New gas and particle sensing technology detects cables overheating in LV equipment

by Abderrahmane Agnaou and Mathieu Guillot

Executive summary

Deteriorating cable connections in electrical systems continue to be a major cause of fires in buildings, resulting in damage to equipment, business downtime, and safety risks to personnel. Traditional infrared (IR) thermography can miss hot spots that occur between periodic inspections. Continuous thermal monitoring is a more comprehensive approach, but is best suited for applications with few connection points, such as medium-voltage equipment, busways, and main low-voltage busbars.

This paper introduces a cost-effective technology – ideally suited for low-voltage switchboards with large numbers of cables and connection points – that uses advanced gas and particle analysis to detect and alarm on cable overheating risks before equipment damage or fire can occur.

Introduction

Problems in electrical equipment continue to be one of the leading causes of fires in commercial and industrial properties. The European Fire Academy (EFA) estimates that 25% of building fires are electrical in origin,[1] while the U.S. Fire Administration estimates a 26% increase in nonresidential buildings fires, in which 7.8% of the fires are attributed to electrical malfunctions and resulting in losses of nearly $373 billion. Further, it was noted that heat from powered equipment was the primary cause of fires in non-confined, nonresidential buildings.[2] In terms of damages, an Allianz Group global study of insurance claims between 2013 and 2018 revealed that "fire and explosion incidents … cause the largest claims for insurers and businesses" and that "faulty workmanship" is one of the top causes of liability losses for businesses.[3]

Electrical fire events have very real impacts on people and property. In 2018, a transformer fire at an electrical center run by the national transport network southwest of Paris paralyzed traffic in and out of the city's Montparnasse train station, affecting 100,000 travelers. It also prompted an evacuation of 2,500 people – including an adjacent Microsoft headquarters – and caused a power cut to approximately 16,000 homes.[4] In 2015, a fire caused by an electrical fault devastated part of a terminal at Rome's Fiumicino airport and caused many flights to be canceled impacting thousands of passengers.[5]

These kinds of statistics and stories highlight that there are further opportunities for reducing electrical fire risks.

Figure 1

The European Fire Academy (EFA) estimates that 25% of building fires are electrical in origin.

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[1] European Fire Academy

[2] U.S. Fire Administration

[3] "Allianz global claims analysis", 2018

[4] "Fire halts train traffic at Paris's Montparnasse station", France24, July 2018

[5] "Rome's Fiumicino airport in chaos after terminal fire …", ABC News, May 2015

Electrical safety in low-voltage (LV) electrical equipment has made great progress in recent decades, largely thanks to the IEC 61439 standard that defines best practices for LV switchgear and controlgear assemblies.[6] The electrical industry has also better mastered thermal behavior of equipment, which has helped reduce the risks of mains overheating. Further, the electrical breaking capacity of protective devices has limited the short-circuit consequences, such as mechanical damage, due to excessive electrodynamic forces.

Selection and protection of cables are also well mastered, thanks to the IEC 60364 standard for LV electrical installations,[7] and related national wiring rules. In addition, many software tools on the market support electrical designers in properly selecting cables and related overcurrent protection.

However, one risk that is still not fully covered by design standards is poor connections – in particular, connections of conductors to terminals in LV assemblies such as switchboards and panelboards. These connection issues remain a large cause of defects in electrical installations, the worst of these being loose or faulty connections that cause hot spots, thermal runaway, and ultimately, ignition of a fire in an electrical enclosure.

Several steps can help reduce these risks, including:

1. Choosing the best electrical equipment designs that are manufactured to high standards. Devices such as circuit breakers can include innovative device terminal solutions that help maintain a tight cable connection.
2. Ensuring that panel builders follow best practices for equipment assembly, e.g., applying proper torque to all connection points.
3. Ensuring that electrical contractors follow best practices for equipment installation.
4. Perform periodic maintenance according to the manufacturer’s recommendations.

However, even with the best equipment and practices, connection problems can still occur. For this reason, there is a need for monitoring.

Traditionally, thermographic infrared (IR) analysis has been used, but it can miss problems that occur between scheduled inspections. Newer thermal monitoring technology offers a safer, more effective solution by using thermal sensors to continuously monitor thermal conditions at primary connection points. However, this solution is better suited for applications with lower density connection points, such as medium-voltage (MV) electrical switchgears, electrical busways, and LV busbars.[8]

Until recently, there remained the challenge of reliably and cost-effectively detecting thermal risks within high-density LV electrical switchboards that include large numbers of cables and connection points.

This paper introduces new technology designed to help prevent electrical fires in such enclosures by detecting cable thermal decomposition in a range of temperatures that provide early warning of an imminent risk of fire.

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[6] IEC 61439: Low-voltage switchgear and controlgear assemblies

[7] IEC 60364: Low-voltage electrical installations

[8] “White Paper, “How thermal monitoring reduces risk of fire more effectively than IR thermography”, Schneider Electric

This paper will also show how insulation decomposition detection (IDD) devices offer a more simple and reliable way to preventively detect cable connection issues for the great majority of LV cable types on the market by providing unique benefits versus other established fire detection systems. The following topics will be covered:

- Typical connections issues in LV electrical assemblies
- LV cable selection criteria and insulation behavior
- Using particle and gas detection to identify insulation decomposition
- System-level solution for alarming on thermal risks: smart IDD device, gateway, and cloud-based application

Typical connection issues in LV electrical assemblies

The equipment inside LV switchgear and panelboards is susceptible to a range of fire risks, as defined by the IEC 63054 standard (see **Figure 2**). Of these risks, poor connections are the most frequent.

Figure 2

IEC/TR 63054:2017 LV switchgear and controlgear – fire risk analysis and risk reduction measure

Mechanism	Frequency
Poor connections	Most
Arcing across a carbonized path	↓
Arcing in air	↓
Excessive thermal insulation	↓
Overload	↓
Ejection of hot particles	↓
Dielectric breakdown in solid or liquid insulators	↓
Miscellaneous phenomena	Least

LV assemblies contain numerous connections between bars, or between device terminals and cables. Each of these connections can suffer from bad installation or degradation over time.

Cable connections can start to deteriorate due to improper tightening torque or constant vibrations over time. Deterioration can also occur because of damaged surfaces due to corrosion, excessive pressure, or excessive friction.

These conditions can be exaggerated by frequent temperature cycling. Fluctuations between cold nights and hot days, or low and high current, cause small movements of the connection, thus reducing the effective contact surface.

In any of these conditions noted, a critical sequence of events can begin: increasing electrical contact resistance induces a rise in temperature that accelerates the damage and the result is a thermal runaway that leads to overheating wire connections and/or overheating cables (see **Figure 3**).

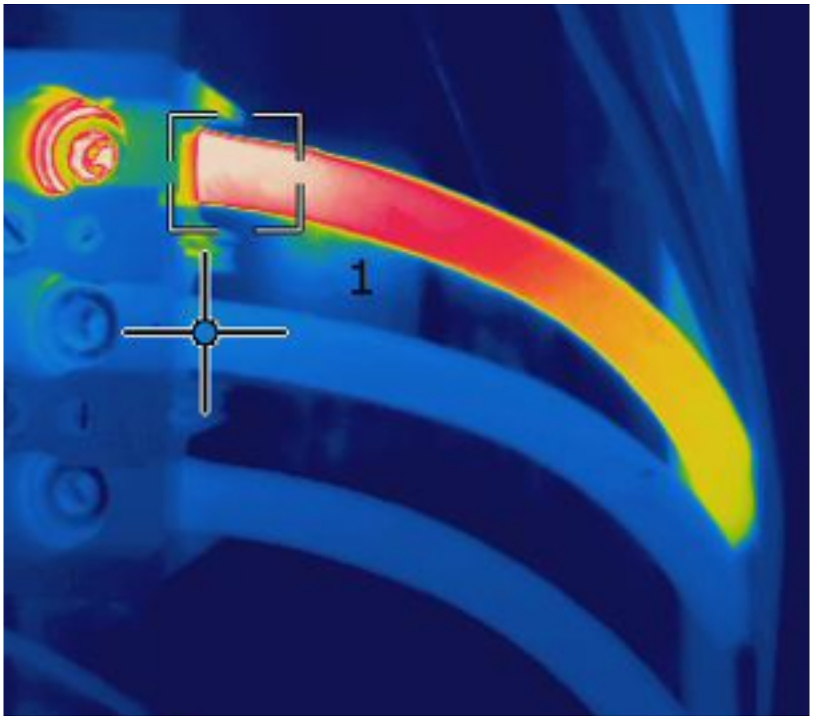

Figure 3

A thermographic image of a cable connection on a molded-case circuit breaker showing how a loose connection causes the connection point and cable to overheat.

> "As the heat dissipated at the connection depends on the contact resistance, which is a function of the normal mechanical load applied across the mated contact surfaces, a loose connection may result in overheating, glowing, arcing, and/or potential fire ignition."
>
> – Source: IEC/TR63504:2017

For more information on aging mechanisms of contacts and connection terminals see ***IEC/TR 60943:*** **Guidance concerning the permissible temperature rise for parts of electrical equipment, in particular for terminals**

– Source: IEC/TR 60943

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[9] IEC/TR 60943 *Guidance concerning the permissible temperature rise for parts of electrical equipment, in particular for terminals.*

LV cable selection criteria and insulation behavior

LV cables are selected according to two main criteria:

1. **Cross-section:** This is determined by the expected load current in a given installation condition.
2. **Type of insulation material:** This is determined by the environment, mechanical withstand, easiness of handling or bending, and regulation (in particular, behavior in case of fire).

The IEC 60364 standard and related national regulations set the rules to protect against overload and short-circuit. IEC 60364-4-43 specifies the coordination rules between the overcurrent protective device and the cables according to the current carrying capacity and the type of insulation material. IEC 60364-5-52 provides the methodology to determine current carrying capacity according to core material, cross-section area, and insulation material.

The most common cable insulation material for LV conductors are thermoplastic (e.g., PVC) and thermoset (e.g., XLPE).

Due to environmental concerns, a new type of 'halogen-free' insulation material is now increasingly present on the market. Also, some special applications may require mineral or silicone insulation material. These materials provide a sufficient level of protection against thermal effects due to overload or short-circuit. This principle relies on the hypothesis that the cross-section area of the conductor is consistent along the entire circuit and so the current carrying capacity is effectively the calculated one.

In practice, cable connections are made through lugs or directly in a terminal block onboard a device. This can put at risk the hypothesis of the theoretical cross-section area used to calculate the current carrying capacity. Any accidental reduction of this effective cross-section area can create a hot spot not detected by the overcurrent protective device.

How insulation materials behave according to temperature

As noted above, as a result of a poor connection, a thermal runaway condition can occur that causes connected cable(s) to rise in temperature.

In LV systems, the most common cable insulation materials are two sub-families of polymer:

- Thermoplastic: e.g., polyvinyl chloride (PVC)
- Thermoset: e.g., ethylene-propylene-rubber (EPR), and cross-linked polyethylene (XLPE)

Though each insulation material has different behavior in case of temperature rise, they all face a similar thermal decomposition process called *pyrolysis*. The stages of this process are as follows (see **Figure 4**):

- **Stage 1:** The insulation polymer changes from a harder, more brittle material into a viscoelastic state material.
- **Stage 2:** When the temperature is increased, the polymer begins to degrade and the molecular weight of the polymer decreases as pyrolysis occurs, producing combustible gas and micro carbon soot.
- **Stage 3:** At this point, the quantity of emitted combustible gas is sufficient to start ignition.

To achieve greater mechanical strength, flame retardancy, aging resistance, other components are added to the insulation material. This can include a stabilizer, plasticizer, lubricant, filler (calcium carbonate), and colorant. These additives can release gas and particles at an earlier stage.

Halogen-free, flame-retardant cables will release different types of gas and particles, but the thermal decomposition process is quite similar and detectable as well.

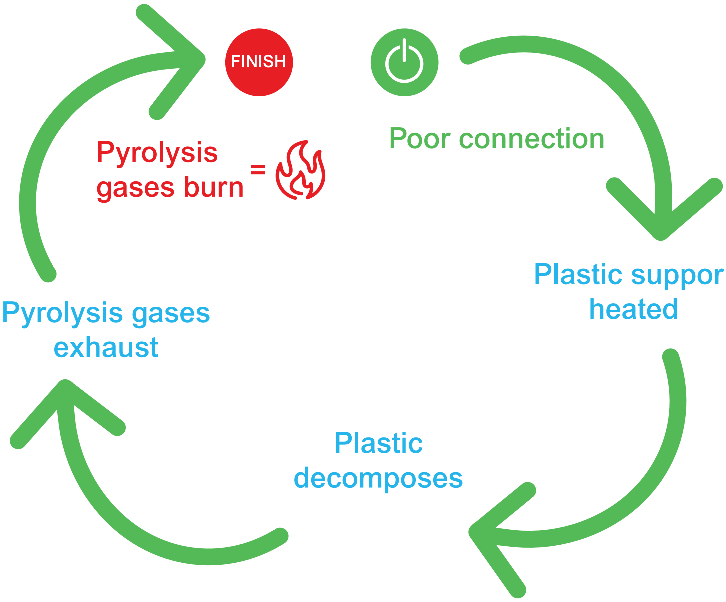


Figure 4

How fire starts in cable insulation when a hot spot appears

Pyrolisis of insulation material will occur at various temperatures according to the material, but all types will start releasing a combination of gases and microparticles when a heat overload condition occurs.

See **Figure 5** for an example of this characteristic for PVC insulation.

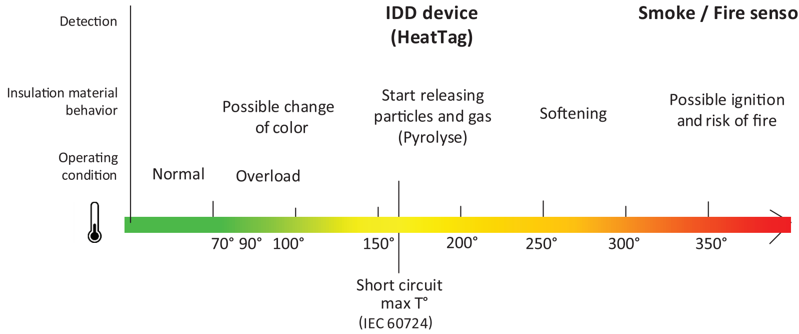


Figure 5

PVC insulation material behavior with increasing temperature

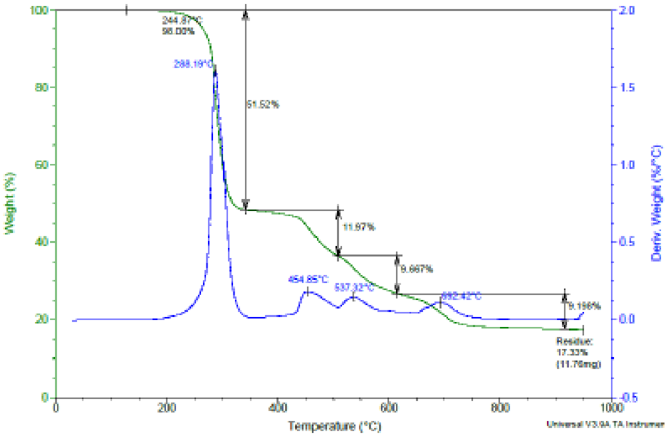


Figure 6

Example of TGA of PVC cable insulation material of a PVC cable

Thermogravimetric Analysis (TGA) is a common way to illustrate this phenomenon, see also **Figure 11** for ignition temperatures estimation by TGA of usual types of insulation material.

Electrical equipment insulation behavior

Under extreme high heat conditions, the insulation material that surrounds connection points in various switchgear and control-gear equipment, such as circuit breakers, will also deteriorate. In most cases, this deterioration will occur at higher temperatures than that of cable decomposition. In addition, per IEC/EN 60947-1 2020 8.1.2.2, all devices are subjected to a glow wire test procedure at a temperature of 850°C or 950°C to demonstrate that the device will not ignite a fire in case of abnormal temperature rise of the terminal.

Using particle and gas detection to identify insulation decomposition

New technology has recently emerged based on an innovative smart device that can analyze gas and particles inside a switchboard. Insulation decomposition detection (IDD) takes advantage of the behavior of cable insulation decomposition during a thermal runaway situation, detecting this abnormal condition before any smoke or insulator browning occurs.

Gas and particle sensor

IDD technology has been tested and validated to work in common types of LV switchboards and most LV cable types. A single IDD device (see **Figure 7**) must be installed in each column of a cubicle. No additional accessories are required. A single sensor device will detect an overheating problem with any cable inside that column of the switchboard, enabling a solution that is very simple and fast to install and integrate.

Figure 7

HeatTag™ smart insulation decomposition detection (IDD) device by Schneider Electric

The IDD device is installed at the top of the switchboard (see **Figure 8**). Airflow travels to the top thanks to natural convection. The IDD sensor device has a fan that helps to aspire air inside the sensor. IDD devices have been validated to work in systems with no forced ventilation (fan) or cooling and rating equal to or above IP31.

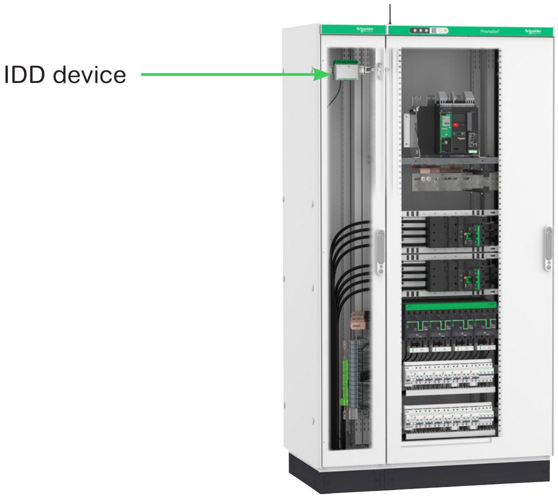


Figure 8

Installation of IDD device inside an LV switchboard

Inside the device, multiple chemical sensors detect physicochemical compounds in the air that are being emitted by the insulation of all cables inside the equipment during abnormal heating. The gas mixture and concentration of different gases and a variety of micro-particles are reliably measured. Temperature and humidity are also continuously measured.

Analytic algorithm

The IDD device uses its onboard artificial intelligence to apply a complex algorithm to the multi-dimensional sensor data. The algorithm compares and classifies internal cable issues, separating them from other phenomena.

The multi-criteria analysis must identify the correct concentration of gases and particles, combined with changes in ambient temperature and humidity, to identify a condition that indicates a cable is overheating (see **Figure 9**).

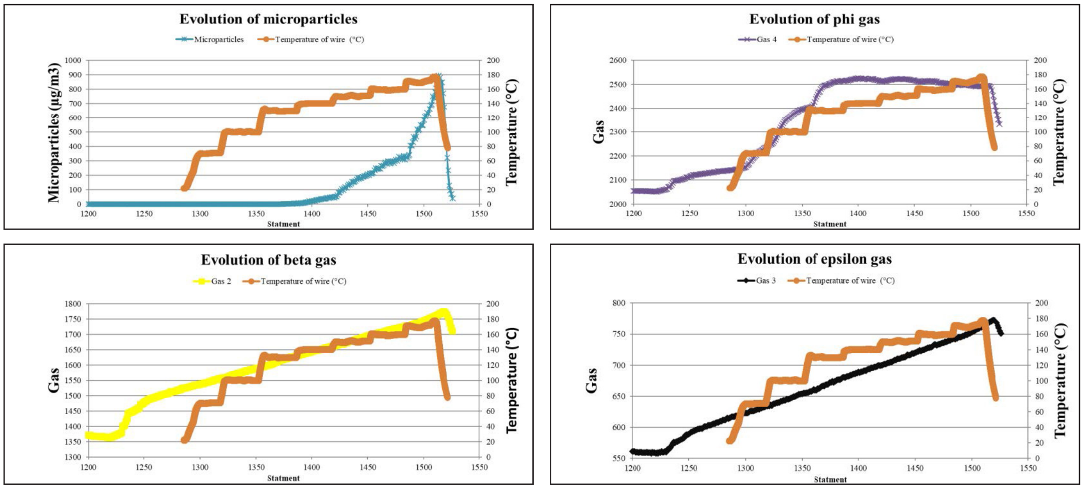


Figure 9

Example of multidimensional particle and gas analysis performed by an IDD device

Advantages of IDD over smoke and fire sensors

IDD technology has distinct advantages over traditional smoke and fire sensors. Smoke sensors prevent fire risks by detecting white smoke from the combustion of flammable materials, whereas insulation decomposition detection will identify a thermal risk *before* the point when smoke is emitted by the insulation.

Fire sensors react to the radiation emitted by all kinds of flames and will quickly warn of the presence of fire. However, the flame detector only acts *after* a fire has already started (see **Figure 10**). IDD technology can detect the default much earlier than smoke and fire detectors to provide maximum protection.

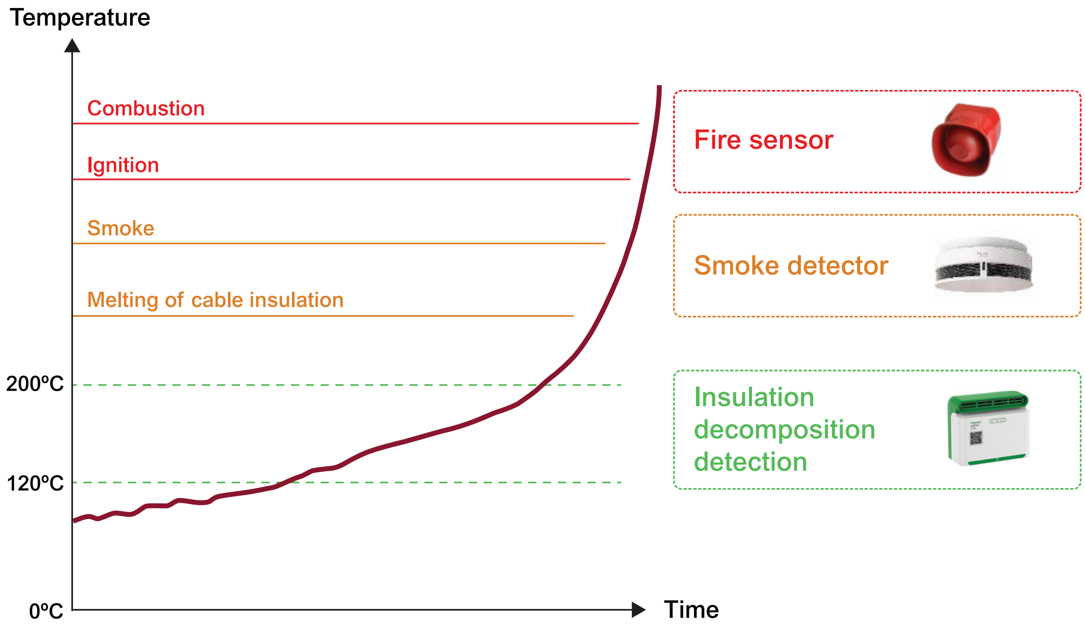


Figure 10

Comparison of IDD, smoke, and fire sensors

Note: There is no time scale on this figure as the speed is very dependent on the contact quality. The thermal runaway can occur in a few days for a very poor connection, and weeks, months, or even longer for a not so bad connection.

Figure 11 illustrates how overheating detected by IDD compares to ignition temperature calculated by TGA for various cable types:

Figure 11

Comparing IDD and TGA overheating detection.

Cable Type	Cable Insulation Material	Cable Operating Temperature (°C)	IDD Alert T°[1] (°C)	Ignition Temperature[2] (°C)
H07V-K	PVC	70	150	> 272
H07VR	PVC	70	150	267
H07RNF	EPR	85	150	363
H07VU	PVC	70	160	260
U1000AR2V	XLPE (ALU)	90	210	278
U1000R2V	XLPE (CU)	90	180	278
H07Z1-KAS	Halogene fee	70	250	363
FS17	PVC	70	160	255

[1] Tests conducted in real enclosure.

[2] This ignition T° is based on TGA analysis of the cables samples tested with IDD providing onset decomposition temperature (Td) and peak mass loss rate temperature (Tp). According to *DOT/FAA/AR-05/14, "Polymer Flammability", Office of Aviation Research, Washington, D.C.* the average value of Td and Tp give a good approximation of ignition temperature.

Combining IDD with thermal monitoring sensors

As noted in the introduction, thermal monitoring technology using thermal sensors is effective and ideally suited to applications where individual sensors can be cost-effectively installed on the most important connection points, such as inside MV switchgears and on busways. In this way, thermal monitoring can be a good complement to IDD technology, with the latter used within the LV switchboard.

Though thermal monitoring sensors could also be used on busbar connections within LV switchboards, it is typical for there to be multiple cables connected to a single LV busbar connection point. In such cases, if only one cable of a multiple cable connection experiences a thermal risk condition, the resulting heat rise may not be enough for the thermal sensor to detect. In contrast, IDD technology will detect if only one cable in the switchboard is overheating.

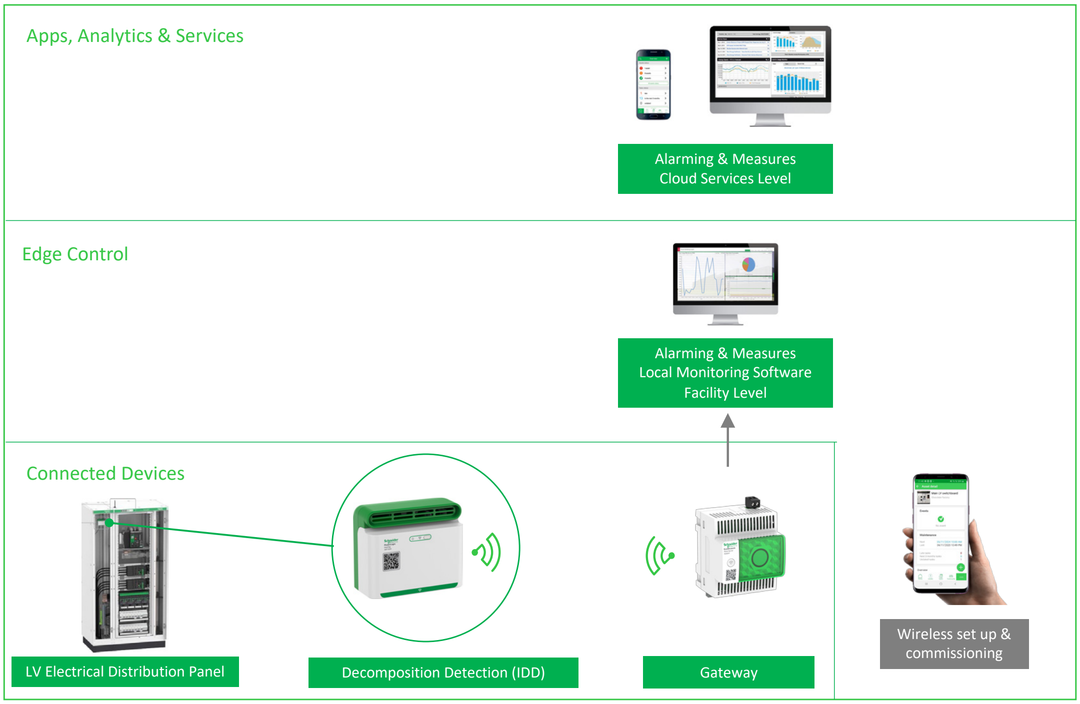
System-level solution for alarming on thermal risks

IDD technology can be used as part of a complete system solution. Each smart sensor includes integrated wireless connectivity that is used to connect to a communication gateway. The gateway transfers data to a cloud-based application (see **Figure 12**). A mobile app allows for fast and simple configuration of all IDD devices connected to the gateway.

Figure 12

IDD integration with onsite and cloud-based applications and services

Communication architecture



Once uploaded to the cloud, data, and alarms can be accessed by facility teams, contractors, or expert advisory services. In this way, IDD devices will deliver alerts immediately to all stakeholders, enabling maintenance personnel to take action to locate and correct an issue before damage or a fire can take place. Alarms can be sent by email or SMS to any mobile device.

Connectivity also enables IDD to be upgraded in the future. As algorithms are enhanced over time, they can be made available as a firmware revision downloaded to the device.

Conclusion

Loose or degraded cable connections are a common contributor to thermal runaway and risk of fire in LV switchboards. Innovative IDD technology identifies abnormal heating in cables before a thermal risk becomes out of control.

A single IDD device can monitor all cables within a LV column with no need for additional accessories, making it a cost-effective solution that is simple and fast to install in greenfield or brownfield projects. Wireless communication makes multiple IDD devices simple to configure and integrate within a cloud-based or on-site solution. This offers advantages over IR thermography by providing 24/7 monitoring of conditions inside each LV switchboard and delivering immediate mobile alerts to facility teams or advisory services in the event of thermal risks.

An IDD can be used in a complementary way to augment thermographic inspections, and smoke, or fire sensors. It can also be used together with thermal monitoring sensors, with the latter best suited for installation in MV switchgears, on busways, or LV busbar connections.

About the authors

Abderrahmane Agnaou is a technical expert working in innovation at Schneider Electric LV power products division. He has held various positions in R&D, mainly in charge of thermal expertise for machine control panels and switchboards. He was also in charge of the thermal monitoring architectures for large and critical applications.

Mathieu Guillot is a power system expert in charge of LV power product applications marketing. He has held various positions in MV R&D, in Solution and Services for MV and LV, and LV circuit-breakers marketing for Schneider Electric. He is also a member of the IEC TC64/MT2 working group, in charge of overcurrent protection and thermal effects in the IEC 60364 series.

Resources

White Paper 161, “How to ensure a secure, long-lasting power connection within your electrical installation”, Schneider Electric

White Paper, “How thermal monitoring reduces risk of fire more effectively than IR thermography”, Schneider Electric

IEC/TR 63054:2017 Low Voltage Switchgear and Control gear – Fire risk analysis and risk reduction measure

White Paper 268, “Using Infrared (IR) Thermography to Improve Electrical Preventive Maintenance Programs”, Schneider Electric

DOT/FAA/AR-05/14, “Polymer Flammability”, Office of Aviation Research, Washington, D.C.

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