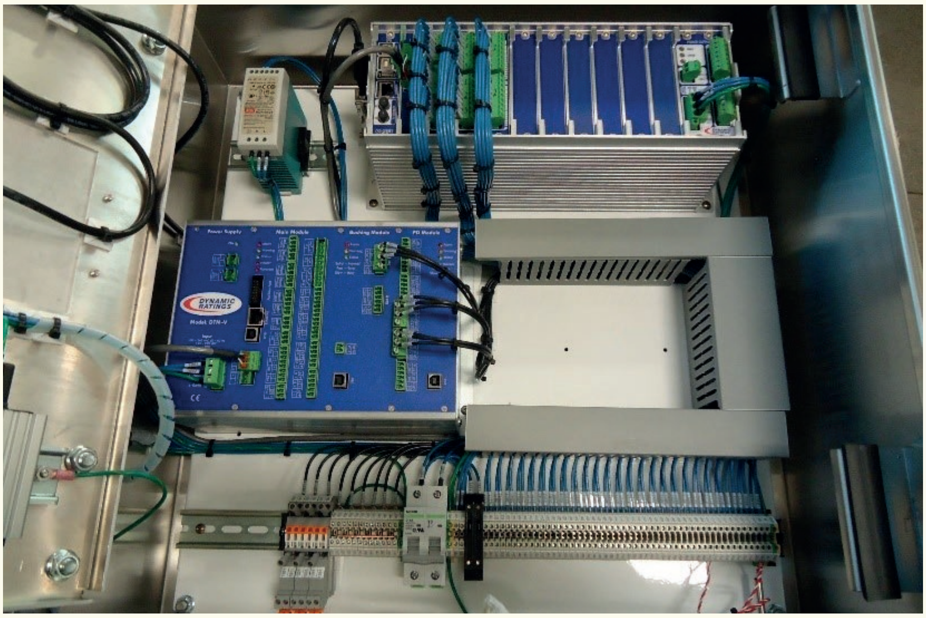


Figure 1: Dynamic Ratings Comprehensive Transformer Monitoring System

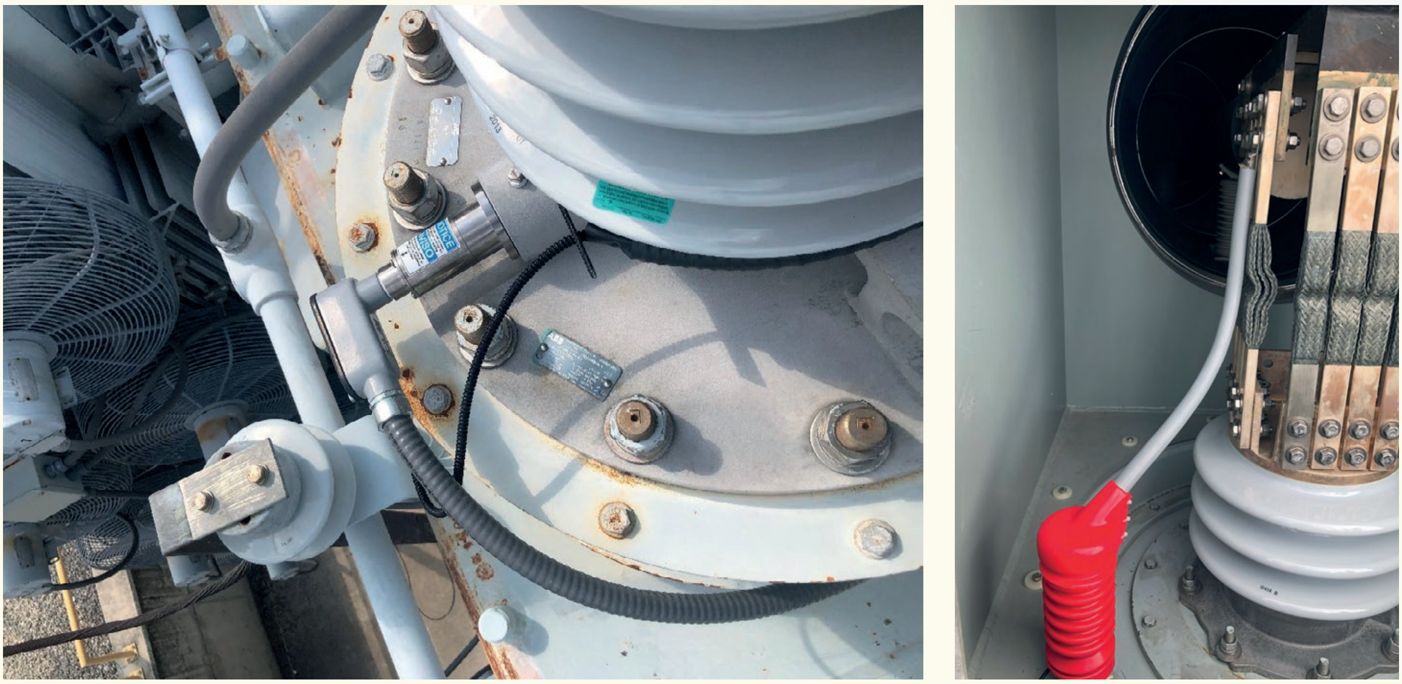


Figure 2: Bushing and Partial Discharge Sensor Installed on a GSU

Photo: Dynamic Ratings, Shutterstock

Since the analysis identified that the discharges were coming from outside the transformer, Dynamic Ratings recommended that the customer scan the high voltage yard with a corona camera.

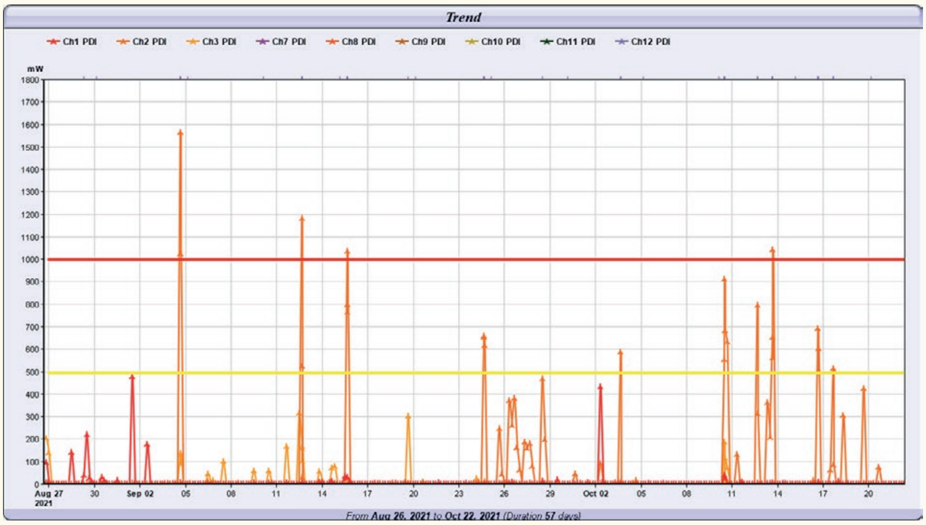


Figure 3: Trend of the partial discharge intensity

Using the corona camera, the customer was able to identify multiple sources of partial discharges. The most concerning problem was an issue that was identified with the bushings on the high voltage SF6 breaker protecting the transformer. Large amounts of partial discharge were eminating from the bushing cap and a visual inspection of the bushing cap identified corrosion problems on this bushing as well as 12 other GCB bushings in the plant. As a result of the partial discharge monitoring and the follow up corona camera inspections, the customer contacted the breaker manufacturer to perform a visual inspection of the HV gas

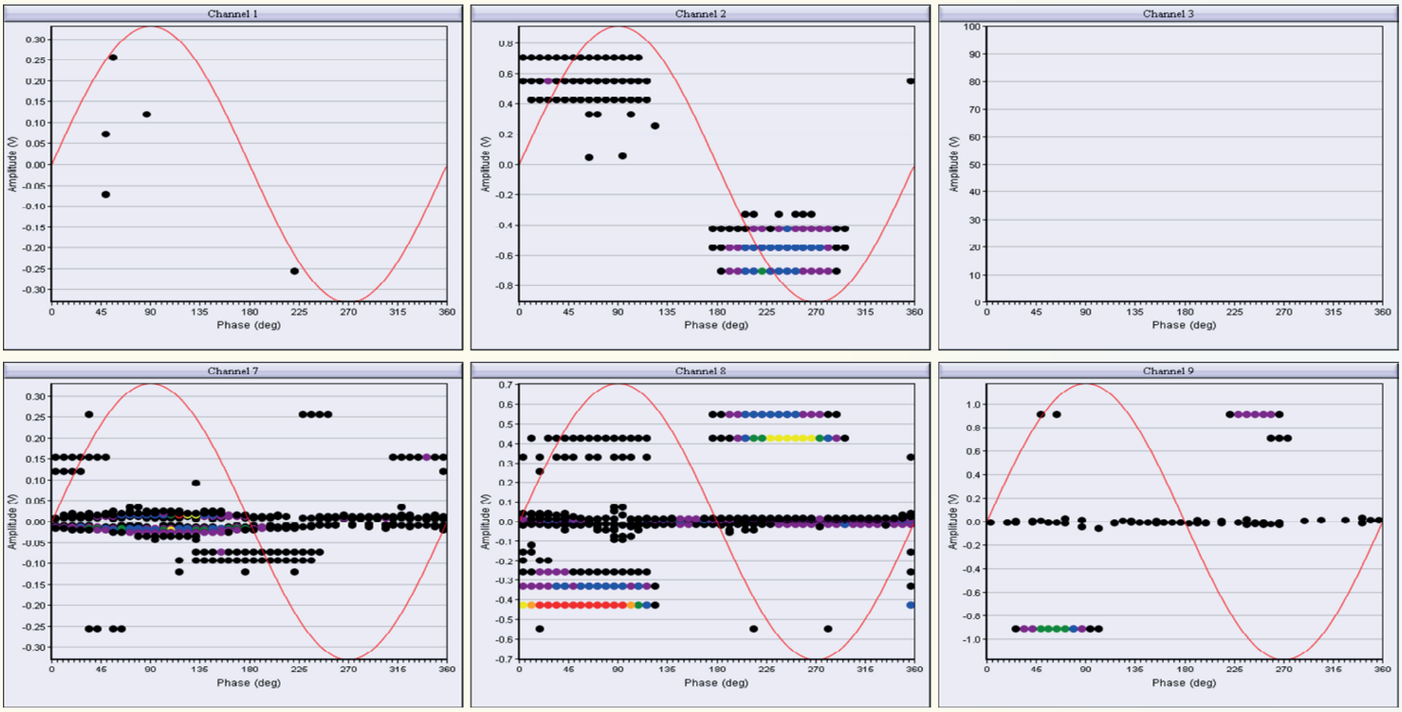


Figure 3: Trend of the partial discharge intensity

The bushing and PD system consisted of sensors installed in the test taps of the high voltage bushings, Rogowski coils installed around the porcelain skirt closest to the bushing flange, and coupling capacitors connected to the bolted connections of the flexible links connected to the LV bushings. Coupling capacitors were used to monitor the LV winding of the transformer since the LV bushings did not have test taps. Pictures of the monitoring system and sensor installations are provided in figures 1 and 2.

Shortly after the monitor was installed, the customer began receiving alarms due to high levels of partial discharge intensity. Partial discharge intensity is an estimate of the energy of the partial discharge. The trend chart shown in figure 3, shows that the partial discharge intensity from all sensors was acceptable except for periodic spikes associated with activity on channel 2 of the monitor which exceeded the warning and alarm thresholds.

Since the analysis identified that the discharges were coming from outside the transformer, Dynamic Ratings recommended that the customer scan the high voltage yard with a corona camera.

circuit breakers. The manufacturer has recommended the replacement of 12 bushings on the GCB's protecting the transformers.

Online condition monitoring of high voltage electrical equipment is an effective way to identify degrading electrical assets at an early stage. Utilizing a comprehensive approach allows utilities to implement technologies to identify and prevent nearly all failure modes typically found in their high voltage electrical assets. While technologies like DGA and online bushing monitoring have been used for years to identify degrading high voltage electrical

Photo: Dynamic Ratings

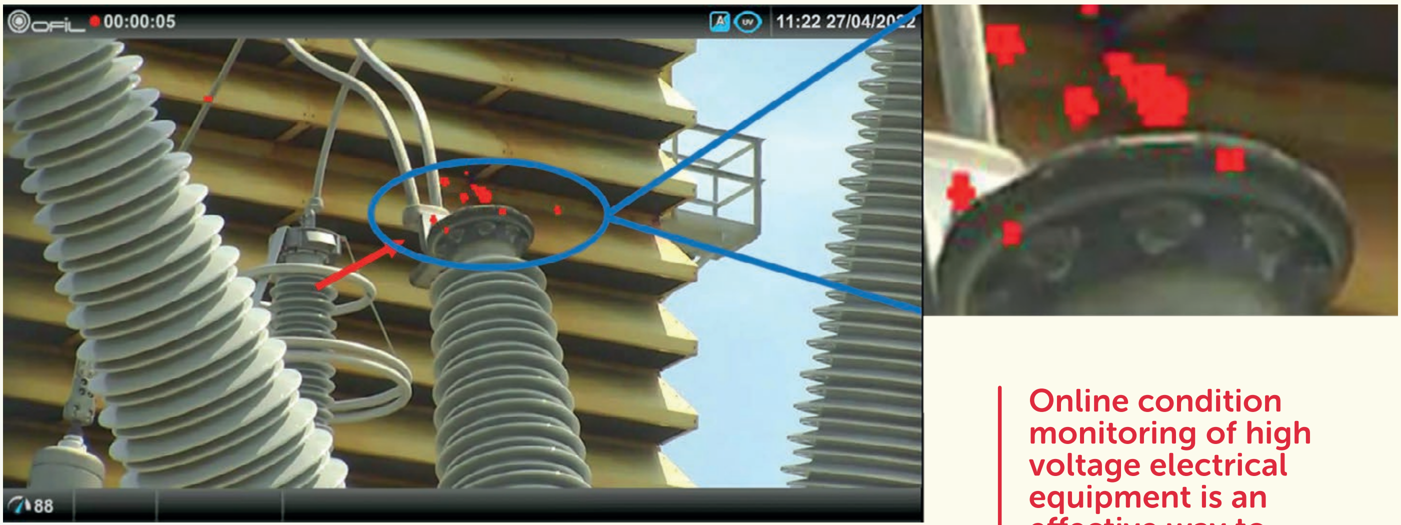


Figure 5: Corona camera image of the transformer HV SF6 breaker

Online condition monitoring of high voltage electrical equipment is an effective way to identify degrading electrical assets at an early stage.

assets, implementation of online partial discharge monitoring is not as common. However, since partial discharge is typically the first indicator that an electrical asset is degrading, it makes sense to include partial discharge monitoring as part of a comprehensive approach to monitoring your high voltage assets.

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COMPANY SPOTLIGHT
DELTA-X RESEARCH

> "Applying science to transformer risk management

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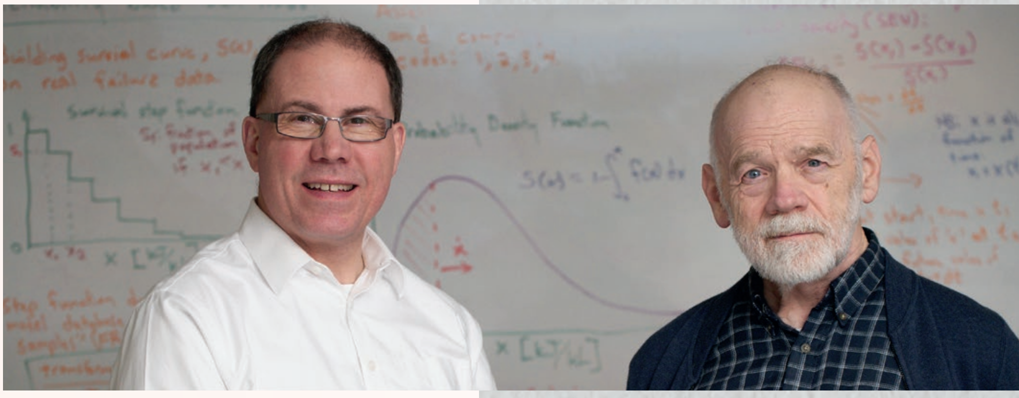

DELTA-X RESEARCH is trusted by 14 of the top 20 electric utilities in the USA to help safeguard their critical assets. Founded in 1992 and headquartered in Victoria, BC, Canada, Delta-X Research provides science-based decision-support tools that help electric utilities and energy-intensive companies assess the health and operational risk of their high-voltage apparatus.

Assessing high-value assets (like power transformers) using conventional diagnostic methods does not always detect fault conditions and occasionally raises false alarms. A better approach is to understand the relationship between observable test parameters (e.g. dissolved gases) and actual equipment failures. Using advanced statistical analysis, apparatus at risk-of-failure is more correctly identified and the risk of continued operation can be explicitly quantified.

Pushing past conventional paradigms

Our decision-support tools – Transformer Oil Analyst™ (TOA) and Monitor Watch – manage and interpret insulating liquid test data, including dissolved gas analysis (DGA) to:

- More correctly identify abnormal apparatus behavior to avoid unplanned outages and false alarms.
- Prioritize your transformer fleet for repair-or-replace decisions;
- Maximize return-on-investment on aging assets and capital expenditures;
- Evaluate risk for better risk management and efficient maintenance.

TOA uses Reliability-based Dissolved Gas Analysis, an innovative method for interpreting DGA data that more correctly detects transformer abnormalities earlier and avoids false alarms. With Delta-X Research's reliability-entered approach, a utility's maintenance and asset management strategies can be elevated without changing any fundamental business processes. We lead with science.

Our products and services are built using the scientific method. This means we welcome questioning and constructive criticism because they help us improve our offerings. In a conservative industry, Delta-X Research is trusted to innovate in a responsible way.

We work hard to make it easy

Interpreting test and monitor data can be hard... our job is to make the complex simple. We invite customers to talk directly to our scientists so you can ask questions and get the information you need to make critical decisions with confidence. Our open, secure solutions give you unfettered access to leverage your data 24/7.

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Commitment to science means commitment to objectivity, which gives us the freedom to be independent and neutral. We work with all other companies and laboratories, so you can choose your suppliers to assemble a complete best-in-class and best-fit solution. Regardless of the data source, knowing that your data is secure and is interpreted in a consistent manner supported by sound science allows you to manage risk with confidence.

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The evolution of transformer reliability and maintenance and the relationship to monitoring and diagnostic technology

by **Todd Hurst**

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THE MID-20TH CENTURY SAW THE INTRODUCTION OF DGA (DISSOLVED GAS ANALYSIS) AS A POWERFUL DIAGNOSTIC TOOL FOR ASSESSING THE CONDITION OF TRANSFORMER INSULATION. DGA INVOLVES ANALYZING GASES DISSOLVED IN TRANSFORMER OIL TO DETECT AND IDENTIFY INCIPIENT FAULTS SUCH AS OVERHEATING, ARCING, AND PARTIAL DISCHARGES. THIS TECHNIQUE REVOLUTIONIZED TRANSFORMER DIAGNOSTICS, ENABLING EARLY DETECTION OF POTENTIAL ISSUES AND PROACTIVE MAINTENANCE STRATEGIES.

Todd Hurst is the Executive Vice President at SDMyers, LLC, in Tallmadge, Ohio, where he leads strategic growth and innovation. SDMyers is an electric reliability company specializing in transformer maintenance, fluid testing, field service, and training. As a dynamic leader in a broad range of roles and industries, Todd is passionate about leading teams to right-fit solutions for the industry and customer needs. He presents a leadership style that prioritizes serving the greater good through setting vision, empowering team members, and building trust. Before joining SDMyers, Todd had various executive roles in the plastics and resins manufacturing space and marketing leadership in consumer goods. Todd holds a Bachelor's degree in Marketing & Management, Direct Marketing, Entrepreneurship, and Economics from the University of Mount Union.

Some History

The evolution of monitoring and diagnostic technology for liquid-filled transformers has been marked by significant advancements driven by technological innovations and industry demands for improved reliability and efficiency. In the early days, (late-19th century) of transformers, monitoring, and diagnostic practices primarily relied on visual inspections of transformer components such as bushings, windings, and insulation materials. These inspections were limited in scope and effectiveness, often requiring transformers to be taken offline for detailed examination.

The mid-20th century saw the introduction of DGA (Dissolved Gas Analysis) as a powerful diagnostic tool for assessing the condition of transformer insulation. DGA involves analyzing gases dissolved in transformer oil to detect and identify incipient faults such as overheating, arcing, and partial discharges. This technique revolutionized transformer diagnostics, enabling early detection of potential issues and proactive maintenance strategies.

With the advent of telecommunications and computing technologies (late 20th century), remote monitoring systems for liquid-filled transformers emerged. These systems allowed for real-time monitoring of transformer parameters such as temperature, oil level, moisture, and gas concentrations from a central control center. Remote monitoring systems improved the efficiency of maintenance activities and facilitated potentially faster response to abnormal operating conditions.

Current State

Early fault detection via multi-gas monitoring systems allows for the simultaneous measurement of multiple gases dissolved in the transformer oil, such as methane, ethane, ethylene, acetylene, hydrogen, and carbon monoxide. As noted, DGA is a widely used method for detecting incipient faults within transformers. Increases in gas concentrations can indicate various faults, including overheating, insulation degradation, partial discharges, and arcing. Early detection of these faults enables timely intervention, preventing potential failures, minimizing downtime, and extending the life of the transformer.

Many recently manufactured transformers implement advanced sensors within the transformer to provide real-time data on parameters such as temperature, oil level, pressure, and gas concentrations. These sensors can be integrated with Internet of Things (IoT) platforms for remote monitoring.

Leveraging remote monitoring capabilities enables operators to access transformers' data regardless of location. This facilitates timely decision-making and allows for predictive maintenance strategies to be implemented. Integration with asset management systems provides a holistic view of transformer health, maintenance history, and operational data. This comprehensive approach enables informed decision-making regarding maintenance schedules and resource allocation. By combining data from various monitoring technologies and employing predictive maintenance strategies, maintenance activities can be scheduled based on the actual condition of the transformer and supplement predefined intervals when required. This optimizes maintenance efforts while maximizing reliability.

Predictive maintenance assisted by AI (artificial intelligence) algorithms can analyze large volumes of data collected from sensors to identify patterns indicative of impending failures or abnormalities in transformer behavior. By predicting potential issues before they occur, AI enables proactive maintenance interventions, minimizing downtime and reducing the risk of catastrophic failures. AI-powered diagnostic systems can automatically detect and diagnose faults within transformers by analyzing data from various sources, such as dissolved gas analysis (DGA), temperature sensors, and load measurements. This automated process accelerates fault identification, allowing for corrective actions to be taken.

Photo: Shutterstock

What's Next

The future of monitoring and diagnostic technology for liquid-filled transformers is poised for further advancements driven by emerging technologies, evolving industry needs, and the growing complexity of power distribution networks. Future monitoring systems for liquid-filled transformers will likely incorporate more advanced sensors capable of measuring a wider range of parameters with higher accuracy and precision. These sensors may include advanced optical sensors, acoustic sensors, nanotechnology-based sensors, and IoT-enabled devices, providing comprehensive insights into transformer health and performance.

Data analytics and AI will continue to play a crucial role in transformer monitoring and diagnostics. Advanced AI algorithms will be deployed to analyze vast amounts of sensor data, identifying patterns, anomalies, and trends indicative of potential faults or abnormalities. Predictive analytics techniques will enable proactive maintenance strategies, further improving reliability and reducing downtime.

The future of transformer maintenance will shift towards predictive and condition-based monitoring approaches. Predictive maintenance models will leverage AI and machine learning algorithms to forecast potential failures and

PREDICTIVE MAINTENANCE ASSISTED BY AI (ARTIFICIAL INTELLIGENCE) ALGORITHMS CAN ANALYZE LARGE VOLUMES OF DATA COLLECTED FROM SENSORS TO IDENTIFY PATTERNS INDICATIVE OF IMPENDING FAILURES OR ABNORMALITIES IN TRANSFORMER BEHAVIOR. BY PREDICTING POTENTIAL ISSUES BEFORE THEY OCCUR, AI ENABLES PROACTIVE MAINTENANCE INTERVENTIONS, MINIMIZING DOWNTIME AND REDUCING THE RISK OF CATASTROPHIC FAILURES.

prescribe preventive measures based on real-time data and historical trends. Condition-based monitoring systems will enable continuous assessment of transformer health, allowing for timely intervention and optimization of maintenance schedules.

Remote monitoring and control capabilities will be further enhanced, enabling operators to access and manage transformers from anywhere in the world remotely. Advanced communication technologies like 5G and satellite connectivity will facilitate real-time data transmission and remote diagnostics, improving operational efficiency and responsiveness.


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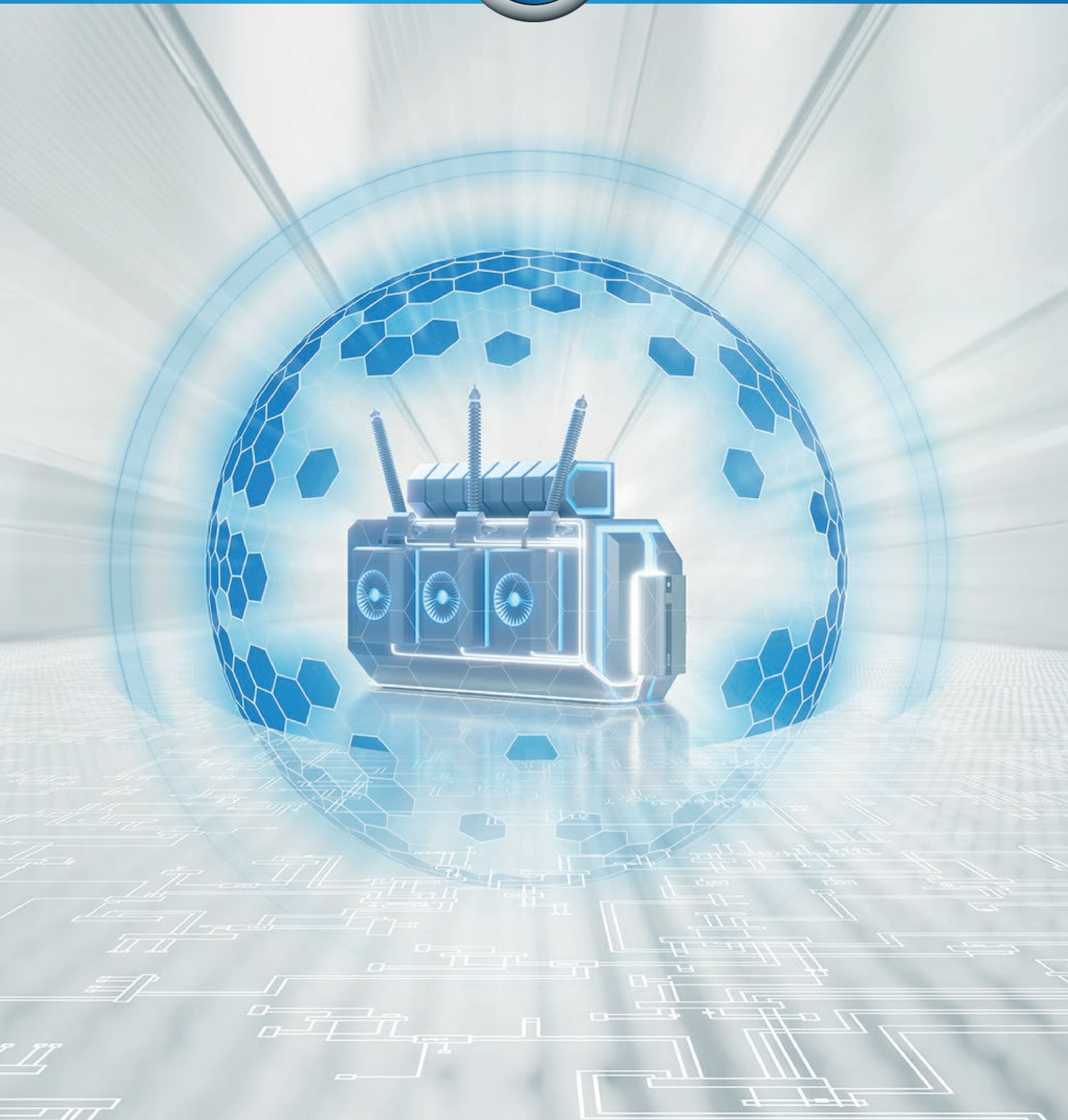
Emerging technologies such as quantum computing, advanced materials, and even robotics may also influence the future of transformer monitoring and diagnostics. Quantum computing algorithms could revolutionize data analysis and optimization tasks, while advanced materials may lead to more durable and reliable transformer components. Drones may be employed to inspect transformers in challenging environments remotely.

The AI Reality

AI technology, specifically Generative AI with Large Language Models (LLMs), has grown exponentially and can potentially provide significant benefits to society. However, these generative tools have yet to be fully integrated into all areas of transformer monitoring and diagnostics. This presents an opportunity for Reliability Engineers, Electrical Subject Matter Experts, and Asset Managers to enhance their transformer diagnostic training and substantially increase their knowledge to support their transformer reliability philosophy. By leveraging Generative AI, they can gain a deeper understanding of transformer monitoring and diagnostics and improve their reliability programs. It's essential to invest the effort now with the available technology to reap the benefits in the long run.

Overall, the evolution of monitoring and diagnostic technology for liquid-filled transformers has been characterized by advancements in sensor technology, data analytics, and limited artificial intelligence. These advancements have significantly improved the reliability, efficiency, and safety of liquid-filled transformers in power distribution networks. The exact when and how of the emerging technologies is yet to be determined. What is known is that the evolution will continue, and so will the need for a resilient electric power system.

UNDERSTAND THE CONDITION OF POWER TRANSFORMERS & OPTIMIZE THE MAINTENANCE STRATEGY



An aging fleet of power transformer with increasing fault susceptibility and fluctuating transformer loads, due to the feed-in of renewable energy are just some of the challenges facing the electric power industry. In addition, the constant expansion of the grid leads to an increased demand for new transformers, which in turn leads to higher costs and long delivery times. The bottom line is that the installed old equipment is more loaded and new equipment takes time to acquire.

Therefore, monitoring and diagnosis of transformers becomes more important to understand the exact condition of the assets. Based on the accurate diagnosis, life-extending measures can be initiated on existing transformers to keep them on the grid for a longer time span, alleviating the supply shortage while maximizing the value of the assets. This ensures reliability for a safe operation.

MONITORING AND DIAGNOSIS OF TRANSFORMERS BECOMES MORE IMPORTANT TO UNDERSTAND THE EXACT CONDITION OF THE ASSETS. BASED ON THE ACCURATE DIAGNOSIS, LIFE-EXTENDING MEASURES CAN BE INITIATED ON EXISTING TRANSFORMERS TO KEEP THEM ON THE GRID FOR A LONGER TIME SPAN, ALLEVIATING THE SUPPLY SHORTAGE WHILE MAXIMIZING THE VALUE OF THE ASSETS.

Data is needed to know the condition! Understanding the condition of a transformer is very similar to the human health. A diagnosis is also based on symptoms. Measurements can help to categorize the symptoms and provide information about possible diseases. Like the human blood count, the analysis of the insulating medium oil provides information about the state of health and indicates thermal and electrical faults.

According to IEC 60599, the dissolved and free gas analysis (DGA) is one of the most widely used diagnostic tools for detecting and evaluating faults in oil-insulated transformers [1]. The key gases can be measured either by taking a sample and subsequently analyzing it in the laboratory, which is done at a certain time interval (e.g. yearly). To minimize the uncertainty between these intervals an additional option is to install a DGA sensor, which has been described as “the heart of on-line monitoring” [2]. Sensors that collect real-time data under real operating conditions enable continuous condition assessment, which facilitates the transition to condition-based maintenance. The gained transparency supports decision making and optimized planning of maintenance and repair measures.

Transformers generate a lot of data over their lifetime. But what does data mean for a transformer and its health?

For an accurate diagnosis, it is best to include and combine several pieces of information. The large amount of data produced by the transformer makes it possible to determine its failure more precisely and at an early stage. Just like humans, where the diagnosis of diseases is based on certain symptoms. In the case of symptoms such as a runny nose, loss of taste and fever, the doctor could suspect a corona infection. He can then confirm his assumption with specific tests, such as a PCR test, in order to treat the disease correctly.

The same approach can be applied to the energy sector. Based on the early warning system, targeted on-site testing can be initiated. Maintenance is carried out when it is needed and can be scheduled when the transformer is shut down anyway.

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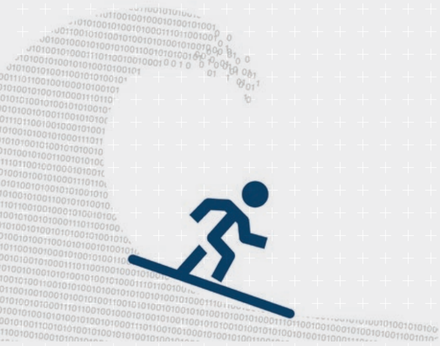
DURING THE LIFE TIME OF A POWER TRANSFORMER, A WIDE VARIETY OF DATA CAN BE COLLECTED. MASTER DATA, MEASUREMENT DATA FROM PHYSICAL INSPECTIONS AND TESTS, AND CONTINUOUS TIME SERIES FROM AN INCREASING NUMBER OF INSTALLED SENSORS.

Lots of Data can be Overwhelming!

During the life time of a power transformer, a wide variety of data can be collected. Master data, measurement data from physical inspections and test, and continuous time series from an increasing number of installed sensors.

In practice, this data is often scattered across different systems and drives. This makes it difficult to maintain an overview and perform a holistic assessment. But it is not just the distributed data that is a challenge - interpreting it correctly is also a challenge. The ppm measurements from the laboratory report are usually incomprehensible to the layperson, as most of the people looking at the results have not studied chemistry. Digital solutions in the form of assistant and analytical tool make the process easier!



TESSA® ASSET PERFORMANCE MANAGEMENT IS AN INTEGRATED PLATFORM FOR COLLECTING AND STORING ALL INSPECTION AND SENSOR DATA IN A CENTRAL DATABASE, COMBINED IN A USER-FRIENDLY INTERFACE PROVIDING CONCISE INFORMATION AND AVAILABLE ON ANY DEVICE.

Discover Data-Driven Asset Management

Maschinenfabrik Reinhausen offers a customized and modular automation solution for monitoring and diagnostics of power transformers.

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TESSA® Asset **P**erformance **M**anagement is an integrated platform for collecting and storing all inspection and sensor data in a central database, combined in a user-friendly interface providing concise information and available on any device.

Photo: Maschinenfabrik Reinhausen

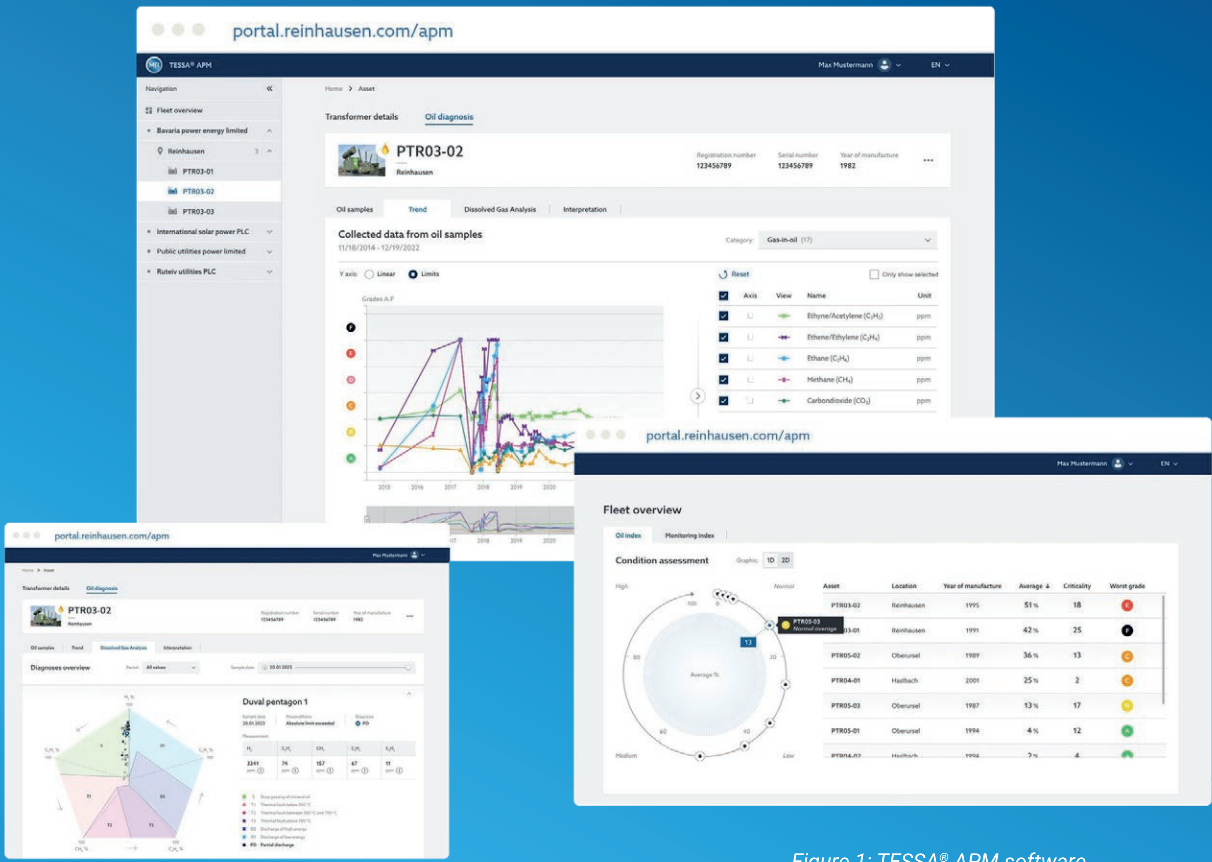

Figure 1: TESSA® APM software

This helps to identify and track the condition of power transformers. Gain an overview of the condition of your fleet and gain meaningful insights into the health of individual assets along with their individual components. Transform your inspection and sensor data into advanced analytics and identify irregularities at an early stage. Evaluations based on the latest standards and a unique algorithm that provides actionable recommendations.

TESSA® APM supports Asset- and Service Manager in the ISO 55000 process by simplifying the time-consuming, manual analysis process.

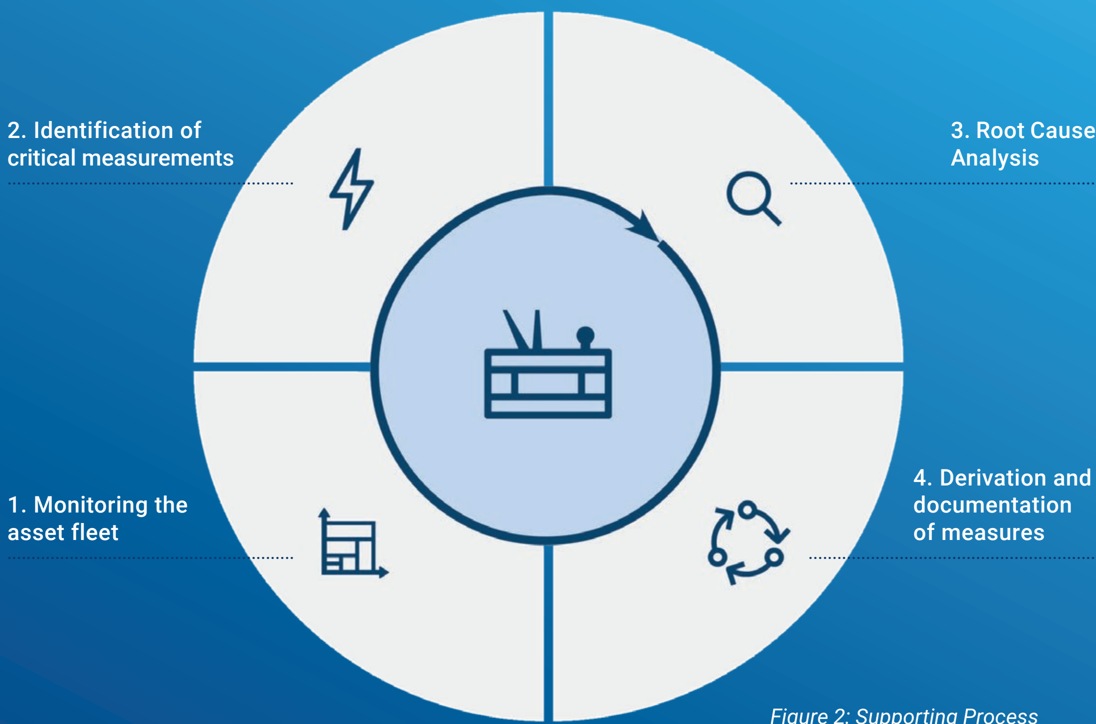

Figure 2: Supporting Process

Transformers Digitalization

Benefits

- Save time with process automation
- Save cost through life-time optimization
- Understandable assessments and analysis for further decision making
- Based on transformer expert knowledge




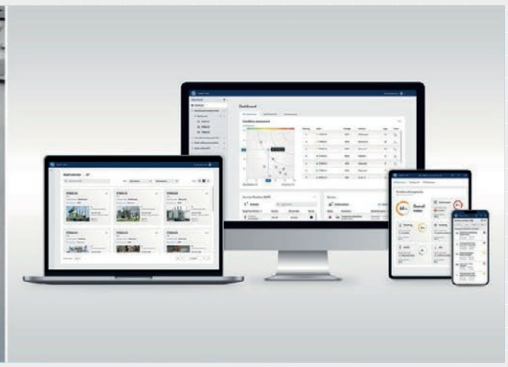

Photo: Maschinenfabrik Reinhausen

Organize all the master data (e.g. nameplate information) relevant to the assessment as each transformer is unique and must be analyzed according to its individual characteristics. Store all measurement data in a structured way, either time series from sensors such as MSENSE® DGA or point measurements from laboratory oil test!

Recognize increasing values with configurable alarms that provide information when thresholds are reached. Enable life-prolonging actions to be taken before it becomes an expensive repair or even a failure with a power outage.

Visualize data automatically in a graphical or tabular trend view. A custom selection of measured values, axes and time periods can be used for a detailed analysis of historical trends. Compare past data with current data and identify trends by assessing the deltas and the rate of increase over different time periods.

Assess transformers and their components based on health indices according to international standards such as CIGRE, IEC and IEEE. The condition of the fleet is displayed in a condition and risk matrix with a prioritized ranking. This helps to easily identify the critical units! A powerful visualization with an advanced grade system displays single measurements with their respective thresholds either in a table view or in graphical trend chart. Make comparisons of current and historical measurements and trends of health and conditions indices.

Analyze root-cause using common failure classification methods such as Duval Triangle and pentagon. Unique algorithms show the probability estimate for the most likely transformer problems with a fault description.

Define required actions with recommendations based on standards such as IEEE C57.104 from 2019 or unique algorithm. Support decision making process and optimize maintenance planning.

Document the findings and generate easy interpretation reports with a single click. Customize the report layout to match your corporate design. All relevant files of any type can be stored with the associated asset or component for quick access.

Leonhard Link studied Business Administration at the OTH Regensburg. During his studies, he completed an internship at Maschinenfabrik Reinhausen in the field of software and business model development, then stayed on as a student trainee and wrote his bachelor's thesis on the topic of requirements evaluation and documentation in agile software development. He has been a product manager of TESSA® APM for more than one and a half years.

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Ensuring Grid Reliability: Integrating Digital HV Switchgear and Artificial Intelligence

by **Saad Habib**
and **Saifa Khalid**

Photo: Shutterstock

- The US HV switchgear market is evolving with advancements in smart grid development, driven by the deployment of renewable energy sources and the widespread adoption of electric vehicles (EVs).
- Using digital HV switchgear and integrating artificial intelligence (AI) into HV switchgear will amplify the grid's capacity to cater to bottlenecks and provide tangible results in addressing evolving energy challenges.
- HV switchgear is essential to maintain grid stability and flexibility amidst high demand and intermittent supply.

The power grid dynamics are evolving in response to a shifting energy landscape, marked by a surge in energy demand from electric vehicle charging and the integration of intermittent renewable energy resources at high voltage (HV) levels. This evolution necessitates intelligent autonomous monitoring and control solutions to manage the changing grid conditions effectively.

High-voltage (HV) switchgear is a key equipment to maintain power grid stability; however, traditional monitoring methods are becoming inefficient for HV switchgear. Advancements in technology, data science, and artificial intelligence (AI) have been crucial to upgrade HV switchgear monitoring capabilities to make it compatible with the evolving energy landscape. Integrating HV switchgear with these advancements is expected to facilitate grid optimization, especially in the US, where it will contribute positively to the resilience of the energy landscape.

Dynamics in the US Market

The US HV switchgear market is evolving with advancements in smart grid development, driven by the deployment of renewable energy sources and the widespread adoption of electric vehicles (EVs). The government is actively promoting the deployment of grid infrastructure to prevent fluctuation and strain due to the rising demand. Multiple challenges like intermittent power outputs from renewables, fluctuating load patterns from EV charging, and bidirectional power flow highlight the importance of innovative grid designs. There is a need to redefine the operational structures of grid management by incorporating advanced functionalities in HV equipment to overcome these challenges. The US government has introduced several grid management and deployment initiatives, including the GRIP Program, to cater to grid challenges.

Grid Resilience and Innovation Partnerships (GRIP) Program

The government has funded the Grid Resilience and Innovation Partnerships (GRIP) Program to modernize the grid infrastructure. On November 18th, 2022, the Department of Energy (DOE) unveiled a historic USD 10.5 billion investment plan through GRIP, supported by the Bipartisan Infrastructure Law. This funding targets the expansion and modernization of the national electricity grid, marking the most significant single federal investment in critical transmission and distribution infrastructure. The figure below shows the investment division across multiple programs under GRIP Investment.

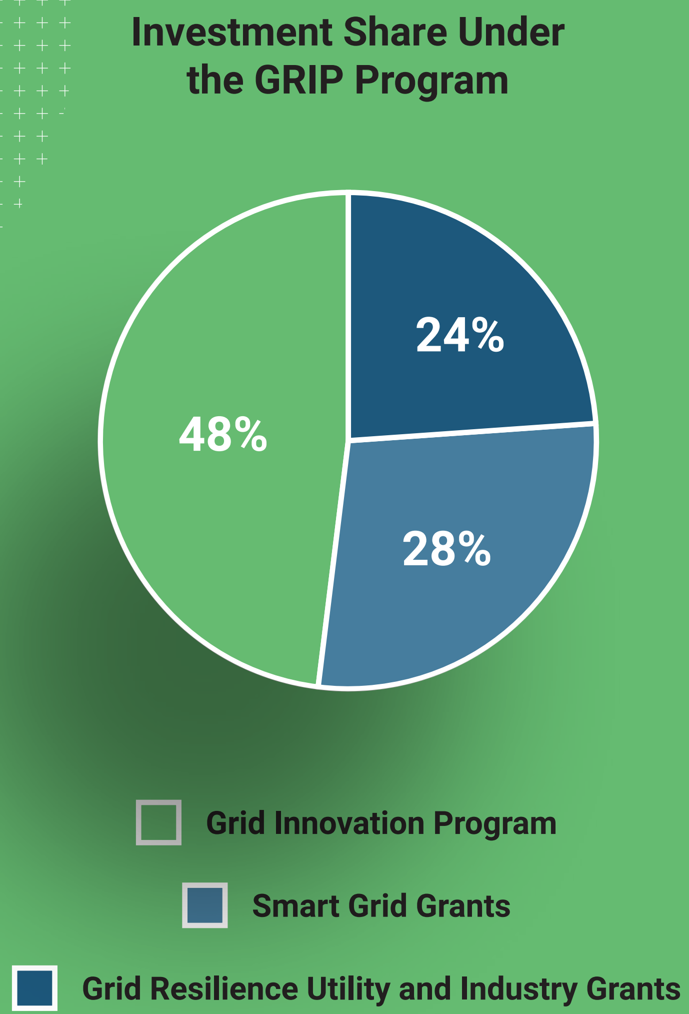
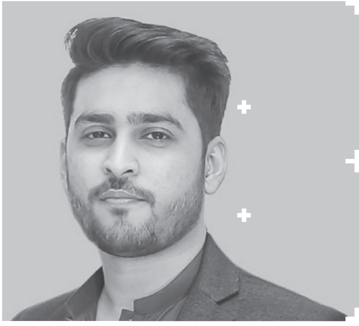


Figure 1: Investment Share Under the GRIP Program. Source: PTR Inc.

Using digital HV switchgear and integrating artificial intelligence (AI) into HV switchgear will amplify the grid's capacity to cater to bottlenecks and provide tangible results in addressing evolving energy challenges.



Saad Habib currently serving as a Market Analyst at PTR Inc. with a focus on High Voltage (HV) and Medium Voltage (MV) Switchgear within the Power Grid team, brings a wealth of experience to his role. Previously, as a Project Manager at Future Gulf Tech. Cont., a prominent project management and consultancy firm in Pakistan, he demonstrated his expertise in the field. Saad holds a Master's degree in Business Administration from CBM and a Bachelor's degree in Electrical Engineering from FAST National University. His professional strengths include keenly analyzing market trends, evaluating the impact of renewable energy updates, and assessing country policies that shape the switchgear landscape.

Saifa Khalid serves as Senior Analyst at PTR Inc. Her main area of interest is power systems. Currently, she leads the power grid research team in developing PTR's syndicated power grid services and manages custom research projects for Fortune 500 clients globally. The topics under her mandate include HV switchgear, MV switchgear, power transformers and distribution transformers. With a background in Electrical Engineering, Saifa brings technical proficiency to her role, ensuring impactful solutions in the dynamic realm of power systems.

Through the GRIP investment, the US allocated USD 2.5 billion for Grid Resilience Utility and Industry Grants, USD 3 billion for Smart Grid Grants, and USD 5 billion for the Grid Innovation Program. These funds serve multiple purposes, such as enhancing regional and community grid resilience, improving electric system flexibility and efficiency, and deploying innovative transmission and distribution infrastructure approaches. Together, the GRIP investment strengthens the smart grid by focusing on multiple grid optimization techniques, fostering real-time adaptability and operational efficiency. Additionally, using digital HV switchgear and integrating artificial intelligence (AI) into HV switchgear will amplify the grid's capacity, efficiency, and resilience.

Integrating digital technologies into HV switchgear can revolutionize energy infrastructure by enhancing the smart grids' performance, reliability, and sustainability.

Role of Digital HV Switchgear

HV switchgear is essential to maintain grid stability and flexibility amidst high demand and intermittent supply, as discussed earlier. Integrating digital technologies into HV switchgear can revolutionize energy infrastructure by enhancing the smart grids' performance, reliability, and sustainability.

Digitalization of HV switchgear provides multiple advantages, such as predictive and condition-based maintenance, increased flexibility, precise and remote monitoring, and cost savings.

Predictive Maintenance

Digital HV switchgear enables real-time data analysis and decision-making, enhancing grid monitoring capabilities and facilitating predictive maintenance for efficient energy management. Predictive maintenance allows for eliminating unplanned downtime and diminishing risks of equipment failures.

Photo: Shutterstock

Increased flexibility
Digital HV switchgear enables seamless integration of renewable energy sources through dynamic monitoring and control capabilities. Moreover, it supports versatile network configurations and is a scalable platform for upcoming modernization initiatives.

Remote operations
Digital HV switchgear allows for real-time alerts, diagnostics, and control through remote monitoring, ensuring safety by reducing manual intervention and personnel need to operate in hazardous environments.

Cost savings
Digital HV switchgear contributes to cost savings by optimizing resource allocation and minimizing disruptions by optimizing maintenance schedules, minimizing downtime, and improving overall system efficiency.

Research suggests that AI-based predictive maintenance can reduce equipment downtime, leading to substantial cost savings and improved grid reliability.

AI Integration in HV Switchgear

Introducing artificial intelligence into HV switchgear, alongside digitalization, unlocks a new era of performance and efficiency. Unlike reactive maintenance, where repairs occur after failures, AI enables predictive maintenance, anticipating potential issues before they become critical. This is achieved through continuous monitoring of equipment health and performance using sensors and real-time data analysis. For example, AI-powered anomaly detection algorithms can analyze vibration patterns, temperature fluctuations, and other parameters to identify early signs of wear and tear in circuit breakers and other critical switchgear components. This allows for proactive interventions, like targeted maintenance or minor adjustments, preventing major breakdowns and significantly extending the lifespan of vital assets.

Photo: Shutterstock

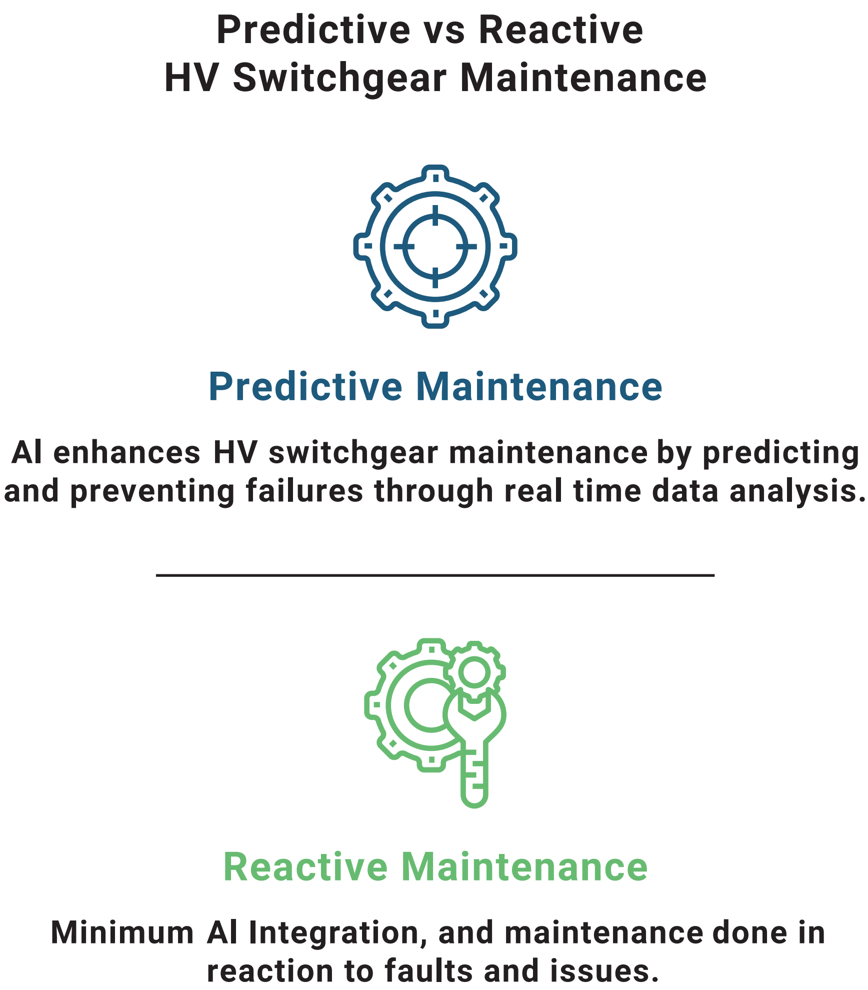


Figure 2: Predictive vs Reactive HV Switchgear Maintenance.
Source: PTR Inc.

In addition to predictive maintenance, AI plays a crucial role in asset management, optimizing the lifecycle of components and ensuring their sustained efficiency. Research suggests that AI-based predictive maintenance can reduce equipment downtime, leading to substantial cost savings and improved grid reliability. Furthermore, AI goes beyond traditional monitoring, facilitating real-time condition monitoring, fault diagnosis, dynamic load management, and cybersecurity. The combined benefits of AI with digital HV switchgear offer promising prospects for the future of the grid. With advanced predictive maintenance, real-time monitoring, and improved asset management and cybersecurity, AI paves the way for a more resilient, efficient, and reliable power infrastructure.

Way Forward

The recent strides in technology, data science, and artificial intelligence (AI) have ushered in a transformative era for high-voltage (HV) switchgear monitoring. The integration of AI addresses historical challenges associated with manual inspections and aligns seamlessly with the broader smart grid revolution. Recognizing the pivotal role of HV switchgear in ensuring a stable power supply, the shift to AI-driven monitoring signals a promising trajectory toward a more resilient, responsive, and sustainable power infrastructure.

The recent strides in technology, data science, and artificial intelligence (AI) have ushered in a transformative era for high-voltage (HV) switchgear monitoring.

The mutual relationship between AI and digital switchgear streamlines operations and opens avenues for remote management, adaptive control strategies, and insightful human-machine collaboration. As we move forward, embracing this transformative integration is crucial for optimizing power grid management, ensuring efficiency, and meeting the evolving needs of modern energy systems. This marks a significant step towards building a reliable, intelligent, and future-ready smart grid ecosystem.

Managing the Distribution Grid and Cloud Computing

By **Bidesh Kar** Director of Product Management
Sentient Energy

Photo: Shutterstock

The US Electric Distribution Grid is the backbone of all other innovation that the country has delivered over decades. Our reliance on the power systems has increased to an extent where minutes of interruption can be crucial as it may interrupt internet connectivity while working from home or miss witnessing live a historic last-minute touchdown in a Superbowl. Additionally, the grid has started to evolve in ways never imagined or planned such as bi-directional power flow from residential homes to mitigate peak demand by feeding power back to the Utilities. The increasing expectations of reliability and proliferation of Distributed Energy Resources has made it imperative to have near real-time know how of how the grid is operating.

Bidesh Kar is the Director of Product Management at Sentient Energy a Koch Engineered Solutions company. He has about 20 years of experience working in the Electric Utilities industry. He spent the first half of his career in various engineering roles at Infosys Technologies and Itron working on areas such as Demand Response, AMI implementation, Customer Care & Billing. In the last eight years he has been in various product management roles at S&C Electric and most recently at Sentient Energy. Bidesh has led several products from concept to market and at Sentient Energy he leads the portfolio of intelligent line sensors for Underground Distribution and Ample Analytics Platform. He has worked with utilities globally to help them think through how to effectively gain visibility of underground cables and equipment in preparation for the transformation led by DERs, EVs, and rooftop solar. Bidesh also represents Sentient Energy at Power Delivery Intelligence Initiative as a Partner member.

THE INCREASING EXPECTATIONS OF RELIABILITY AND PROLIFERATION OF DISTRIBUTED ENERGY RESOURCES HAS MADE IT IMPERATIVE TO HAVE NEAR REAL-TIME KNOW-HOW OF HOW THE GRID IS OPERATING.

The Rise of Secured Cloud Computing

With exponential advancements in virtualizing IT hardware in past few decades, the rise of Cloud Computing has come as an aid to utilities seeking to process and actionize high volume, variety, and velocity of data.

The advances towards auto-scaling IT infrastructure on Cloud means the thousands of intelligent devices – sensors, reclosers, automated switches can report data back to IT/OT systems without having to worry about constantly upgrading IT infrastructure.

Additionally, a Cloud deployed solution natively is "High Availability" by leveraging multiple geographic locations as hosting zones to protect from severe weather in one region.

Moreover, in case of large IOUs where there are multiple operating companies, a shared resources architecture can bring in immense cost-effectiveness towards IT investments. For smaller utilities like Munis and Co-ops who have limited IT resources in house, they can now focus on business applications and let the IT infrastructure piece handled as part of Cloud deployed solution.

Finally, a cloud centric approach supports consolidation of data from disparate sources and application of advanced analytics, which in the past had been constrained by complex system integration and limited IT hardware capacity on-premises. Advanced analytics and the cloud work beautifully together so new analytics possibilities will certainly be a foothold for cloud use within Utility operations IT systems. As per IDC's IT/OT Convergence survey, over 30 percent of North American utilities prioritize the investment of cloud based operational data and analytics within their IT/OT related initiatives.

Challenges and Opportunities

Despite the progress that has been made, there are still some major challenges that need to be addressed to fully transition to a Cloud based paradigm. One challenge is ensuring data is as cybersecure on the Cloud as it is On-premises. While Cloud vendors such as Amazon and Microsoft go through a variety of compliance measures to meet requirements from standards relevant for the distribution grid such as NERC-CIP, FRED-RAMP, and ISO-27001, application providers must also go through stringent cybersecurity evaluation procedures. An industry standard would tremendously simplify and ease standards around solution acceptance prior to deploying on the Cloud.

Another challenge is the need to reassess regulatory frameworks in conjunction with FASB rules to support cloud investments as Capex. While FASB rules exist on how to structure contracts that allow capitalization, there needs to be clarity around which costs may be subject to deferral and do so in an objective manner. In addition, utilities must review the impact of these decisions on their financial indicators of performance. Therefore, a company wide look at cloud strategy would be crucial to ensuring not only true financial impact but also organization wide necessary change management to achieve successful transition. However, as Utilities deploy more systems on the Cloud and capture the value from those investments, we will see increasing adoption and

Photo: Shutterstock

THE FUTURE HOLDS EXPONENTIAL INCREASE IN ADOPTION OF CLOUD COMPUTING FOR DISTRIBUTION GRID.

streamlined compliance processes. In addition, there is growing regulatory support for transitioning to cloud-based OT/IT systems for the distribution grid and Utilities are starting to implement policies that support moving a subset of systems into the Cloud, and it is a matter of time when we would see a greater adoption.

The Future of Cloud Computing for Distribution Grid

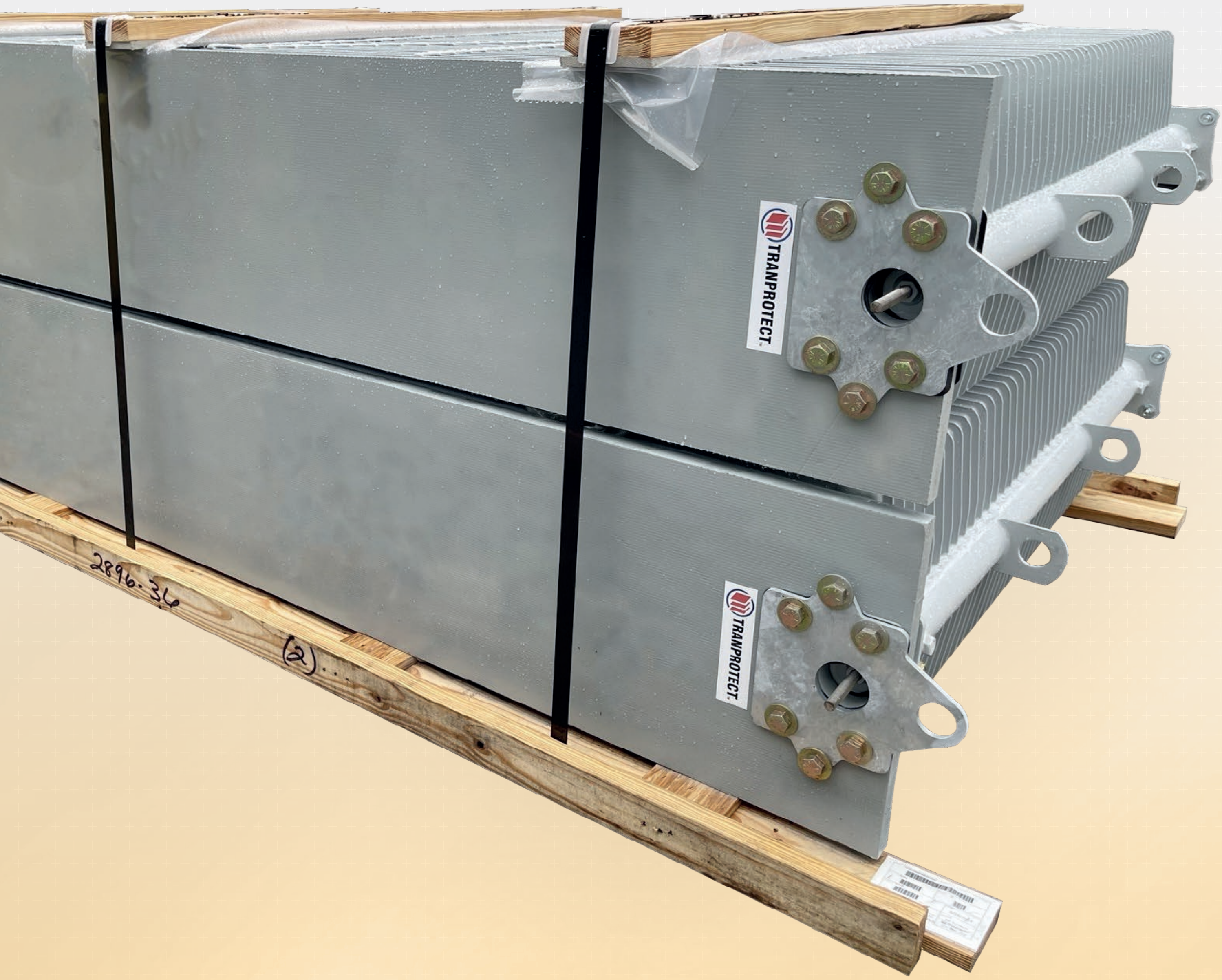
The future holds exponential increase in adoption of Cloud computing for distribution grid. The total cost of ownership has improved dramatically for cloud deployed solutions when compared to hosting on premises. While there are still challenges to overcome, with greater need to monitor the grid and analyze petabytes of data you need a system that can auto-scale with increase in the volume of data flowing in from the field.

To summarize, three key points to consider are:

- The importance of a companywide IT strategy and change management initiative.
- With increasing smart devices in the field, what will be the TCO on premises vs. Cloud?
- Collaboration with regulators to ensure cloud deployments are not disadvantaged due to capex and accounting rules.

We believe that there are a variety of applications in OT/IT that do not control or deenergize circuits and can therefore be a candidate to reside on the Cloud. Systems those can energize or deenergize circuits can be looked at in the future and migrated to cloud on a case-by-case basis. Let's empower every department within the Utilities to leverage streaming of data from field devices and focus on business outcomes rather than spending majority of time worrying and implementing complex IT projects.

TRANTECH RADIATOR PRODUCTS, INC.



TRANSFORMING THE POWER OF IDEAS INTO PRODUCTS

In 1932, Trantech embarked on its mission to provide a wide range of customers with cooling products. We started with milk delivery truck cooling plates before evolving into transformer cooling radiators for Westinghouse. Today, we continue to lead the industry with products and services that provide our customers around the globe with trusted products.

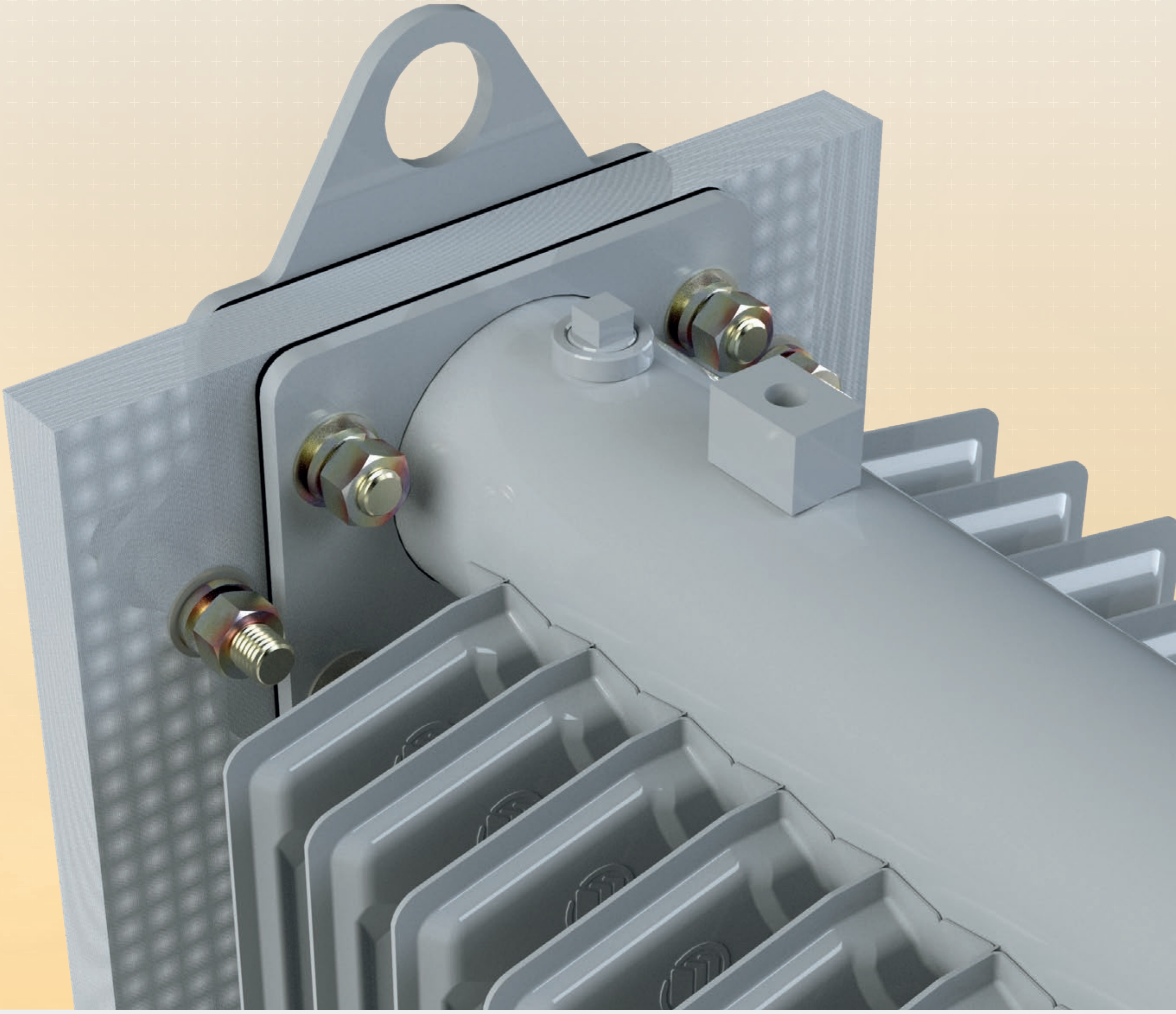
Photo: Trantech

The Power to Protect

Corrosion remains the largest contributor to transformer cooling system failures; however, new threats have emerged for these components that keep our assets cool. Ballistic attacks, fires, and other terrorist events, also known as human incidents, have increased by +382% from 2017 to 2022 according to the Department of Energy.

Over 60% of known ballistic attacks on transformers are directed at the radiator cooling systems due to their large footprint and thin materials, we set our sights on future product developments to meet these challenges.

In 2023, Trantech launched the TRANPROTECH® line of ballistic radiator protection panels. From a distance, these innovative panels resemble normal radiator plates but, they are actually UL 752 Level 8 ballistic panels.



These panels are also rated for 1-hour of direct flame fire and can absorb bullets with no spalling or ricochet for rounds up to 7.62 (AK-47). They will absorb 5 shots within a 5” square. Typical AR-15 rounds pose no threat to these radiator-mounted panels, with no compromise in cooling efficiency. This innovation showcases the ingenuity of the Trantech Engineering team.

The Power to Respond

While developing new products around grid support and protection over the last two years, Trantech has never lost sight of the fact that our loyal customers need reliable products and deliveries for their role in ensuring grid resiliency. Our commitment to these efforts led Trantech on a path to further upgrading our manufacturing processes. In 2023, following years of development and large capital investment, we launched our new hybrid radiator product. Partnering with Weldbot LLC, Trantech developed this innovative piece of equipment to replace our Brazed Radiator Product line. It has been an overwhelming success, continuously enhancing our efficiency, reliability, and potential output.

These hybrid radiators support a growing 50-3000kVA distribution transformer market. State-of-the-art robotics integration, utilizing Fanuc robotics and Fronius welding systems, lies at the heart of our one-of-a-kind CMT welding cell. This process produces superior welded joints along with cleaner welded areas. Additionally, the new process reduces the environmental footprint of integral header radiator production by more than 30%. This combination of superior product quality, enhanced reliability, longer lifespan, and environmentally friendly manufacturing processes is a significant win for both Trantech and our customers.

This combination of superior product quality, enhanced reliability, longer lifespan, and environmentally friendly manufacturing processes is a significant win for both Trantech and our customers.

Photo: Trantech

The Power to Restore

In today's global transformer manufacturing landscape, where components come from various locations, this assurance provides peace of mind to Trantech MAC unit owners.

Another breakthrough product to combat events such as overheating transformers or attacks that compromise cooling systems is the Trantech MAC unit. Offering a range from 40 to 215kW of cooling capacity per unit with 3-stage capability (ONAN, ONAF, and OFAF), these units are designed to operate in the harshest environments for decades. They are compatible with most transformer styles. One notable feature of the Trantech MAC unit is the guaranteed stock of all replacement parts, which can ship the same day in most cases. In today's global transformer manufacturing landscape, where components come from various locations, this assurance provides peace of mind to Trantech MAC unit owners. Feedback from our customers on these newly designed units has been overwhelmingly positive, citing benefits such as:

- Providing protection for overheating transformers or those with compromised cooling capacities
- Availability of emergency cooling for short periods
- Availability of long-term cooling solutions
- Potential to reduce downtime in the event of a terrorist attack
- Utilization of industry-standard cooling methods and technology
- Self-contained and portable design
- With mission-ready trailer packages available, Trantech currently has MAC units in production for major utilities and will soon commence production on a rental fleet.

In today's global transformer manufacturing landscape, where components come from various locations, this assurance provides peace of mind to Trantech MAC unit owners.

Photo: Trantech

How Trantech Views Reliability and Resiliency

While reliability and resiliency are crucial topics when discussing our current power grid, these principles also apply to Trantech's manufacturing and product development processes. Investments in innovative technology, improved processes, and our quality focused workforce have enabled Trantech to remain a trusted source for transformer components for almost a century. Utilizing the Trantech Operating System (TOS), we focus on improving reliability for our customers using Lean Manufacturing principles. This same system, along with prioritizing the deployment of new products and initiatives that support our customers' future needs, adds to our resiliency as a company. Partnering with our suppliers to ensure the continuity and availability of materials, just as our customers partner with Trantech, are key steps in preventing high-consequence disruptive events. These disruptions are becoming more frequent in the transformer component market due to the unpredictability of factors such as ocean cargo congestion, material shortages, and geopolitical issues. Trantech prepares for these challenges, as any great supplier should, to protect our customer base.

Investments in innovative technology, improved processes, and our quality focused workforce have enabled Trantech to remain a trusted source for transformer components for almost a century.

TRANTECH
RADIATOR PRODUCTS, INC.

About Trantech

Trantech is the most customer-oriented and diverse manufacturer of power transformer cooling systems in North America. Today, Trantech offers engineering or re-engineering for any type of transformer cooling system solution internationally. We provide cooling products, components, and services to a wide range of global industries, including transformer manufacturers, fossil fuel and nuclear power generating facilities, as well as petrochemical sites.

A Profile of John McDonald

Photo: John McDonald

A Pioneer in Power System Automation and Leadership

John McDonald

From the Managing Editor: *When I first met John McDonald, he was emceeing a client conference for GE. It struck me that his vast knowledge of, and commitment to excellence in his career, his volunteer life, and in his personal life, is a model for what I believe we must try to follow as engineers, as husbands, fathers and as leaders. I got to know him a little at the conference.*

I got to know John a lot better at our lunches at Seasons 52, an Atlanta restaurant we both love, where I learned that John was a gift to our industry and a gift to IEEE PES and CIGRE based on his commitment to his career and his willingness to share with others. At many events John has been one of my "Go To" interviews of thought leaders for insight into the power industry.

When I read this profile published in PAC World Magazine in June 2020, calling him a Guru, I knew we had to share it with our community, as a way of challenging each of us, especially for those young engineers just entering the industry.

Many thanks to: ***PAC World Editor-in-Chief, Dr. Alex Apostolov****, himself a Guru, who graciously allowed us to share this interview they did with John.*

How did you become involved in the development of energy management and control systems?

JM After nearly five years with Bechtel Corporation, I joined Brown Boveri Control Systems, Inc. (BBCSI) in Santa Clara, California, in 1979. The parent company Brown, Boveri & Compagnie (BBC) was a power engineering company with a new SCADA subsidiary. I became the first power engineer in BBC's SCADA subsidiary. That role introduced me to the development of energy management and control systems. On my first day, the top executive told me that BBCSI was short listed on a $1 million proposal for a SCADA/Automatic Generation Control (AGC) system for a Midwest municipal utility. The proposal included four power system applications: Automatic Generation Control, Economic Dispatch Calculation, Interchange Transaction Scheduling and Interchange Transaction Evaluation (Economy A). BBCSI had a meeting scheduled in one week with a consultant steeped in power system application experience. BBCSI had no previous experience with SCADA/AGC systems.

I had one week to learn about SCADA and the four power system applications to convince the consultant that BBCSI could successfully perform the project. We won the project.

After about 15 years work on energy and distribution management systems (EMS/DMS) you decided to become a consultant. What triggered the change?

JM By 1995, if you add in another four years working for McGraw-Edison Power Systems, I had worked on SCADA/EMS/DMS for 17 years. I had been active in the IEEE PES Substations Committee, leading standards development in substation automation and communications protocols. I had been active in developing the Utility Communication Architecture (UCA) in North America, later integrated with Europe's IEC 61850. I knew a lot of people across the power industry. I had never thought about going into consulting. But I felt well prepared to leverage my experience in a new way. I wanted to stay in Atlanta. Through a friend, I learned of a need at the precursor to KEMA Consulting and signed on in 1995.

In 2007 you joined GE Energy and you were there for 16 years, until retiring on November 30. What led you to work for a manufacturer?

JM By 2007, I had enjoyed working for KEMA Consulting for 12 years and thought I'd do that for the rest of my career. A friend alerted me to an executive level position open at GE, reporting to the CEO of its T&D business. With changes underway at KEMA, it seemed like a good time for a career change. GE was the fourth automation system supplier (manufacturer) I worked for in my career.

When I was interviewed at GE, I was 56 years old, with 34 years of experience in T&D and 17 years of experience with three automation system suppliers. I had held many leadership positions in IEEE, IEEE PES and IEEE-SA (Standards Association). I had vastly more experience than anyone in the GE T&D business. GE's executive team saw the value I could bring to their business. Thus, I started working for the largest company in my career at the end of my career, which is the opposite of what I recommend to young professionals.

You had started working with RTU-based EMS and have seen the transition to IEDs and integration-based systems. Was that transition difficult?

Yes. Our focus, for decades, was on data the RTU collected, processed, and sent upstream to the operators in the control center. With the advent of IEDs, we had two different types of data in the device to manage - operational and non-operational. However, our expertise, business processes, and organizational structure and skill sets were based on the traditional RTU data flowing to the operators. IEDs produced data that was not being utilized. The industry simply wasn't prepared to use it.

Eventually, the industry had to transition from an RTU-centric substation architecture to a network-based, distributed architecture with IEDs and data concentrators that could also route non-operational data to business groups across the utility. At that time, I led the IEEE PES standards development in substation automation as the IEEE PES Substations Committee Subcommittee C0 Chair. When we updated IEEE Std C37.1 (for SCADA) in the early 1990s we introduced the term "Intelligent Electronic Device (IED)" so we would have an industry-wide term for the new microprocessor-based devices.

I introduced the concepts of operational and non-operational data in a guest editorial I wrote for IEEE Power & Energy Magazine (March/April 2003) titled *"Substation Automation: IED Integration and Availability of Information"*. Even today, utilities are not realizing all the potential benefits from the available non-operational data throughout their enterprise. Sorry, I can't stop evangelizing for non-operational data!

During the more than 40 years of your career, what was the most challenging project that you have been involved in?

JM When I joined BBCSI in 1979 and helped win the SCADA/AGC project with a municipal utility, BBCSI had no power application software and no experience with SCADA/AGC system projects. I had to source the four power application software programs we needed, then integrate them with our SCADA platform. I spent two months at corporate parent BBC in Baden, Switzerland, evaluating their power application software. Meanwhile, the project had already begun. I learned that Power Technologies, Inc. (PTI) in Schenectady, NY had developed the needed power applications for a utility in the Midwest, and they would run on the identical computer platform as our project. I licensed the four applications from PTI, did source code training at PTI, then worked with our software programmers at BBCSI to integrate the four applications with our SCADA platform. Since this was a "first" for BBCSI I wrote the documentation, test procedures and training material. I was 27 years old and had learned about SCADA and these four power applications a few months earlier. This was a very challenging project, with a lot of pressure to succeed, and we did.

And the most satisfying one?

JM During my years with KEMA Consulting, three SCADA projects stand out.

One was a municipal utility, which had never had SCADA and lost a substation to a transformer explosion. I guided their SCADA implementation and substation automation.

Another municipal had SCADA, but it relied on a proprietary communications protocol from a defunct supplier. I helped them replace the SCADA master, implement substation automation and use protocol converters to use an industry standard protocol.

The third was a municipal agency with aging SCADA and a very slow scan rate. They needed a more accurate indication of customer load because they sold the difference between their generation and load on the open market. The new SCADA system we implemented paid for itself in months.

You have been actively involved in the development of the Smart Grid. How did that happen?

JM Actually, when the term "Smart Grid" first appeared, I took offense to it. Adding intelligence to the electric grid was not new. Many of us had been adding intelligence to the grid for decades. At Purdue my focus on digital computer modeling and analysis was truly new. I spent 50 years of my career on power system automation – adding smarts. So, I developed a PowerPoint slide I call the "Smarter Grid", which reflects already existing intelligence as well as the intelligence we were adding as part of "Smart Grid". It is important to recognize this point.

To young engineers

Much of our work is art rather than science. One has to master the science, but it takes many years to learn the art – the application of the science.

In the last 25 years we have been developing IEC 61850. It is used today in thousands of substations around the world. What do you think about its role in the Smart Grid and why are some people still not using it?

JM The need for standard communications protocols and networking exists at three levels. For control center to control center data exchange, the one global standard is the Inter-control Center Communications Protocol (ICCP). For control center to field communications, the two standards globally are IEC 870-5-101 and 104 for European suppliers and IEEE 1815 (DNP3) for North American suppliers. For communications within the field, North American suppliers and utilities use IEEE 1815 (DNP3) and are beginning to adopt IEC 61850. The remainder of the world uses IEC 61850 to a much greater extent. I've seen a lot of global convergence in the past 25 years.

Globally, except for North America, utilities are comfortable with turnkey substation projects. Utilities in North America have standardized on one supplier's protective relay, a different supplier's transformer monitoring and diagnostic device, yet another supplier's tap changer monitor and control. With the turnkey approach the supplier has full control over all components,

Photo: John McDonald

therefore it's much easier to implement IEC 61850, due to long-established interoperability of components. The North American approach requires an integrator. That poses more risk due to potential lack of interoperability and that hampers greater implementation of IEC 61850.

When and why did you join the IEEE?

JM I joined IEEE in 1971 as an undergraduate EE student at Purdue. When Professor Ahmed El-Abiad suggested that we join IEEE, we didn't question him! Looking back, it has been invaluable to my career and 2024 marks 53 years of membership!

You have been very actively involved for many years at all levels of the IEEE PES. How did you manage your high-level management positions at GE with all your responsibilities at the top levels of the IEEE PES?

JM Briefly, it's about time management and staying ahead of deadlines to do quality work for either job or volunteer work. When collaborating, reach out early. My professional roles enabled my volunteer work, just as volunteering advanced my career. And I manage these two roles in order to enjoy family time and respond to collegial requests for help. In addition, I mentor over 20 students and young professionals worldwide on a regular basis. You find the time to do the things you want to do.

You are still very active also in CIGRE. What do you think is its role for the electric power industry compared to IEEE?

JM The two organizations are complementary by having different approaches. First, CIGRE taught me a more global perspective on technology, as functionality and business cases differ by region. Second, participation in CIGRE by C-level executives translates to global networking opportunities. Third, CIGRE's focus is practical, not academic. Though IEEE is moving towards the policy implications of technology choices, it has vast and deep technical expertise. I would contrast them, but not compare them. Long ago I realized being a "complete" power engineer requires active involvement in both.

Photo: John McDonald

What do you consider your greatest professional achievement?

JM All the education and professional work I've done has enabled me to help others. No matter how busy I am, I will find time to help others succeed, without expecting anything in return. I've earned the opportunity to pay back the help I've received.

To young engineers

My professional roles enabled my volunteer work, just as volunteering advanced my career. And I manage these two roles in order to enjoy family time and respond to collegial requests for help.

What do you consider your greatest personal achievement?

JM Being happily married for over forty years with two children who are both happily married and having three grandchildren. I've managed my work/life balance, including extensive travel, in order to participate in my family's activities. By extension, that includes my own, my son's and my volunteer participation in Cub Scouts and Boy Scouts, as well as promoting STEM education for girls and boys. My son and I are Eagle Scouts.

You have received many awards. Is there a specific one that you consider the most important?

JM Three stand out. I was named an IEEE Fellow in 2003 "for technical leadership in the development of substation integration and automation". I helped pioneer the field of IED integration and substation automation and being named an IEEE Fellow recognized that work. I received the IEEE PES Meritorious Service Award in 2015, bestowed by past winners for those who've made outstanding contributions in leadership, technical activities, and educational activities of IEEE PES. That was humbling. And now I'm chair of that award committee.

In 2022 I was elected to the National Academy of Engineering "for leadership in smart grid development and for advancing the professional growth of power system engineers". Election to the National Academy of Engineering is among the highest professional distinctions accorded to an engineer. Academy membership honors those who have made outstanding contributions to "engineering research, practice, or education, including, where appropriate, significant contributions to the engineering literature" and to "the pioneering of new and developing fields of technology, making major advancements in traditional fields of engineering, or developing/implementing innovative approaches to engineering education".

You have so much knowledge and experience. How do you share it?

JM I write, talk, teach, travel and mentor. After 50 years in the business, I have assembled my thoughts on career decisions in a talk titled *"Key Insights to Career Management"*, to help young professionals, in an interview on mentoring for IEEE-HKN as Career Conversation Episode 2, and a talk titled *"Building and Leading a Volunteer Organization"*.

To young engineers

Much of our work is art rather than science. One has to master the science, but it takes many years to learn the art – the application of the science.

COMPANY SPOTLIGHT

Measurements International

“Precision in Power: The AccuLoss® Advantage

Measurements International
Metrology is Our Science, Accuracy is Our Business™

Photo: Measurements International

MEASUREMENTS INTERNATIONAL is a world leader in the measurement of losses in transformers, with the development of the World's most accurate Transformer Loss Measurement system. The AccuLoss® Transformer Loss Measurement System is key to accurately measuring losses in reactors and transformers. This, in turn, paves the way for the design and production of transformers characterized by minimal losses, thereby unlocking unprecedented energy savings and a notable reduction in CO_2 emissions.

Measurements International, headquartered in Prescott, Ontario, Canada, is a leading manufacturer of Transformer Loss Measurement Systems, which have been sold and installed by Transformer manufacturers worldwide. Measurements International ALMS systems are designed and manufactured in Canada, and the company's research and development designs offer leading-edge solutions to customers.

In an era marked by a pressing need to curtail CO_2 emissions within the electricity sector, the critical task of accurately measuring losses in power transformers and reactors has risen to paramount importance. Enter the AccuLoss® Transformer Loss Measurement System, an all-encompassing solution engineered to meet the demands of today's sustainability-driven landscape.

Transformers and CO_2 Emissions:

The electric power sector significantly contributes to CO_2 emissions, with transformers playing a pivotal role in this narrative. As the demand for electrical power escalates, so does the need for more transformers, a scenario that could exacerbate emissions. However, an avenue exists for substantial CO_2 reduction by adopting low-loss transformers.

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As the drive to reduce CO_2 emissions intensifies, the AccuLoss® Transformer Loss Measurement System emerges as a beacon of precision and efficacy. This groundbreaking system comprises a holistic array of components expertly tailored to the task. These power analyzers use simultaneous sampling technology.

Our latest innovation, the 2020A series of Power Analyzers, has revolutionized the AccuLoss® Transformer Loss Measurement System. Leveraging simultaneous sampling technology, these power analyzers infuse the system with advanced features, heightened accuracy, and unwavering reliability.

Technology that Matters:

Simultaneous sampling technology takes center stage, delivering unparalleled precision, especially at low Power Factors. Coupled with the minimal phase errors of the high voltage capacitive divider and the two-stage compensated current transformer, it creates a substantial advantage in loss measurement across the entire spectrum of power factors.

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Precise loss measurement becomes non-negotiable in a world governed by standards such as IEC/TS 60076 and the Ecodesign Directive. AccuLoss® stands ready to ensure your compliance.

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

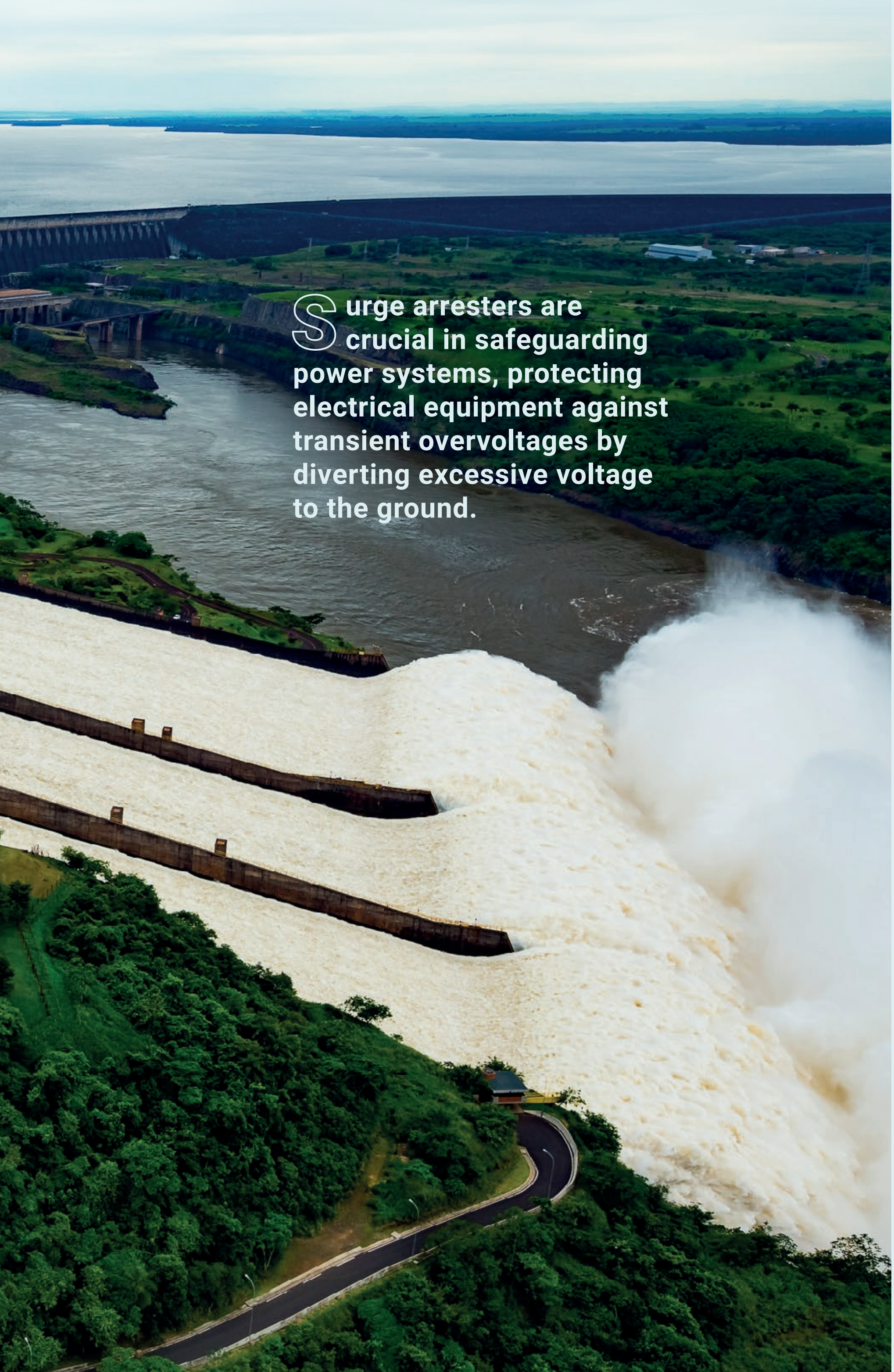
by **Mario Augusto Caetano dos Santos**
and **Florent Giraudet**

Photo: Itaipu Binacional

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



Mario Augusto Caetano dos Santos received his BSc in Electrical Engineering from UNIDERP, Brazil in 2010 and his MSc in Technology Development from LACTEC Institute, Brazil in 2017. He joined AES Corporation as Area Maintenance Coordinator for distribution power grid in 1998. After that he joined Eletrosul – Eletrobras focusing in maintenance of high voltage equipment in 2002. Since 2011 he take place in Maintenance Engineering Division of Itaipu Binacional managing high voltage assets. He is also secretary of the CIGRÉ Study Committee A3 (Brazil) and coordinator of the Technical Group for Substation Equipment – Association of Brazilian Power Transmission Companies.

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.

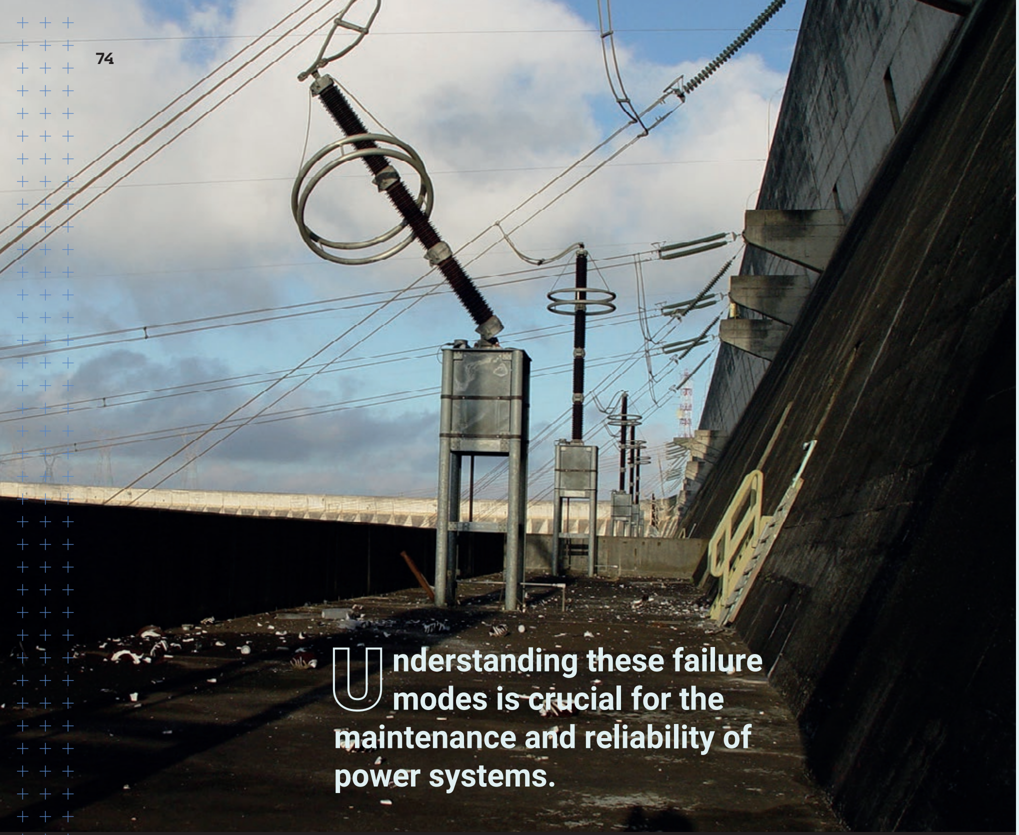

Understanding these failure modes is crucial for the maintenance and reliability of power systems.

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 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

Photo: Itaipu Binacional

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 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 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 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 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 measurement lines positioned at each section.

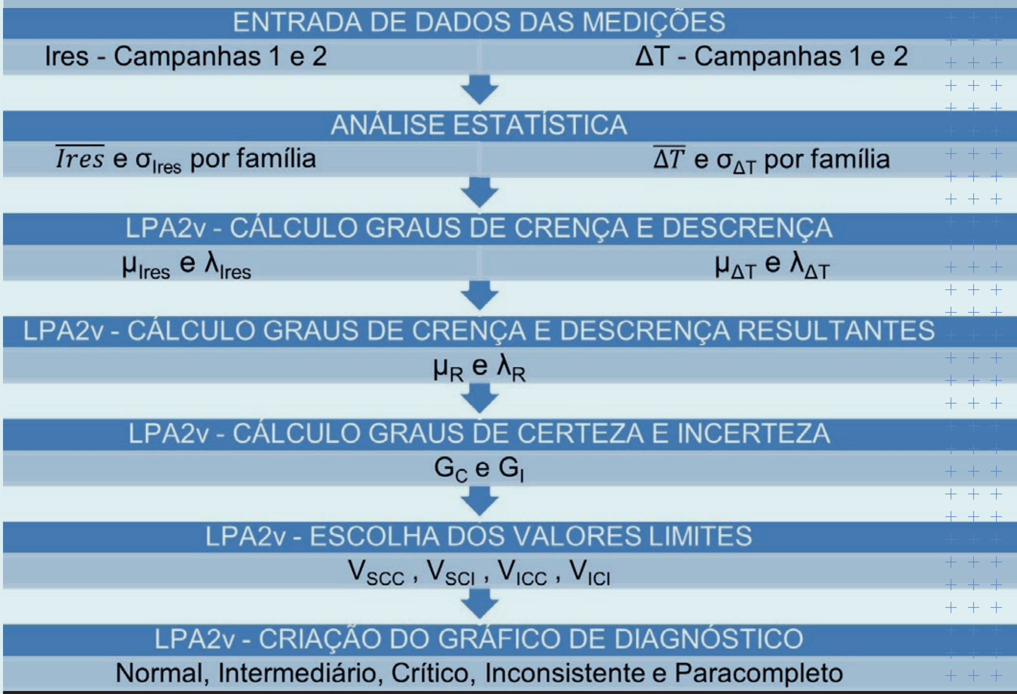


Figure 4. Flowchart of the diagnostic process by APL2v

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

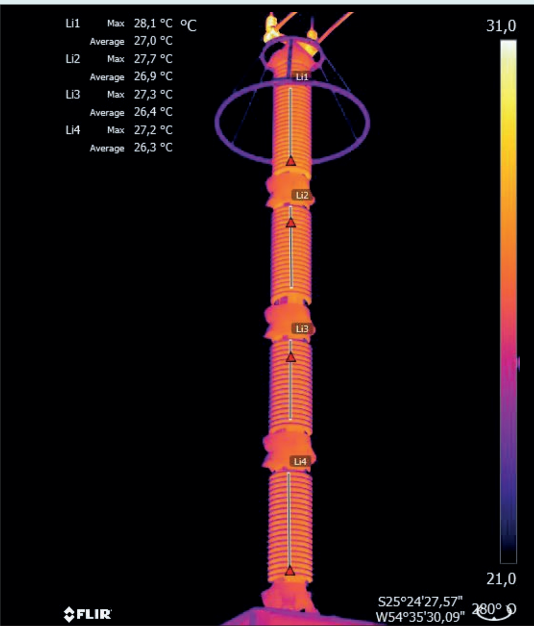


Figure 3. Example of quantitative thermal analysis on a 420 kV surge arrester

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.

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 (Gc) and uncertainty (Gi), as delineated by equations (1) and (2), respectively.

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

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

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).

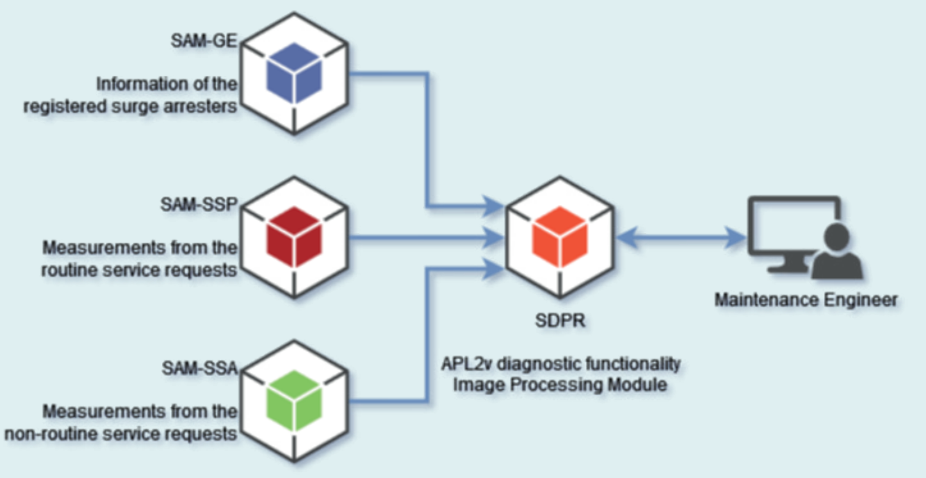


Figure 5. SDPR software architecture

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)

Photo: Itaipu Binacional

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.

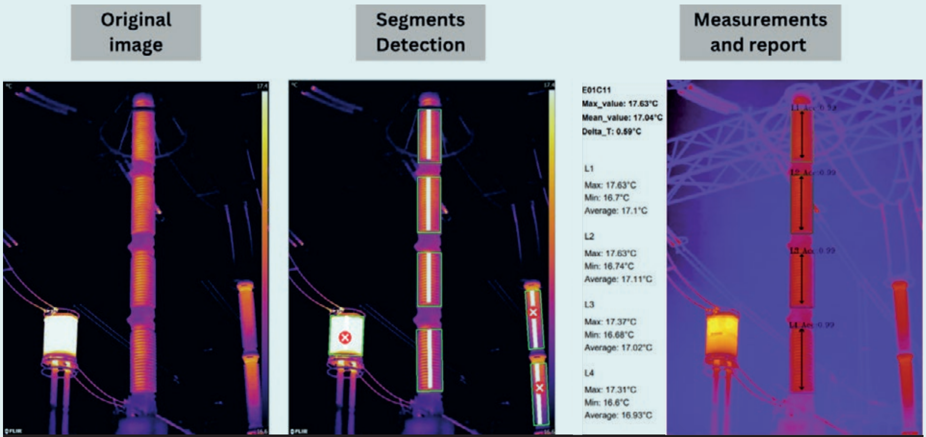


Figure 6. SAD-API steps

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 techno-logical 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 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 a 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.

POWER PANEL DISCUSSIONS

Tony McGrail
Senior Solutions Director, Doble Engineering Company

Nathan Jacob
Senior Asset Specialist, Camlin Energy

Alan M Ross
Managing Editor, APC Media

Monitoring and Diagnostics:

When Equipment Speaks Where are we now?

POWER PANELS

> Condition based maintenance means not just having an early warning to failure, but to really optimize the asset.
>
> **Nathan Jacob**

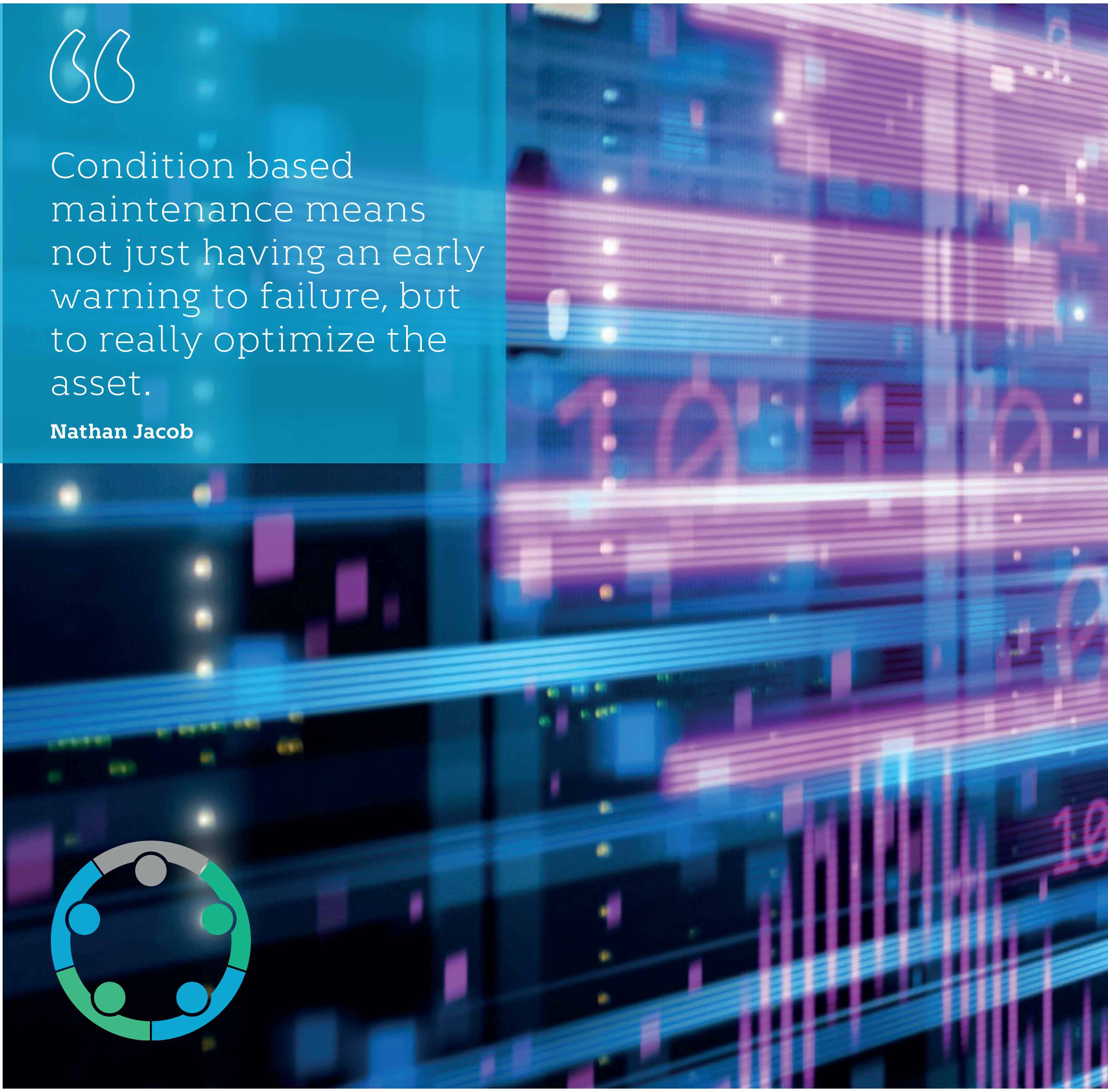


Photo: Doble Engineering Company, Shutterstock

Alan Ross: My two guests for our Power Panel today are Tony McGrail, Senior Solutions Director of Asset Management and Monitoring at Doble, and Nathan Jacob, Senior Asset Specialist for Camlin Energy. Gentlemen, thank you for joining us.

Gentlemen, we will present the first part of our Power Panel discussion in this Issue and Part Two in our April/May Issue. We will look at where the industry is going in the use of advanced testing, AI and ML. For now, please share your experience and your perspective on where we have been and where we are now, as an industry, when we consider asset monitoring.

Let me start with you, Nathan.

Nathan Jacob: In the early stages of monitoring, I think a lot of people conceived these as devices to alert and alarm primarily. They were like protection systems, where it was just binary states. Is the alarm alarming or not?

Now there's a shifting perspective where people are looking to gain more value from the data they're collecting, and they're wanting to use this data to make maintenance decisions. Condition-based maintenance means not just having an early warning of failure, but to really optimize the asset. If there is a way to be predictive in their maintenance, they're really focusing on that as well.

Another key distinction today is greater integration, moving the data to the cloud

and having better visualization of the data and better interpretability of the data. With the data being more accessible, and easy to visualize in a single interface, they can have their SMEs review that data more effectively and make better decisions on that basis.

I think the last point I would make is that for single assets, like transformer DGA monitoring, there's also a lot of motivation to do more holistic monitoring, combining sensors for different components on a single asset.
For power transformers specifically, it's the combination of DGA monitoring with partial discharge monitoring, with bushing monitoring, with monitoring of arcing and other system events, and really having all that data combined in their analytics to make more effective decisions from that data.

AR Thank you. Tony, your perspective?

Tony McGrail: I think it's a journey of what you might call a triumph of hope over expectation. Many years ago, when you got into condition monitoring, it was a box with lights on. It was something that they did over there. Over time people have realized that monitoring is a useful thing rather than an engineering toy.

As the photo above indicates, this goes back with development at National Grid UK of a multi-gas DGA system, 25 plus years ago. It was in the real world. It worked. It did what it had to do.

The main concern I had was that the transformer that we were examining overheated substantially. My main concern was that to analyze the oil I had to take the oil out of the main tank, take it into my little examination cabin, which I would call a relocatable DGA device, not necessarily portable, but relocatable, where we did lots and lots of analysis and experiments, with all the available devices that were on the market including our own devices.

My main concern was that the oil would leak out from that and get into the local reservoir, which would be feeding northeast London, and I'd be on the 06:00 news. So, my own monitoring was to get up on the first night I stepped in the cabin and walked around the whole thing every 30 minutes. And what this does is it reminds me of not just the fact that we're doing something beautifully technical, but there are consequences if this thing goes wrong, and there are consequences not just if the data is not valid or correct or precise or relevant, but if we analyze it without reference to the context, and if we analyze it just in independence.

What I've seen over the years is the move away from condition monitoring being something that they do to being something that the organization does, for organizations which are aware of, for example, ISO 55000 asset management, which has as a requirement that you monitor the performance of your assets. It doesn't prescribe how to do it, but it says, as you have these assets, you need to know which ones are in good condition, and you need to know what the plans are for each asset.

That has changed things where the context has changed. Condition monitoring becomes a lot more vital for the whole organization, and it needs to be embedded in the organization. People have to understand what value it can bring.

When we talk to, for example, insurance companies, they will tell us that the big loss payouts, for example transformer failures or substation asset failures, it's not to do with the replacement cost of the asset, but it's to do with the business interruption. That identification, not just of the technical need, but the business need and the asset management context, is hugely important in deciding which box, with which lights, and then how we use it; what our expectations are, how to make sure that we get value from it so we don't go "from ignorance to negligence". This is a quote from Tommy Salmon, formerly of Dominion Energy, now at GE, because they did have cases where the data implied one thing, and they did something else. People who are making the decisions need to have something which is useful, contextual, and supports decision making.

> Condition monitoring becomes a lot more vital for the whole organization, and it needs to be embedded in the organization.
>
> **Tony McGrail**

DATA-DRIVEN DECISION MAKING

AR Let's go from the idea of machines collecting data to data-driven decisions with subject matter experts. Tony, I'm going to start with you on that one. Where are we right now with that?

TM I think it depends on where you look, since the whole role of condition monitoring is to provide data for supporting decisions. These decisions previously were often made by default. If no one's complained that it's gone dark in their town, then our transformer in our substation is likely to be okay, so let's just leave it alone. Now that we have data, it behooves us to make sure that we do something useful with it. And it's also a case of there's no point in putting a condition monitoring device on anything, unless we have some expectation as to what the numbers should be.

As slide on the left shows, this is very simple condition monitoring from something which is less abstract than a power transformer. This is from just an automobile, a car, and we're looking at the tire pressures. I've got four tires; I've got three at 37 and one at 39. Did one of them rise or did three of them fall? Condition monitoring on the tires is based on, in this case, what I expect it to be.

In the right case, I've got four tires, two at 38, one at 29, and one at 51. This is condition monitoring data. I have got it. It's valid. What on earth do I do with it? So not only do you have to have expectations, you also have to have a plan to respond. And to have a plan to respond, you need to know what levels or trends or diagnostics are included in a way that you can say, *I need to do something now*.

That plan has to be in place from when you install the monitor, because if it isn't, what will happen is you'll get an alert, come in, and then you'll call a council of the wise and come together and we'll start to discuss data and timescales and rates of change and consequence, and the thing will fail in the meantime. You've got to be very, very careful that condition monitoring is seen as something which is managed ahead of time.

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> For power transformers specifically, it's the combination of DGA monitoring with partial discharge monitoring, with bushing monitoring, with monitoring of arcing and other system events.
>
> **Nathan Jacob**

> There's no point in putting a condition monitoring device on anything, unless we have some expectation as to what the numbers should be.
>
> **Tony McGrail**

We used to say that there were two main reasons to do condition monitoring. One was to learn about the monitor and one was to learn about the asset. These days, there's a third reason, and that's to learn whether the organization is capable of managing the whole of the condition monitoring process, from specifying a monitor through to gathering the information and making decisions with it. That's a big if, because a lot of people are not prepared for this. They install the monitor and it really is just a box with lights.

I would say that people who are good at condition monitoring tend to be good asset managers as well. There is a corollary to that from Guy Don Schubert of Marsh Insurance who said: "People who are good at asset management are also good at condition monitoring. But the reverse, just applying condition monitoring does not make you a good asset manager." It just means you're good at spending money. You must be very careful spending money.

AR Going back to the tire pressure illustration, were the 51 and 29 bad and the 38 was normal? Tony, you can't just leave us hanging.

TM For most people, two of them were okay, slightly down. This was an actual rental I had, where one tire was blown up at the garage, the 51, so it was way too high. When I called the rental agency, they said I'd be fine, just leave it for a week since you've got the car for a whole week. Just leave it, you'd be fine. The theory is they know what they're doing, and since my knowledge on these things is relatively limited, I had to trust the SMEs.

AR That's an interesting point. The asset owner didn't really have a plan. If that 51-pound tire had blown up because you hit a bump or the other one at 29 pounds had gone flat because it was already going flat, you're the guy stuck out there wondering, *what am I going to do now?*

Nathan, same question for you, as we look at this idea of data, and data-driven decision making.

NJ I like the sentiment in Tony's comments, it makes a lot of sense in terms of a monitoring strategy. A lot of utilities will approach the problem knowing that they just want better reliability out of their asset and then they'll deploy monitoring, but without understanding the impact of that on their organization, like where the data is going, who will respond to alarms, how you respond to alarms as part of a larger strategy.

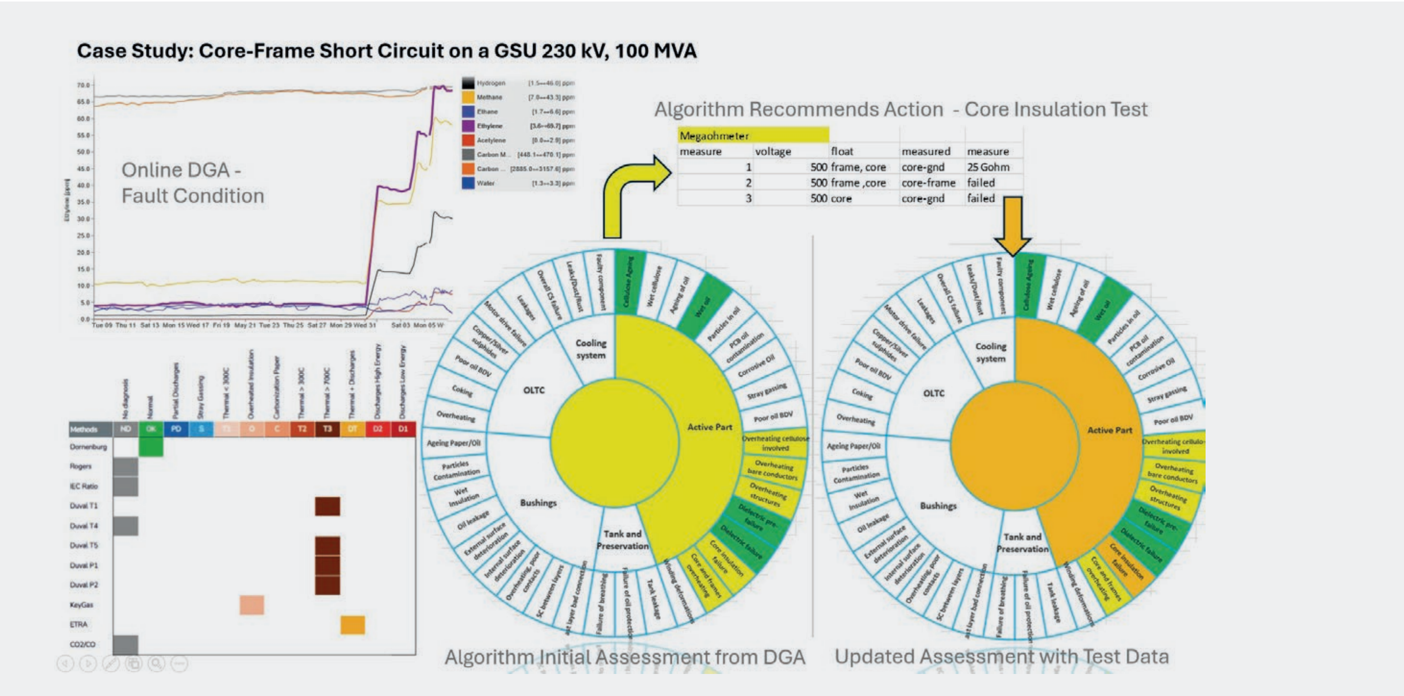
It is an important consideration to really think about what your overall strategy for monitoring is, but then also for the asset manager, and the use of data, and the analysis of the large volumes of data.

In the slide on the next page we see an example of a kind of an intelligent algorithm that utilizes data from multiple sources. This is a real example of our algorithm that's processing data from the original online monitoring information. In the upper left corner, we see online trends of DGA information. We can see clearly later in the trend that there's a sudden rise and some step increases in gassing. Right now, of course, the monitor alerted the users to that condition, but just that bit of information alone.

Knowing that there was an alarm doesn't determine the actions we must take immediately. We have a few analytical tools kind of displayed here, but in the bottom left, you actually see what's called the DGA matrix. That is an evaluation of the different concentrations of gas by different industry standard diagnostic methods. You can see most of them indicate a thermal fault. There's some variability in the diagnostics. Different methods will determine different classes or outcomes for the type of diagnosis or the severity of the fault, but it is at least a clue.

When you look at this, what does a thermal fault there mean actually? The fact that the monitor detected something, it did its job, you're still not really any further ahead in terms of diagnosing the actual problem. In terms of integrating a kind of holistic solution and having more information working together in concert with each other, to give a clearer picture of what the issue is inside of an asset, that's really what we're going for here.

And when that data, the DGA information, is processed, it immediately throws a couple of



suspected potential fault conditions. That is very important because it at least equips the asset manager with the information to know these are potential areas they could look at next. There are a few suggestions for potential faults indicated in yellow, and then to a lesser degree, or lesser confidence of identifying the other potential faults indicated by green. In the green highlighting in the wheel you can see some of the suggested potential faults: overheated cellulose, overheated bare conductors, overheating structures, and then core insulation failure. The identification of potential faults indicates to the asset manager, *I should attempt one of the recommended actions here, the core insulation test*. We can see above in the table where the arrow is pointed to the yellow arrow, that two of the tests failed, indicating a short between the frame and the core.

Clearly there's a core insulation failure with a higher degree of confidence that this is the identified failure mechanism. This is the type of visualization we have, the type of concept we have, indicating that you should really integrate all the tests, all the monitoring data, all the maintenance that's applied on the transformer or any asset, and attempt to have this kind of decision support tool that an asset manager can use to help them determine the next step. But then, when they have a larger body of data to do analytics on, it will give a clearer picture of what the potential fault conditions are. A lot of it is like a logical model, applying logic and applying correlations that a human expert would apply. This is the type of tool that could be used for that type of purpose to integrate all the data that's being collected.

AR Tony, do you have a comment?

TM Nathan, that is a good example. I had a question about the step in the data and how long it was between the step appearing and the transformer being taken out of service, because it looked as if it was about ten days from the axis.

NJ Yes, that is correct.

TM When you have the data suddenly rise, to wait to get more data is a decision that has to be made or not made, since it is in a default situation, which is keep it. That step by itself should be an indication that there needs to be a plan in place to respond to, because you've had a change in the DGA levels. How long was it left in service and energized before it was removed?

NJ Utilities aren't always so responsive to take an outage, so it is a kind of assumed risk which they may feel is necessary to take in certain moments. We talked about the strategy and responding to alarms. That is certainly something that could be defined in the strategy. What is the change in gassing on a monitoring device that has us respond and interrupt the unit immediately? Some of that should be managed through alarm management, right? You should not just wait on feedback from the diagnostic tool and the additional data that's collected over a period of time, but you should have criteria set out as a part of your larger strategy when you take an outage in response to an alarm condition, and what the thresholds are for that.

AR Which is having a plan, a strategy, right?

TM I've got from a case of a bushing and the owners of, I think, about 70 transmission class transformers. They had a lot of the bushings, which fail quickly. And they had the bushing monitor. When the bushing gave top level alert, operations had to switch a transformer out in two minutes. Now, these are transmission units, it is like trying to stop a battleship. It's a lot of work to do. They don't stop very easily. And so that was their written and agreed policy when they install a monitor. That, to me, makes sense, because they knew they were going to fail. They knew that they had this failure mode. And that's the trench bushing problem. The plan was put in place when the monitor was installed, and it was two minutes. Admittedly, they did have some false positives, but they worked out why. Then the false negatives were avoided, and the false positives are the price you pay to avoid false negatives. The result was they saved transformers, and they saved multi-multi-millions of dollars as a result. They're still doing so now. But as soon as I saw that step, I'm like, why aren't we doing something right there?

What was done then? Did they think, *okay, we'll just leave it and see what happens?* Because we've had that as well. And then it fails, and then people say, *your monitor didn't do anything*. But yes, it did. Look, it told you, and you hit the button saying, *do something, acknowledge, acknowledge*. The plan must be agreed and in place by all parties as early as possible.

AR Yeah, you're hitting the point that when the equipment speaks, we are supposed to listen. Sometimes it speaks very loudly, and sometimes it speaks a little less loudly, but trending. I think, Tony, that's kind of your point. When in the trend, do you suddenly take a piece of equipment out of service? Because if you begin to see it, that step function, as you said, was big. In Nathan's slide, that first step function was pretty mean if you looked at, and I can't read exactly what gas was. That first step function, you're pointing to the top left, is that correct, Tony?

TM Yes.

NJ So, in the initial step, both ethylene and methane, are quite dramatic. The ethylene increase may be a clue already in the DGA that maybe this is a metal-to-metal contact that's causing the heating, but it still requires the additional evaluation, the additional testing to be confident to the failure mode. I know we're going to go into machine learning and AI as part of the discussion as we proceed here, but I think there are some thoughts that maybe you could have an AI applied just to trends like this and identify faults. I tend to think that's unlikely, so the kind of guidance to do, first the warning from the monitoring system, then the kind of initial diagnostic and the decision support, what should we do next? I think those are all key elements, and I think you do need SMEs working with tools like this to make those sorts of decisions.

TM I think Nathan's got a very good case there. It's an interesting example of the diagnostics coming into support and getting contextual data. The problem on the asset management side is if you take a transformer out because you found condition monitoring data that indicates a possible problem, and you don't find a problem, when you go and dive inside and you do all the testing that can happen, you get yelled at for the fact that you're not using the transformer to generate money somewhere. If you don't take it out and it fails, you also get yelled at. And yes, I've been yelled at. So, there are two places that you really don't want to be, and you're stuck between them, the rock and the hard place.

AR Well, in your example, you get yelled at whichever you do, so it's a Catch 22, right?

TM Yes. The decision maker isn't necessarily going to be an expert in the condition monitoring, or the technical application, or the individual measurements and the failure modes analyzed, and what might be wrong. It does get to be a difficult decision.

AR Gentlemen, this has been a fascinating discussion about where we are now when the equipment speaks, but we must end Part One here. In our April/May issue we will address the rest of our conversation, on AI, ML, advanced monitoring and how things are changing, discussing "Where We Are Going: When the Equipment Speaks." Thank you very much, Nathan and Tony.

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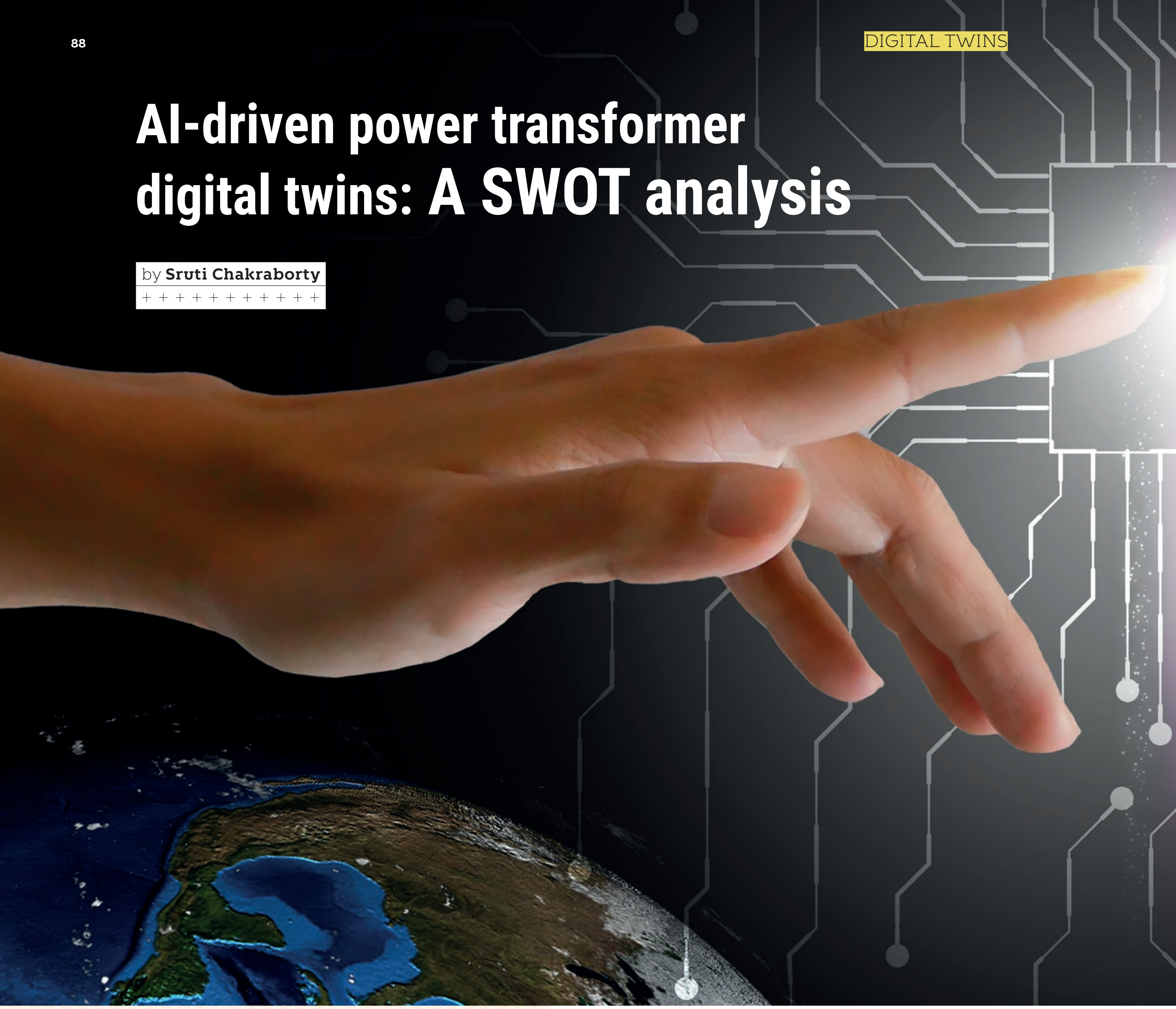
AI-driven power transformer digital twins: A SWOT analysis

by **Sruti Chakraborty**



Introduction

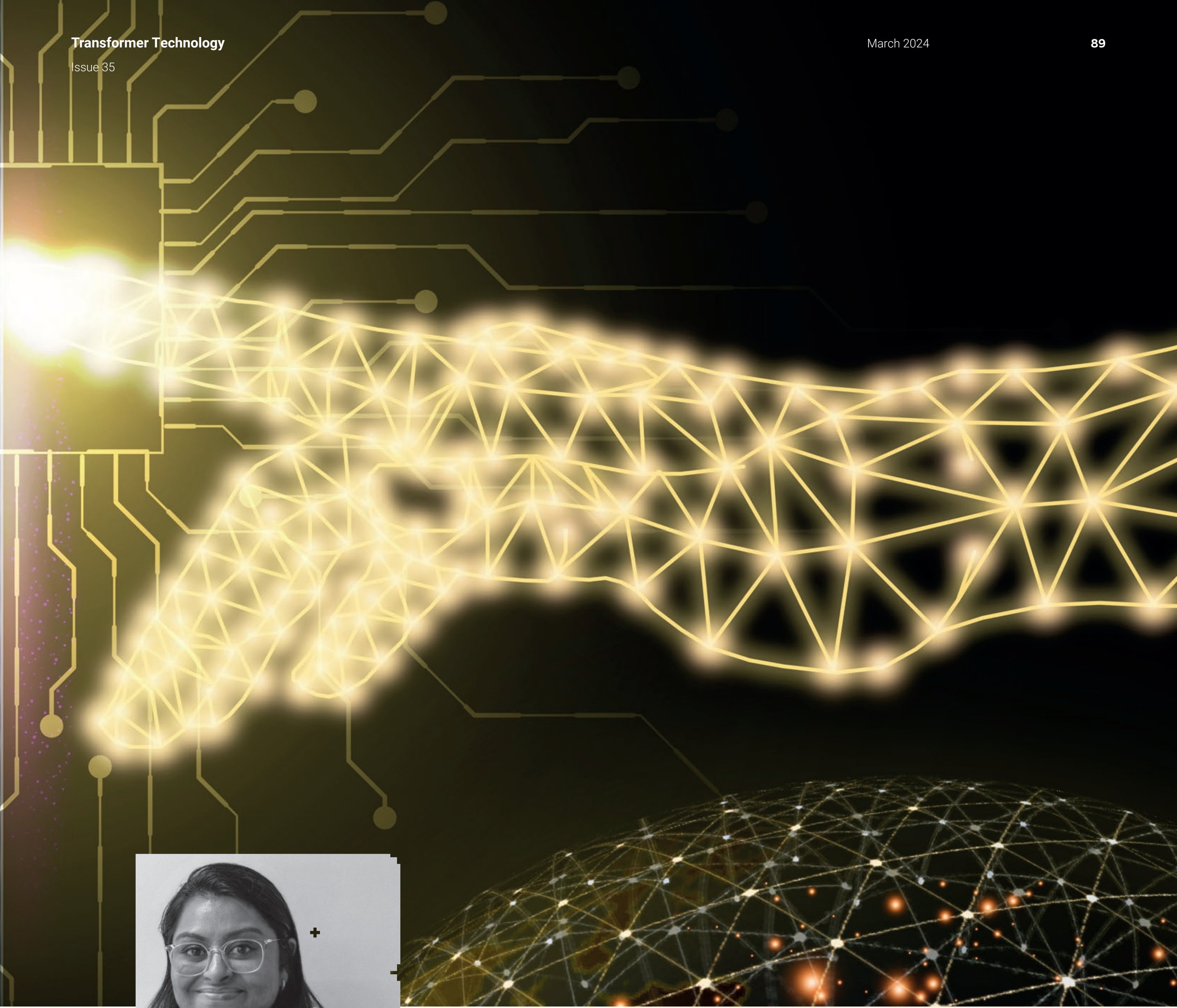
The emergence of digital twin (DT) technology in the power sector has improved the grid operators' confidence to visualize the asset state in real-time and provide decision-support that particularly aligns with the smart grid objectives. According to Conseil International des Grands Réseaux Electriques (CIGRE), a DT is the virtual replica of a physical asset that can foster a dynamic shift in managing its operational efficiency and reliability in real-time. It is useful when the equipment (or process) changes over time, or the data associated with this change can be captured and analysed. This brings the necessary traction for the use of DT in the transformer industry to revolutionize the traditional approaches towards design optimization, monitoring, and asset management.

A transformer DT differs from its simulated model by its forecasting abilities over time-series feedback using bi-directional communication between the physical and virtual assets. However, errors in scaling-down of the physical asset, abstraction of the phenomena under investigation, and obscure objectives can significantly affect its performance. Overall various factors contribute towards the design of a transformer DT which requires a wide range of data, devices, protocols, and expertise thereby increasing its cost and complexity. The focus of CIGRE joint working group A2/D2.65 is to address this reality gap and provide recommendations for the future development of such technologies.

A transformer DT differs from its simulated model by its forecasting abilities over time-series feedback using bi-directional communication between the physical and virtual assets.

Building an AI-driven digital twin

The present-day smart grid is a complex cyber-physical labyrinth comprising of various IoT devices, advanced robotics and automation. The integration of artificial intelligence with typical DGA-based fault detection methods can offer a nuanced predictive analysis.



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Sruti Chakraborty is a Product Manager at Omicron Electronics GmbH and has previously served as the domain expert in Seetalabs srl. She holds a PhD in Chemical Engineering from MNIT-Jaipur, India. Her area of operation includes digital transformation of traditional condition monitoring practices and develop low-cost solutions for risk management and failure mitigation of industrial assets including power transformers. She is hugely passionate about optimizing asset reliability and reducing data complexities in transformer industry using artificial intelligence (AI). She is the working member of CIGRE WG A2/D.65 and A2/D1.67 where she is contributing towards developing recommendations to solve various AI-driven data handling and analytics bottlenecks. She also hosts periodic tech-talks with industry professionals on various challenges and solutions in the field of clean technology, AI, cyber-security, and smart grids.

Dataset at a glance

A transformer DT should have access to its feature database integrated with supervisory control and data acquisition (SCADA) systems where information travel securely through IoT (internet of things) pipelines in to computational spaces that are either cloud or edge based for modelling and analytics. Some utilities also build comprehensive internal databases that are representative of various operational scenarios of their assets by combining, for example, IEC TC 10 database with condition monitoring data to enhance its future use. The user can visualize their asset and fleet information through charts, graphs, and even geographical maps. The user can either examine the asset characters on static and dynamic scales, add-up various assessment functions for analytics, or predict remaining life.

Data preparation: pre-processing, normalization & mining

Transformer data may be sparse, structured or unstructured, static or dynamic, and non-comparable i.e. lacking normalization. Data pre-processing refers to the initial cleaning and transformation of raw data into useful format. It includes managing missing data by removing redundant or inconsistent information and imputing missing fields. Normalization can be achieved by strictly defining the upper and lower limits of attributes or diving the numerical value of features with their IEEE and IEC limits [1]. Managing unclear attributes and arranging data into structured formation increases the full potential of various data mining algorithms viz., regression, classification, clustering, and association to effectively explain the system behaviour. In data-driven modelling terms, *regression* refers to the process of quantifying relationship between two or more variables; whereas, *classification* is finding different classes from a dataset that share a common attribute. Similarly, *association* is the co-occurrences of values for different variables; whereas, *clustering* is the act of finding groups of similar observations within a dataset [2].

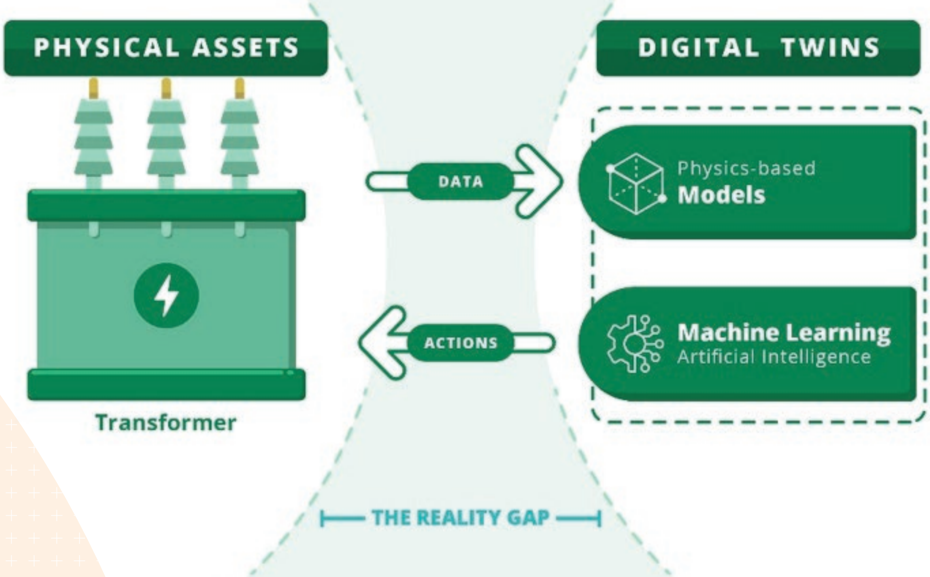


Figure 1:
CIGRE's realisation of transformer digital twins

Feature extraction and selection

Feature scaling through extraction and selection is a significant step in AI-driven model frameworks to reduce data collection cost, avoid computational bias and optimize model performance. Feature extraction is the logical or rule-based creation of sub-features from an existing dataset. Whereas, feature selection refers to the act of choosing a set of features or attributes from the parent dataset based on the quality, continuity, impact, significance etc. Dimensionality reduction is another helpful technique to reduce the feature dimensions of a parent dataset by removing irrelevant information without compromising its distinctive significance.

Feature scaling through extraction and selection is a significant step in AI-driven model frameworks to reduce data collection cost, avoid computational bias and optimize model performance.

Knowledge extraction through AI

Artificial intelligence (AI) refers to the learning ability of machines to simulate human intelligence and perform complex tasks, particularly when it is beyond the human scope. Whereas, machine learning (ML) is the development of a model's capacity to predict better outcomes based on its training on the past data by using one or more algorithms and with additional learning to address uncertain scenarios [3]. Often AI sub-fields e.g. deep learning and neural networks overlap to form new technologies to address other advanced challenges. For example, generative AI is another subset of AI that creates new content, data, or solutions autonomously by learning from the existing data. Popular generative AI model such as Chat GPT excel in natural language processing tasks to produce coherent and relevant text upon receiving related inputs and prompts. There is a similar rise in the use of generative adversarial network (GAN) for synthetic image generation and synthetic minority oversampling technique (SMOTE) or borderline-SMOTE (B-SMOTE) for numerical data generation. The latter is of particular interest in transformer industry due to its ability to generate reliable synthetic dataset for compensating various inconstancy issues. Figure 1 shows a simplified summary of various AI sub-fields that finds diverse application in energy sector.

Often AI sub-fields e.g. deep learning and neural networks overlap to form new technologies to address other advanced challenges.

There is an additional weak description on the dividing boundaries between some methods within an AI sub-field. For example, linear discriminant analysis (LDA) is a supervised machine learning approach that is a classifier and feature selection tool. Similarly, Random Forest (RF) algorithms are classifiers, regressors, as well as model optimizers. Additional examples are illustrated by Figure 2 to represent the use of various algorithms in mining (solid lines) and feature scaling (dashed lines). Therefore, it is imperative to understand the problem objective, data characteristics, computational affordability, and cost before choosing a suitable method.

Error and accuracy

Most comprehensive frameworks use a combination of various models known as ensemble to improve accuracy and reduce errors. It also leverages *boosting* and *bagging* of data to reduce error and uncertainty tolerance during training of the dataset. The trade-off between bias and variance in choosing any method depends on its generalization impact on the model performance. Additional factors such as strategic positioning of algorithm stack (model learnability) is especially decisive in designing an AI-driven framework such as a multi-layered neural network to perform particular jobs while avoiding overfitting risks. Often the use of robust libraries within a programming environment can help to achieve this task.

Data security and privacy

It is pivotal to ensure data integrity while protecting its privacy, particularly in AI models that handle sensitive or

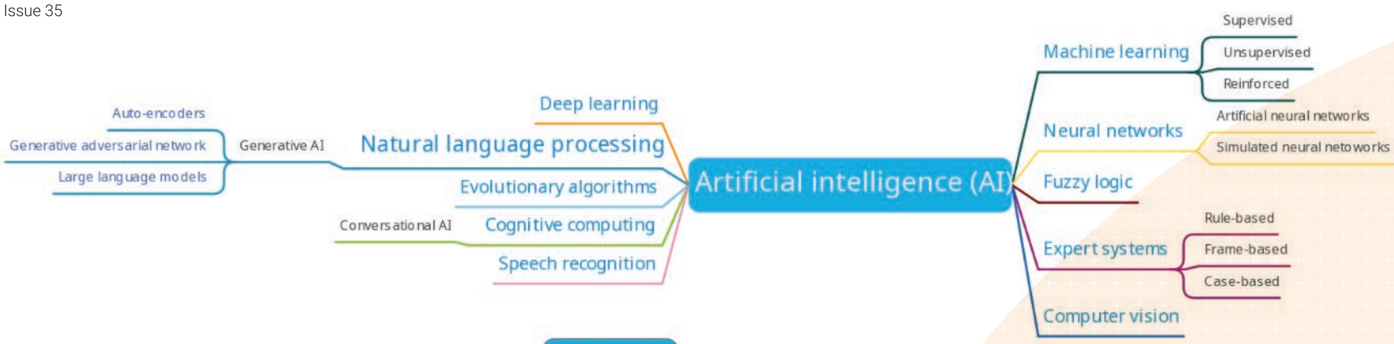
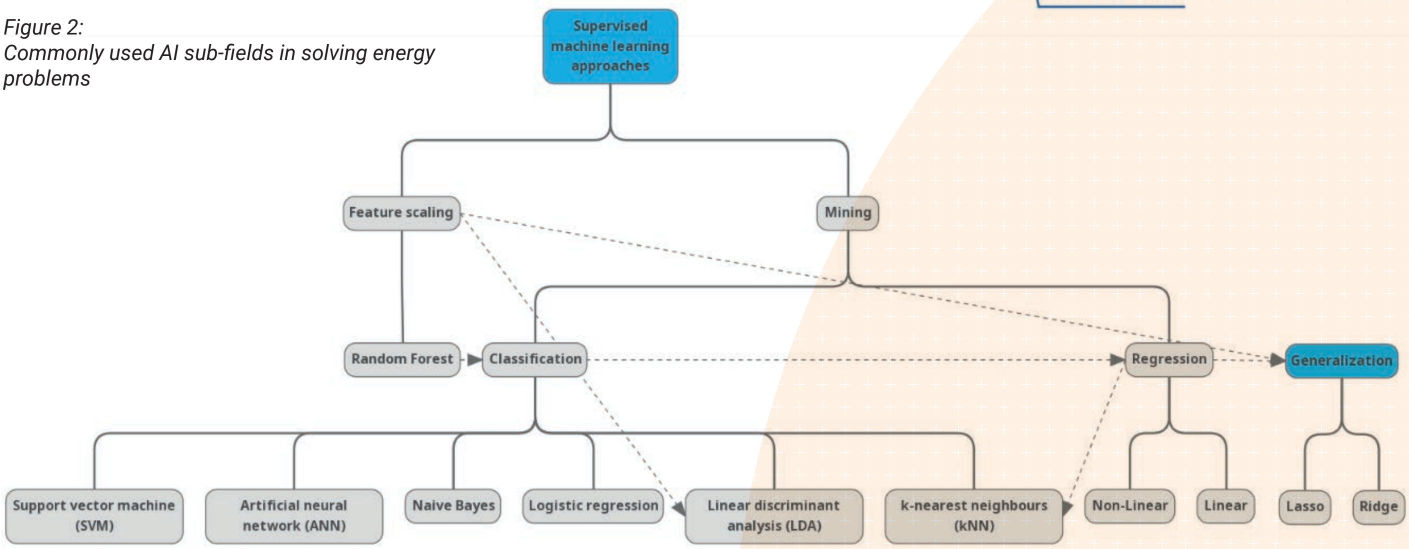


Figure 2:
Commonly used AI sub-fields in solving energy problems



proprietary information. According to the General Data Protection Regulation (GDPR), pseudo-anonymisation of data can dissociate its personal identity such as test results from the data subject (e.g. nameplate information, manufacturer etc). This can ensure that AI-driven training of datasets for a transformer DT can still allow the model to learn and make accurate predictions without compromising security. The choice between popular pseudo-anonymisation techniques such as *encryption* and *tokenisation* depend on requirement, robustness of method, storage requirement, and computational resources.

Reliability assurance

The reliability of any AI-driven transformer DT focuses on the integrity of its model, training data-quality, interpretability and reproducibility. Sparse and low-quality data not only lowers accuracy but also restricts model scalability. Developing model ensembles with adequate stacking of algorithms for pre-processing and feature scalability can also overcome the risk of overfitting during development. This enormously improves the efficiency of AI-based mining algorithms and promotes multi-objective delivery suitable for real-world scenarios in optimum cost.

Deployment

The global expert opinion on the deployment model of transformer DT is divided between cloud, edge, and on-premise. For instance, cloud computing can be seamless, robust, and highly scalable but with latency and data-privacy issues. Conversely, edge computing can offer better data processing in close proximity of the device and robustly automated decision support by triggering alarms or sending alerts. However, the choice does not depend on the advantage of one method over another. Instead, what really drives this discussion is the balance between scalability, cost, and resources for infrastructural support.

Digital twins predicting transformer health index

Various organizations use an in-house or proprietary health index algorithm to rank transformers based on its reliability, risk, replacement and/or refurbishment needs. This requires an extensive usage of nameplate data, operational and maintenance history, various test and inspection

Strength	Weakness
• Enhanced predictive capabilities • Real time performance monitoring • Improved fault diagnosis • Robust decision support • Cost effective	• Lack of data quality and quantity • Model interpretability • High data contingency cost • High deployment cost • Require continuous expenditure for infrastructural support
Opportunity	**Threats**
• Potential for proactive maintenance • Integration with other smart grid technologies • Market expansion and increased adoption rate	• Cybersecurity concerns • Ethical consideration of AI • Lack of regulatory protocols • Compliance issues

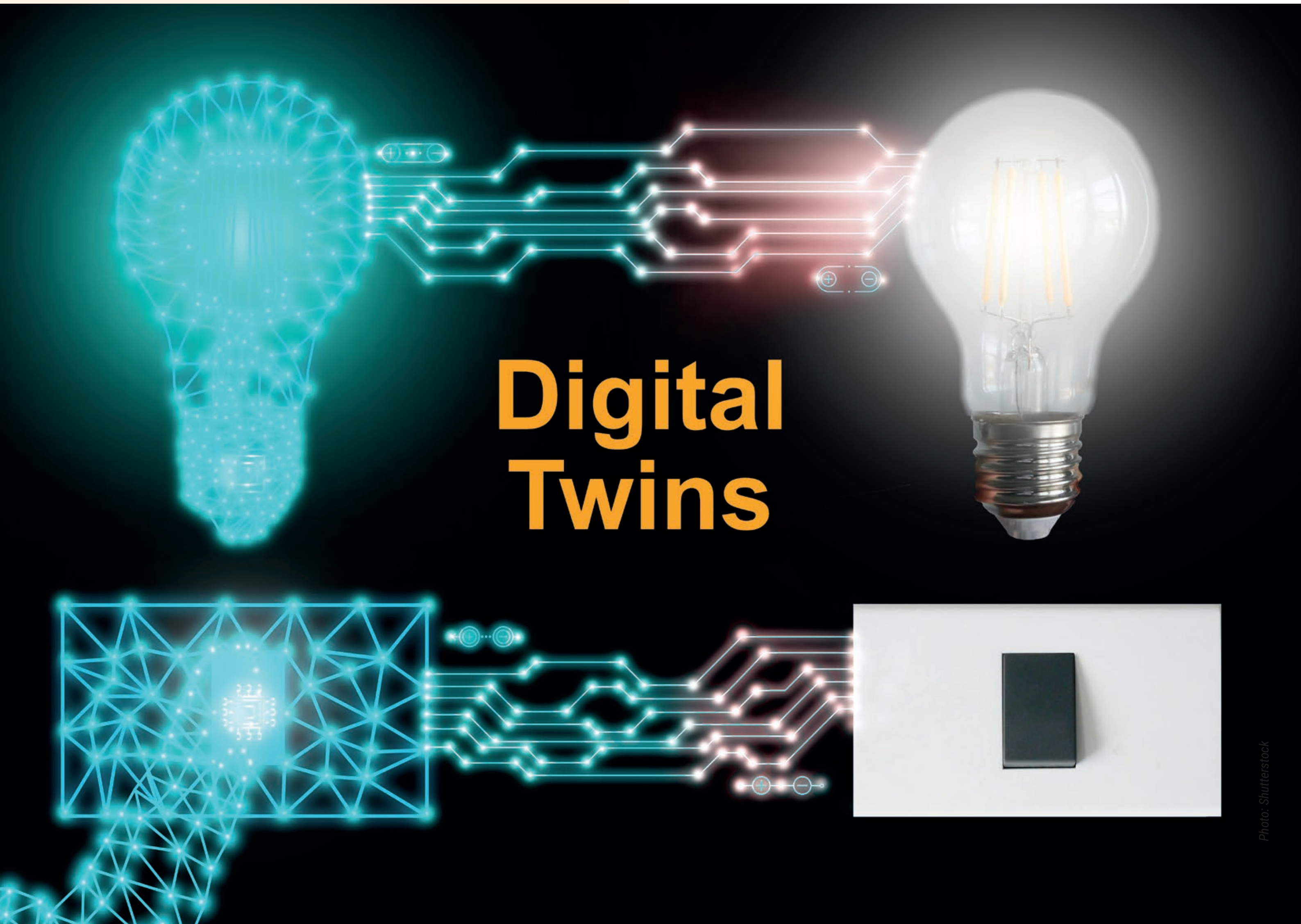
observations, expert opinion etc [4], [5]. Often health index algorithms are based on non- ubiquitous frameworks that align well with PAS 55 and ISO 55000. For example, a health-index classification of “good”, “bad”, “moderate” transformers may use data from DGA, moisture, breakdown voltage, interfacial tension, acidity etc., of oil and furan analysis. A deeper classification on the same may require additional information on tap changers, bushings, physical observations, maintenance history etc.

Depending upon the asset manager’s requirements these algorithms may provide a decision support with a perpetual risk of producing misleading information with low-integrity input. In case of its application on real-world transformers, the training data should be clean, useable, heterogenous and pseudo-anonymized. The training model should assure robustness and accuracy of knowledge extraction using best features or sub-features. There should be sufficient know-how on parameter evaluation, tuning, and AI model validation before its release on unseen and real-world data to avoid over/under-fitting risk. Finally, the user should be able to engage with the physical asset by uploading data and visualizing the analytics through an interactive interface. This will ensure the user (or asset manager) to take necessary actions on the physical asset and immediately update its status to observe future changes. Furthermore, the data transmission between the core model and the user-interface should be encapsulated within well-defined security protocols to avoid cyber vulnerabilities.

An AI-driven approach towards health indexing is definitely a loose use-case of transformer DT that requires additional efforts (in terms of model stacking, data storage, and management) to experience its full potential. Therefore, an obvious matter is to decide if a single DT reflecting health index is sufficient for all transformers in a fleet, or not? Also, if the DT is relatable enough?

An AI-driven approach towards health indexing is definitely a loose use-case of transformer DT that requires additional efforts (in terms of model stacking, data storage, and management) to experience its full potential.

In case of transformer DT, accuracy is not merely a reflection of the model's adept predictive capabilities but an illustration of a calibrated balance between adhering to training data and maintaining adaptability to new and real-world data scenarios. The interpretability and reproducibility of DT outcomes will determine its relatability and reliability. Furthermore, it is difficult to propose that a single DT can mirror the status of all transformers in a fleet, considering even physical twins may behave differently. Therefore, successful deployment and industrial scale transformer DT offering health index



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will not only depend on various practical considerations discussed above, but also on its calibration towards uncertainty tolerance and data influx, particularly if data sources vary. There is a wide scope of investigation on the sensitivity analysis on the impact of data availability rate on the predictive accuracy of such DTs. A summary of the full potential of an AI-driven transformer DT with reference to the knowledge shared is proposed below.

Conclusion

An AI-driven transformer digital twin can adapt to various smart grid objectives by real-time analysis, predictions, and bi-directional communication between the physical and the virtual asset. However, the choice of AI methods will depend on the handling strategies between static and non-comparable data. The accuracy and performance of model can improve by structed stacking and addressing the bias-variance trade-off between various methods based on data complexity. Maximizing return on investment (ROI) for an AI implementation can be challenging and involves do- or buy-decisions. This would mean that the asset manager must decide whether to leverage in-house know-how on building AI models or use existing solutions. This cost and expertise for such customization depends on the downtime impact assessment, internal budgets and user adoption rate. Based on the evident findings, adoption of transformer DT can be a game changer for the smart grid operators.

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