

# THE EYE ON MEDIUM-VOLTAGE SWITCHGEAR

## Protecting critical assets with wireless monitoring

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With ever-increasing power demands, electric utilities find themselves in a race to maximize the reliability of their electrical assets while minimizing downtime. As a critical junction point in power distribution, medium-voltage switchgear represents one of the most vulnerable links in the power grid. These valuable assets are subject to overheating due to excessive loads, normal wear and tear, and challenging environmental conditions. Left unattended, these conditions can lead to failures resulting in costly damage to switchgear and surrounding equipment, power production loss, and in extreme cases, severe injury or death.

Condition-based monitoring has been in practice for some time, most often achieved through periodic manual inspection while the switchgear is powered down. Implementing continuous monitoring gives electric utilities the ability to collect data generated during the switchgear's normal operating conditions, thereby providing awareness to problems in real time.

Real-time trending during full load electrical stresses, vibration, insulation breakdown, and environmental influences, quickly provides insight into the health of the utility's asset. When performing continuous monitoring, it is not critical to identify the exact location of degradation, but to understand the trend of the defect over time. Possessing the ability to monitor and trend the most common failure modes allows for planned maintenance events to assess the health of the asset over time versus running the risk of asset failure resulting in unplanned downtime. Common failure

modes include excessive temperature, partial discharge (PD), and humidity (refer to "Common Failure Modes" sidebar).

### THERMAL MONITORING

One challenge in implementing continuous monitoring of critical connection points (circuit breakers, busbars, and cable connections) inside the switchgear is that the system must maintain the impulse-withstand (Uimp) voltage, also known as basic impulse level (BIL). Consequently, conductors at different

### COMMON FAILURE MODES

**Excessive Temperature:** Circuit breaker, bus bar, and cable connections tend to loosen or corrode, causing thermal failure of the connection and nearby insulation

**Partial Discharge (PD):** Voltage stresses on the insulation lead to surface and internal discharges, degrading the insulation between live conductors and ground

**Humidity:** Moisture within switchgear can create shorts, or be absorbed by the insulators, leading to insulation breakdown

Photo credit (chalkboard): Ilker

potentials must have a minimal distance between each other to prevent breakdown to ensure the impulse rating.

For example, the IEEE Standards Association's C37.20.3: "Standard for Metal-Enclosed Interrupter Switchgear, Section 5.2" states switchgear rated with a maximum voltage of 15 kilovolts must have an impulse voltage of 95 kilovolts, relating to a distance (in air) of approximately 160 millimeters. This requirement eliminates the most common types of direct contact temperature monitoring systems, leaving only non-intrusive systems to consider for switchgear thermal monitoring. Fiber-optic systems, infrared (IR) monitoring, as well as wireless direct contact sensors are non-intrusive options available to utilities.

#### • Periodic IR Monitoring by Technicians

Periodic infrared monitoring techniques require a glass window to be installed in the switchgear, a relatively expensive IR camera, and a technician. Not being a continuous monitoring methodology rules this out as a viable option.

#### • Continuous IR Sensor

Although non-intrusive and continuous, the mounting locations are limited. While a viable solution, measurement limitations are present when adjacent surfaces have different emissivity or reflections. Additionally, utility personnel cannot perform monitoring procedures behind bus insulators and cable shrouds because line of sight is required. Finally, the proper alignment of the single-pixel camera is difficult to achieve and is susceptible to misalignment when subject to vibration and shock.

#### • Fiber-Optic Systems

Fiber requires direct surface contact, and although considered non-intrusive, fiber-optic systems are generally expensive to purchase and install. Moreover, operating in dusty and humid environments (often the case in actual field conditions), the fiber-optic cables can create a conductive ground path, compromising the aforementioned withstand voltages.

#### • Wireless Active (battery-powered) Direct Contact Sensors

At first glance, these systems seem to provide an adequate solution. Unfortunately, batteries have a limited life span, which is typically reduced in high-temperature environments. The associated cost of taking the switchgear out of service to replace batteries is untenable from an operational perspective and, consequently, elevates the actual cost of system ownership.

#### • Wireless, Passive, Direct-Contact Sensors

Wireless, passive, sensor systems provide real-time continuous monitoring, with a direct connection to all critical measurement points. These systems are easy to install, require no maintenance, and have a life expectancy comparable to the switchgear itself. Dissimilar to RFID systems, surface acoustic wave (SAW) temperature sensors have longer reading distances, thus maximizing basic impulse levels, while using lower transmission power to minimize control system electromagnetic compatibility (EMC) issues. The aforementioned features make these sensors the preferred option of wireless passive sensing.



**Continuous, real-time monitoring of MV common failure modes (excessive temperature, partial discharge (PD), and humidity) could have prevented the damage inflicted upon this MV switchgear.**

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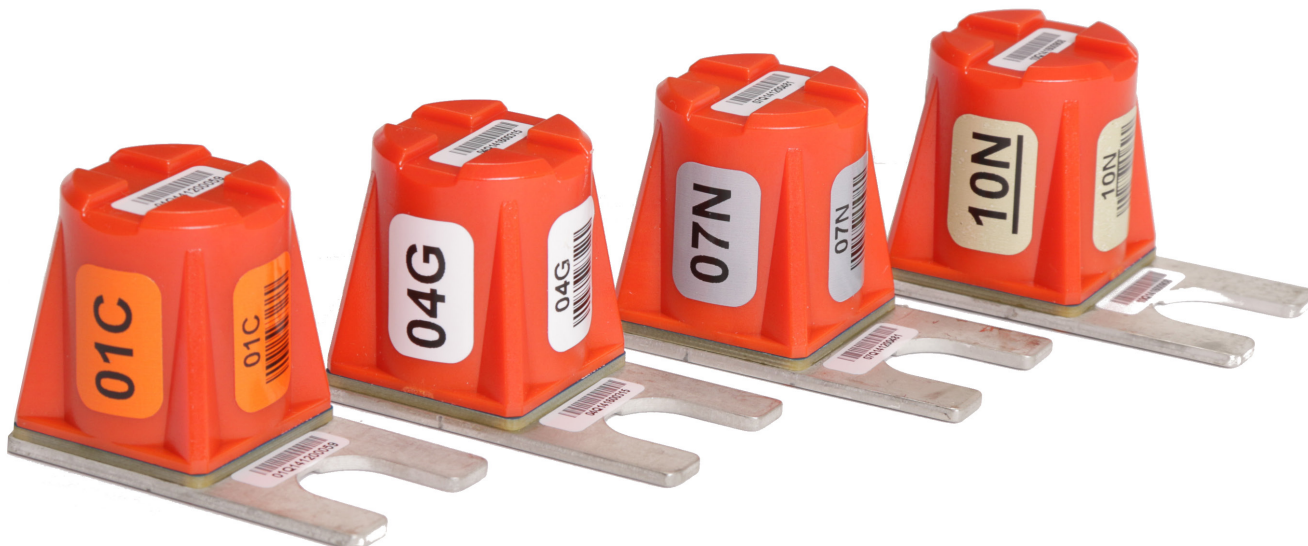
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**Wireless, passive direct-contact SAW temperature sensors used for monitoring MV switchgear thermal hotspots**

### Surface Acoustic Wave Monitoring Systems

A surface acoustic wave (SAW) sensor consists of a piezoelectric substrate (a material that changes electrical charges due to mechanical stresses), an interdigitated transducer (IDT) resonator, and an antenna. An IDT is a device with interlocking metallic electrodes (similar to a zipper) that is deposited on the surface of the substrate. The spacing between these electrodes determines the frequency of the acoustic wave. One of the most common piezoelectric materials used is quartz crystal, and when subjected to temperature, the crystal contracts and expands on a

microscopic level. This physical change alters the spacing between the IDT electrodes; therefore, changing the frequency of the surface acoustic wave.

The SAW temperature sensing process involves an interrogation unit transmitting an alternating current electrical signal, which is received wirelessly by the sensor's antenna. The input signal creates alternating polarities on the IDT where a mechanical wave is generated on the surface of the substrate. The surface wave confined to a resonator is reverted to an electrical signal where it's echoed back to the interrogation unit. The echo frequency, influenced by

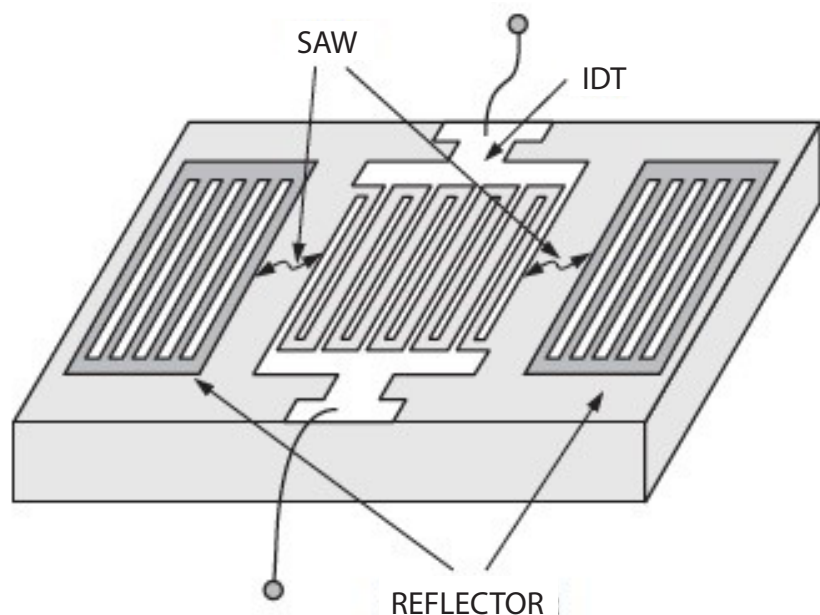
environmental conditions of the sensor's surface material, is processed as a temperature measurement. The wireless passive operations of SAW systems provide many advantages when monitoring medium-voltage switchgear temperature (refer to "Monitoring MV Switchgear Temperature" sidebar).

### PARTIAL DISCHARGE MONITORING

As insulators age, weak spots and defects evolve, and under certain load conditions, a dielectric breakdown will initiate across the defect, causing a partial arc between conductors at different potentials. This effect is known as a partial discharge. The breakdown causes a small, but sudden, rise in current accompanied by a current pulse, as well as electromagnetic (radio or light), acoustic, and ozone emissions.

The most commonly used PD detection instruments directly measure the current and voltage spikes in high-frequency current transformers or high-voltage capacitive couplers as outlined in the International Electrotechnical Commission's IEC 60270 standard: "Partial Discharge Measurements".

This method has several strengths, including an ability to analyze pulse shapes



**Design concept of a typical SAW temperature sensor, showing the quartz substrate with deposited IDT and reflectors.**



**SAW temperature sensors (orange sensors) installed within a MV switchgear at the circuit breaker input and output bus connections**

Photo credit (chalkboard): Ilker

and to assemble a graph of the discharge events relative to the phase of the power line waveform. These systems are very expensive and require trained technicians to analyze the data; therefore, these systems do not lend themselves to permanent, continuous monitoring installations.

In addition, the coupling detectors are contact methods, and—although designed for safe operation at the rated voltages—dust, humidity, breakdown of the nearby insulators, and improper installation can impair their safety over time.

Utility personnel are currently evaluating additional partial discharge detection methods with IEC 62478, a prospective standard for acoustic and electromagnetic PD measurements. These instruments use indirect analytical measurements to obtain a relative signature of PD pulses that testers can use for system trending. Transient earth voltage (TEV), high frequency (HF) as well as very high frequency (VHF), acoustics, and ultra high frequency (UHF) are common types of systems available.

## MONITORING MV SWITCHGEAR TEMPERATURE

The advantages of using SAW systems

- 1** Utility personnel can directly mount sensors onto critical measuring points while ensuring safety basic impulse level requirements are met
- 2** Sensors, manufactured from quartz crystal, offer electric utilities with a monitoring solution for the lifespan of the switchgear—without ongoing maintenance
- 3** Sensors do not require line of sight to the antenna, offering installation flexibility
- 4** Utility personnel can install SAW systems in harsh environments where switchgear is located





**A band-pass UHF partial discharge antenna easily installed in a safe position (upper corner) of a MV bus tie**

#### • Transient Earth Voltage

The TEV method is common for monitoring partial discharges. Utility personnel use TEVs to test the switchgear externally by measuring the electromagnetic emissions conducted to ground. Although testers can use TEVs for continuous monitoring, these voltages cannot always monitor faults between phases.

#### • High Frequency (HF) and Very High Frequency (VHF)

HF/VHF systems operate between three and 300 megahertz (MHz) and use large antennas, high-frequency current transformers, or coupled sensors. Large antennas are not compatible with measurements inside switchgear and direct-coupled sensors impair safety.

#### • Acoustics

Testers use a microphone or similar acoustic sensor to monitor frequencies between 10 hertz (Hz) and 300 kilohertz (kHz). Utility personnel can use this wireless method for continuous monitoring but has a limited detection range due to sound damping within dielectric objects. Instead, acoustics is more suitable for use in corona materials.

#### • Ultra High Frequency (UHF)

This broadband (300 MHz to three gigahertz) detection method monitors transient electromagnetic waves through an antenna. Traditional UHF methods are susceptible to noise from cell phones, radios, and other transmitters. However, vendors and manufacturers have introduced new instruments using selective, banded UHF monitoring to detect partial discharges while rejecting noise sources. UHF provides the safest, most non-intrusive continuous PD monitoring system.

#### BAND-PASS UHF PARTIAL DISCHARGE DETECTION

The development of a PD detection system must provide the relevant information necessary by decision makers to assess the health of the switchgear insulation. Such a design must include band-pass UHF PD detection methods as well as universal installation for all medium-voltage switchgear.

An autonomous approach to partial discharge detection for continuous, condition-based maintenance requires a system to distill an overwhelming amount of complex data down to a

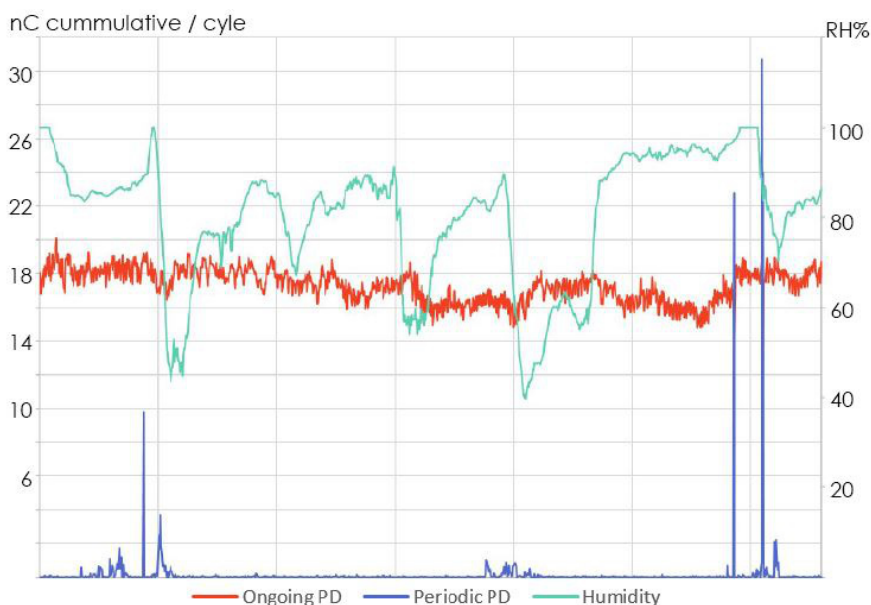
concise piece of information without requiring a highly trained operator.

Band-pass filtered UHF partial discharge detection methods are capable of avoiding strong interfering signals at close proximity while advanced digital filtering methods are capable of detecting the presence of partial discharge—even with residual, unfiltered noise.

#### SELECTING MONITORING BANDS

The selection of the system monitoring bands should be aligned to the electromagnetic characteristics of the switchgear. Low-emission frequencies from 100 MHz to 300 MHz are often found in assets such as motors and transformers and can also be found in long cable runs. Emission frequencies between 400 and 800 MHz are often found in medium-voltage switchgear centered on the cavity resonance while higher frequencies are found in bus ducts that act as wave guides.

A fundamental challenge of any design is to provide a sufficiently low noise figure in the target measurement band while concurrently avoiding “jamming” problems caused by large



**Continuous, real-time trending of partial discharge events capturing periodic PD spikes due to condensing humidity; these events are unrecognizable with traditional (non-continuous) detection methods**



**Medium-voltage substation switchgear lineup benefiting from real-time, continuous condition-based monitoring**

signals outside the desired band. Size constraints and cost targets are also considerations when choosing bands for monitoring.

Frequencies such as 868 MHz industrial, scientific and medical (ISM) devices in Europe, Asia, and Africa, and 902 to 928 MHz devices in the Americas must be filtered, as there are often high power transmitters in close proximity, for example one-to-four watt radio frequency identification (RFID) transmitters.

#### **ANALYZING & CLASSIFYING DATA**

In order to provide an autonomous approach for PD monitoring, advanced system algorithms must be implemented to present data that can be easily processed for health assessment and long-term system trending. UHF emission signals can be broken into three major categories: noise as well as asymmetric and symmetric discharges.

##### **• Noise**

Noise denotes UHF energy in the selected frequency band(s) that does not correlate well with the power line frequency. External radio interference is a reliable classification of noise; however, weak and erratic partial discharge, which occurs early in the evolution of a defect, is also a noise classification.

##### **• Asymmetric Discharge**

Events occur primarily on the negative half cycle of the power waveform, where electrons emitted from the metal ionize the air. Asymmetric discharge (also called corona or surface discharge) presents significant results at both odd and even harmonics of the power line frequency.

##### **• Symmetric Discharge**

Discharge events that occur in the bulk of the material, often referred to as internal or symmetric partial discharge, happen at the positive and negative polarity portions of the power cycle and are often represented as even harmonics of the power line frequency.

#### **SELECTING AN APPROPRIATE ANTENNA**

Whip style antennas, often 20 centimeters or larger, are commonly used in handheld surveying tools, given their efficiency. The basic

impulse level requirements of medium-voltage switchgear will typically not allow for this type of antenna.

A number of broadband antenna structures exist, one of the most promising is the Archimedes spiral. Although slightly larger than desired, these antenna types can provide the required frequency range. Additionally, utilities must consider the bi-directionality of the spiral and the negative reflection off the metal wall it's mounted on as it could result in poor antenna efficiency.

The ideal option is a patch inverted-F antenna (PIFA). The construction of these antenna types is such that all metal parts are bonded to protective earth at 50 to 60 Hz and the entire metal structure may be encased in flame-resistant acrylonitrile butadiene styrene (ABS) plastic to ensure proper safety requirements are met.

The dielectric strength is 32 kilovolts per millimeter, providing a functional insulation to a working voltage of 96 kilovolts. While electric utilities should not solely rely on the ABS to provide safety isolation, it provides supplemental insulation that more than makes up for the 43 millimeters of reduction in air gap with respect to working voltage and basic impulse level ratings. At 200 by 175 by 43 millimeters, a PIFA antenna is well suited to even the most compact switchgear designs.

#### **WHY CHOOSE WIRELESS**

Utility executives want all medium-voltage switchgear operating properly—and continuously. Electric utilities can achieve this goal with a reliable, cost-effective condition-based monitoring system (for example, wireless sensing). Payback periods associated with wireless system deployments are short and the resultant exposure to trending information specific to critical asset health immediately afford enhanced reliability along with reduced downtime through a predictive maintenance regimen.

Moreover, electric utilities can achieve high safety standards when using passive sensing elements, while, simultaneously, affording accurate, reliable, and low-maintenance thermal monitoring. The selected continuous PD monitoring system must fit in all switchgear for a permanent—and safe—installation, and output actionable data that is essential to detecting historical trending and partial discharge events.

#### **FAMOUS LAST WORDS**

Microgrids in a cellular power network, aligned with a modernized transmission backbone, are technically feasible. The remaining technical challenges will likely be resolved, thanks to the economics of the resulting power market influencing the outcome. Meanwhile, business, environmental, and aspirational drivers will push top-down and bottom-up microgrid implementations. These factors will have major implications for all stakeholders and energy provisioning in the 21st century. **ET**

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