Innovative solution to diagnosis and prognosis of defects and failures in cast-resin transformers for sustainable assets and risk management

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> **Up to 25% of distribution transformers are dry-type machines, but only 10% find applications in the power generation sector**

ABSTRACT

Cast-resin transformers represent a small but significant and growing portion of the overall transformer market. They are employed in power distribution and in scenarios where a very low fire risk is mandatory. Evaluating operating conditions and estimating the residual life of transformers helps to provide sustainable solutions for Life Cycle Management (LCM) of electric service, loss prevention, and environmental protection. It follows that on-site and on-line measurement and assessment are particularly important to anticipate potential service interruptions, identify accumulated degradation, and schedule maintenance. Such monitoring activity was performed using a diagnostic and prognostic system that provided information on conditions (pathologies) of cast-resin machines because of several physicochemical properties. The study dates back to 2014, but research is still in progress. The results here presented refer to an innovative device designed, developed, and patented in 2018 (TRL 4-6) as the central component of the system. Data and information about VOC (Volatile Organic Compounds) and ozone formation (Resin Overheating and Corona Discharge), anomalous vibration insurgence (Mechanical Defect or Failures), and superficial temperature (Overheating and Overload) have been collected since 2017. The aforementioned device could sample surrounding air and trap organic molecules in specific cartridges to be analyzed by mass spectrometry. Two private companies (Power and Steel plants) offered to install devices on-site for validation. The acquired information was put through data analysis and interpretation processes through an Artificial Generative Intelligence (AGI) to spot anomalies and obtain trends and forecasting models. Research activities are still ongoing and moving towards an actual industrial application (TRL 9), which is forecasted to take place in 2024.

KEYWORDS:

diagnostics, monitoring system, dry-type cast-resin transformers, measurements, sensors

An innovative electronic device for on-site and on-line monitoring of cast-resin transformers was designed and constructed after four years of lab tests in 2017

Introduction

Transformers can be classified by power, voltage, and insulation type according to the application. Mineral oil is the preferred insulation medium [1]. Other materials are epoxy resins and polyurethane, which are employed to manufacture dry-type transformers and related equipment. In general, up to 25% of distribution transformers are dry-type machines, but only 10% find applications in the power generation sector (Global Market of Dry-type Transformers 2015 [2]). A dry transformer is estimated to have a 20-year life span, as stated in IEC 60076-12 [3], with a failure rate of up to 5% (for instance, in wind farms where stress factors are significant) [4][5].

Errors in design, construction, or installation may cause early life failures. Degradation of materials (thermal and electric) can be responsible for breakdown after several hours of service.

Compared to oil-filled transformers, dry-type (cast-resin) transformers have advantages like fireproofing, low cost, and limited maintenance requirements. Dry-type transformers also have disadvantages, such as no easy access for inspection of components' physicochemical properties.

The mineral-insulating oil family is endowed with technical standards and analytical methods (IEC and ASTM) designed to identify thermal faults and functional and environmental issues. Most analytical techniques on oil samples are performed in specialized laboratories. A limited number of on-site and on-line analytical methods are also available, principally DGA (Dissolved Gas Analysis). However, on-site analysis of cast-resin transformers is not easily realized due to the impossibility of sampling parts and components. Standards and test methods for cast-resin transformers are few and deal mainly with installation and usage conditions.

In cast-resin transformers, the windings consist of layers of conducting foils (aluminum or copper) intertwined with insulation (polyester films) and bonded with a blend of inorganic fillers (silica) and resin (mainly epoxy) cross-linked with suitable compounds. Strong or prolonged electric and thermal phenomena can cause physicochemical damage to transformer components and structures [6]. Thermal stress can induce degradation of polymeric structures (even detectable by a human nose if in sufficient amount) and partial discharge. For some transformers, this may promote material decay [7]. Heating polymers leads to the breakdown of their macromolecules. This reduces chain length and releases smaller volatile or semi-volatile compounds.

Accordingly, on-line and on-site monitoring of electrical transformers becomes extremely important, especially when failure forecasting can reduce downtime, direct costs, and indirect losses. Single spot temperatures and, at times, loads are already monitored with probes connected directly to a machine; partial discharges are occasionally measured in offline mode. However, if more data, properties, and information could be collected and statistically analyzed, the average life span could be inferred (according to IEC 60076-12). Environmental conditions, maintenance levels, and usage intensity must be included and weighted (according to IEC 60076-11).

Consequently, an effective and substantial improvement to the existing situation can be achieved through the development of an integrated device that is able to monitor the different properties and behaviors of electrical machines simultaneously. Volatile organic compounds, vibrations, sound, and surface temperatures may be continuously monitored. As a result, different interconnected physicochemical profiles can be determined. This provides a foundation for a strong diagnostic and prognostic tool to forecast a transformer's residual life, included in a broader scenario of sustainable solutions for Life Cycle Management (LCM) of electric service, damage prevention, and environmental protection.

Experimental setup

An innovative electronic device for on-site and on-line monitoring of cast-resin transformers was designed and constructed after four years of lab tests in 2017. It is equipped with several sensors selected to monitor properties or events as indicators of existing or incipient issues (see Table 1). The OMD (On-line/On-site Monitoring Device) has a technology readiness level

Table 1. List of properties, events, and problems associated with cast-resin transformers.

Investigated property or event	Potential problem	Profile
Formation of volatile organic compounds (VOCs)	thermal and electric degradation of polymeric parts	Temperature, Degradation
Relative humidity, ambient temperature, pollution	influence of environmental conditions	External factors
Superficial temperature of the electrical machine	intensity of load	Operative
Sound and vibration	presence of defects	Operative, Vibration

of 4-6 (technology validated in relevant environment) [8] and was patented [9]. This work must be regarded as the beginning of a journey across the marginally explored territory of cast-resin transformers toward the final goal of achieving a predictive diagnostic and prognostic tool for transformer pathologies. Our first relevant results from the 2018-2020 period are presented here.

Detection of VOCs was performed with a cluster of eight metal-oxide solid-state sensors (MOS) consistent in each installed OMD device

Table 1 lists the investigated properties and associated problems. To each property-problem pair, a characterizing profile is associated. For instance, in the case of temperature monitoring (overheating), we mention a *Temperature Profile,* which can be linked to an *Operative Profile*; when considering ambient temperature, humidity, and pollution, we refer to an *External-Factors Profile*. If vibration and sound are taken into account, both a *Vibration Profile* (mechanical stress) and an *Operative Profile* are involved. Finally, the formation of organic molecules and other compounds like ozone define a *Degradation Profile*. The term *Operative* can be employed whenever all properties and phenomena associated with the working conditions are covered.

Different adaptive approaches were followed in order to obtain meaningful results. Eight OMD devices were installed in nine different three-phase transformers. Power ranged from 2MVA to 5MVA. Primary and secondary circuits were separated. Devices were normally installed on the side opposite low-voltage cables, which are subjected to higher current flow (thus higher heat formation since power loss is proportional to the square of current). The OMDs were placed in a transformer's room at a suitable distance. The sensors were mounted in the most convenient position: some on devices, others close to the electrical machine. Additionally, Background Evaluation Detectors (BED) were employed for evaluation and interference compensation. The schematic experimental setup is displayed in Fig. 1.

Detection of VOCs was performed with a cluster of eight metal-oxide solid-state sensors (MOS) consistent in each installed OMD device. They were selected from the market and shaped around different metal oxide semiconductors, like zinc oxide (ZnO) and tin oxide (SnO_2) [10]. Unfortunately, producers seldom reveal the chemical nature of their sensors. Bibliographic and commercial information reveals that said oxides have been mainly studied and employed for almost 60 years [11] to detect the presence of small molecules for air quality and safety control, yet they seem to be sensitive to larger and more complex molecules as well [12]. These MOS sensors (purchased from Figaro Sensors and Synkera) were placed right above the transformer phases and at other points at varying distances and orientations (outside the transformer's room as well). At the same time, an air sampling system was included to trap organic molecules possibly derived from the degradation of resin or other polymeric parts. For each four-month period since the beginning, cartridges from inside this last apparatus underwent ultrasound-mediated extraction with spectroscopy-grade toluene (purchased from Thermo Scientific Chemicals) and subsequent GC-MS/MS

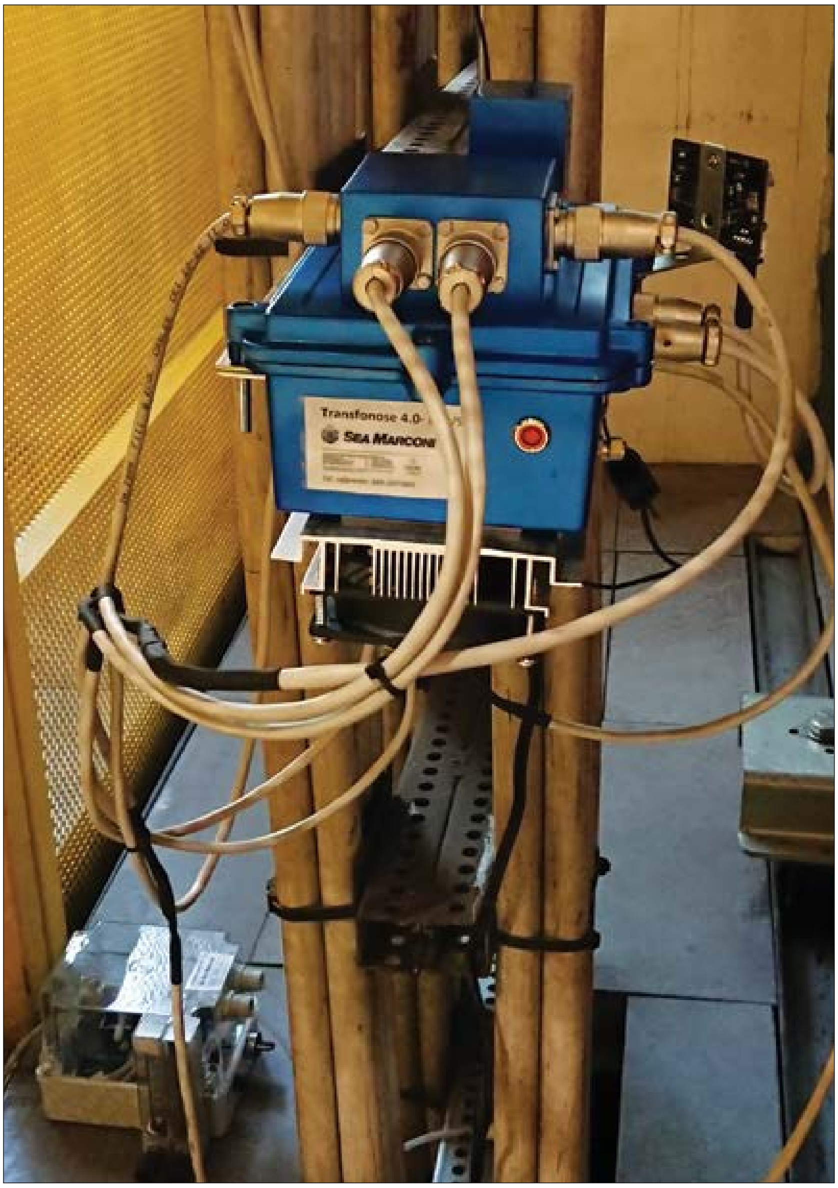

Fig. 1. The experimental setup.

Eight OMD devices were installed and operated for several months (up to 24) in two industrial facilities: a steel plant and a power plant located in the north of Italy

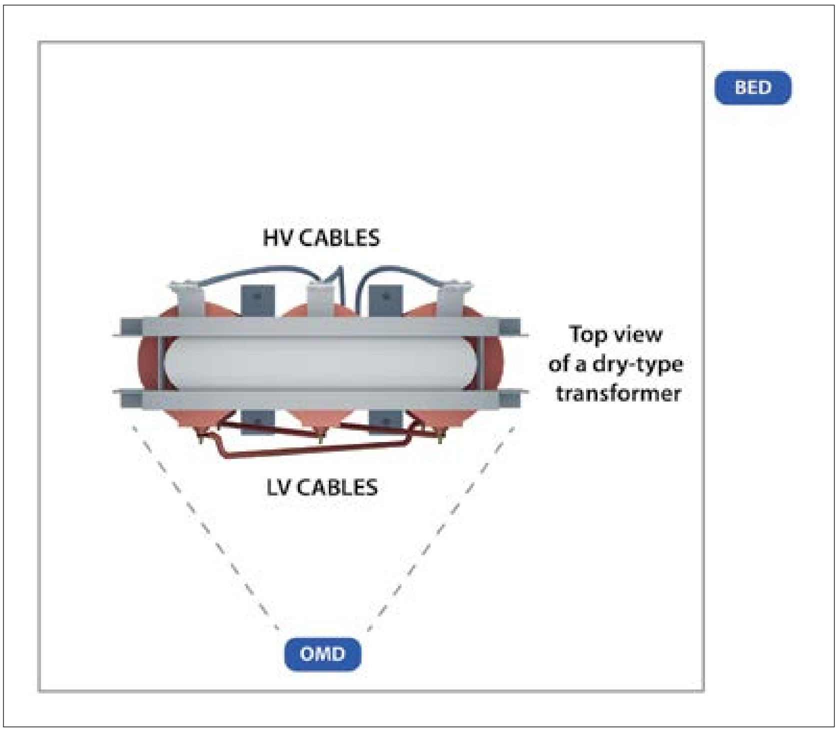

Fig. 2. The innovative device (OMD) with its cables connected to various sensors.

(Gas Chromatography coupled with Triple Quadruple Mass Spectrometry) analysis (Thermo Fisher TSQ 8000 evo). A 768-pixel thermal camera (purchased from Melexis) was also attached. Ambient relative humidity and temperature were measured with another MOS (Purchased from IST), acoustic frequencies were recorded with a cardioid microphone (purchased from Boya), and vibration was investigated with a single-axis piezo-ceramic crystal (purchased from TE connectivity) screwed in the lower part of transformers (on the lower frame girder). Eventually, the formation of ozone was also investigated (sensor purchased from SpecSensors). Ozone is not included among VOCs but can be detected using MOS sensors.

Eight OMD devices were installed and operated for several months (up to 24) in two industrial facilities: a steel plant and a power plant located in the north of Italy. All transformers were confined in dedicated rooms, subjected to different and varying loads (in intensity and form), and exposed to wide ranges of temperature and relative humidity. The innovative device is pictured in Fig. 2. An industrial on-site installation is presented in Fig. 3. In Fig. 2, both the on-line/on-site device and

Fig. 3. Example of an installation

a BED are shown. The latter was equipped with VOC and temperature/humidity sensors and placed outside the transformer's room for detecting the presence of interfering molecules coming from the background.

In Fig. 3 the small box is OMD. The sensors for VOC detection were placed above the gap between the primary and secondary windings (circled in the figure) to take advantage of the chimney effect that could convey organic molecules upwards. Four sensors were installed in each room, one on each phase and one at a certain distance from the transformer. VOC sensors were also placed outside. From the spot where the IR thermal camera was placed, the top half of the transformer could be focused.

All sensors were controlled by a single-board Raspberry Pi 3 computer (by Raspberry Pi Foundation – UK). The device can be connected to the internet through a dedicated router. Data were recorded at fixed times and saved onto a dedicated server for later data analysis and interpretation. Additionally, it was possible to perform real-time data visualization in an attempt to intercept potential aberrations.

> **Eight devices were installed in eight electrical rooms at a convenient distance from the electrical machines for on-site and on-line monitoring carried out for more than two years**

Results

Eight devices were installed in eight electrical rooms at a convenient distance from the electrical machines for on-site and on-line monitoring carried out for more than two years.

The main characteristics of the transformers are collected in Table 2. One transformer failed during the experiments and had to be replaced. Consequently, nine machines were monitored altogether.

The average age and power were 11 years and 3 MVA, respectively. Both AN (air natural) and AF (air forced) types of cooling methods were employed, and with the exclusion of transformer number 4, all machines transformed down to 400 V. The transformer with the highest secondary voltage (3160 V) energized furnaces, while the others supplied different types of loads (resistive, inductive, and capacitive) whose effective and precise allotment could not be assessed.

Failure rates of a machine are higher in the early and late stages of life expectancy, referred to as "infant mortality" and "wear-out period" [13]. The possibility of failure is high during or just after commissioning operations and when machine conditions worsen due to the intensity of use and component decay [14]. Obviously, harsh ambient conditions (very high or very low temperatures, salty atmosphere), hot spots, corona discharges, partial discharges, power imbalances, and abrupt thermal transients all reduce life. Within the sample size under investigation, all items survived infancy. Two exceeded their theoretical life expectancy, being therefore at elevated risk of failure.

Table 2. Main properties of the transformers under investigation. Abbreviations AN and AF are for air-natural and air-forced cooling methods.

#	Manufacturer	Age (Years)	Power (MVA)	Primary voltage (kV)	Secondary Voltage (V)	Primary Current (A)	Secondary Current (A)	Cooling	Temp. Rise	Damage
1	A	22	5	20	400	144	3608	AN/AF	100	
2	A	5	3.1	21	420	68	3437	AN/AF	100	
3	A	3	2.5	21	420	68	3437	AN	95	
4	A	4	4.25	21	3160	116	776	AN	100	
5	A	5	2	21	420	55	2749	AN	100	
6	B	13	2.5	21	420	68	3437	AN	100	*
7	B	11	2.5	22	400	68	3608	AN/AF	100	*
8	B	22	2	21	400	57	2887	AN	100	
9	C	13	3.15	6	420	303	4330	AN/AF	70	
	AVERAGE	**11**	**3**							

> **One of the nine monitored transformers (#6 in Table 2) experienced particularly severe damage that led to failure.**

During the experimental campaign, fatal damage occurred in one transformer (#6 in Table 2). A second transformer (#7) was plagued by faulty components: the sealing end of the secondary cables (not on the machine itself) either because of prolonged overheating or arching (according to the owner). The latter could be brought to light by the sensors (ozone, mainly).

Hereafter, significant results are reported and listed by sensor type or physicochemical property. Concerning the emission of volatile and semi-volatile organic compounds, the study was carried out with a two-pronged approach using solid-state sensors and a sampling device equipped with adsorbing cartridges.

Gas emission

As mentioned before, one of the nine monitored transformers (#6 in Table 2) experienced particularly severe damage that led to failure. A second one (#7 in Table 2) was affected by a less critical issue and given a timely maintenance check. The remaining machines did not show any apparently unhealthy conditions.

Ozone

With reference to the failed transformer, ome interesting results were produced, especially at the time of the event (see Fig. 4).

The ozone profile is displayed in Fig. 5. Ozone can be produced by electric and corona discharges [15], whose occurrence is proven by the clear signs of catastrophic discharges in Fig. 4. The overall signal spectrum and a closeup at the time of failure are shown. The highest concentration of ozone, 326 µl/l (ppm), was detected at the instant of breakdown (see expanded graph where the highest peak is shown). However, it is also interesting to point out that a few hours earlier, a couple of smaller peaks were detected at a normalized value of around 0.1. This was a special case with a disastrous event where the formation of ozone was certainly due to powerful arching. Obviously, using the maximum value is not practical for real-time monitoring. However, through *a posteriori* analysis, it can be determined if small peaks had meaning or were just noise. In fact, considering that the standard deviation

> **Ozone can be produced by electric and corona discharges, whose occurrence is proven by the clear signs of catastrophic discharges**

Fig. 4. The destructive effect of an electrical fault. Catastrophic discharge destroyed the central phase and charred part of the resin. The VOC sensor positioned above the phase was hit by the blow and failed.

is 0.039, one could be inclined to regard those spikes as a sign of ozone formation. However, a broadened observation reveals that 0.11 is the most recurrent and thus probable value (mode), which weakens the strength of the previous proposition and strengthens the assumption of that value being either noise or interference. (The latter is from NO_2 exclusively. Nitric oxide is the principal interfering molecule of ozone detection, as stated in the sensor's datasheet.) On the contrary, the source of other peaks exceeding 0.3 could be associated with ozone formation. This implies that discharge-related incidents might have occurred in previous months, even though a massive presence of NO_2 cannot be excluded. A comparable piece of information is provided by a device installed next to another transformer (#8 in Table 2) for which the value of the mode is 0.08, quite close to the 0.11 value reported above.

Monitoring of the second transformer, which suffered damage (#7 in Table 2), reveals the formation of ozone gas (maximum value 181μl/l). The spotting of high ozone concentration triggered an alert and a consequent on-site verification where a problem was discovered, as mentioned above. In fact, the technicians found that the cable sealing ends on the low-voltage side were loose and partially burnt, possibly due to overheating or arcing. Figure 6 displays an ozone peak at 16:48 (blue curve) and a VOC peak at 4:48 a.m.

VOCs

One behavior investigated is the degradation, promoted thermally and electrically, of polymeric parts and the consequent release of volatile or semi-volatile compounds. In the literature, different

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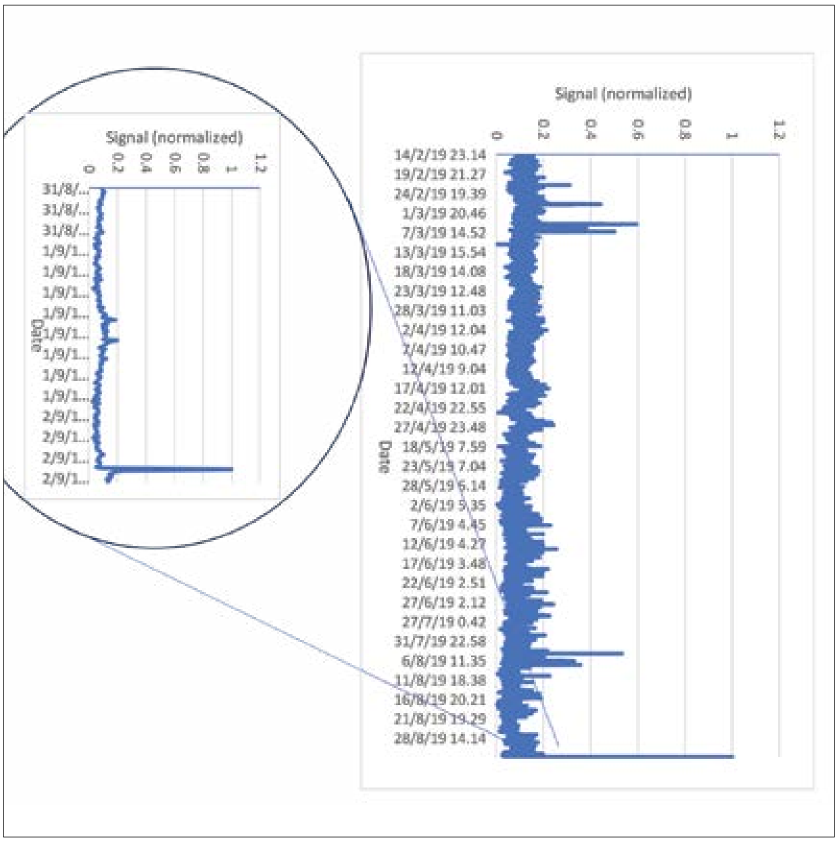

Fig. 5. Ozone profile from the failed transformer: on the ordinate the normalized concentration value, on the abscissa the date of sampling. The arrow points at the moment of failure.

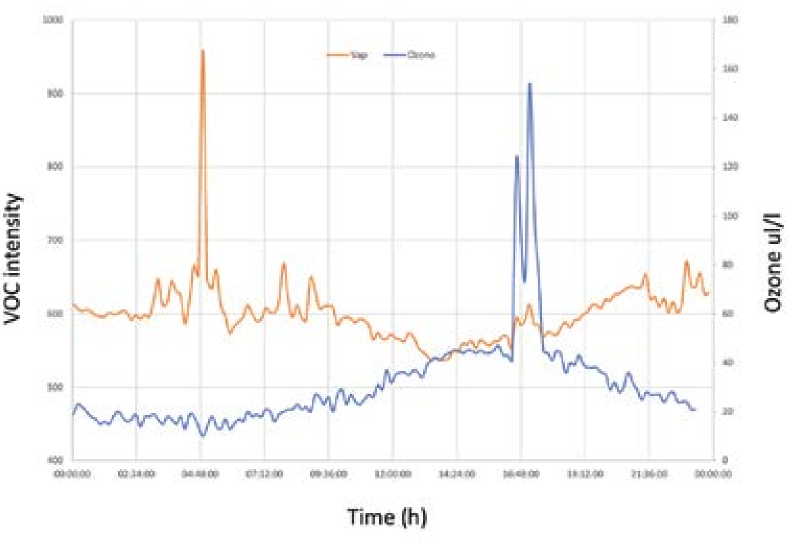

Fig. 6. Ozone profile (blue line) and VOC profile (orange line) from the damaged transformer on the day of the alert. Ozone concentration and VOC intensity are shown on the ordinate and time on the abscissa.

> **Some volatile chemicals (pentane, acetone, isopropyl alcohol, and an industrial degreasing mixture) were released in the air inside a transformer's room**

molecules are reported to be produced by prolonged or excessive overheating of epoxy resins. There can be small molecules like water, formaldehyde (CH_2O), carbon monoxide (CO), and much heavier aromatic compounds such as toluene (C_7H_8) or more complex moieties associated with cracking of curing agents for epoxy resins (typically organic anhydrides) [16].

In general, VOC signal profiles appear quite jagged, both for sensors installed right above phases and for those placed at some distance from the transformer. At the beginning of the study, only one type of general-purpose MOS was employed and positioned in different places inside and outside the room (for background and external interference comparison, see Fig. 1).

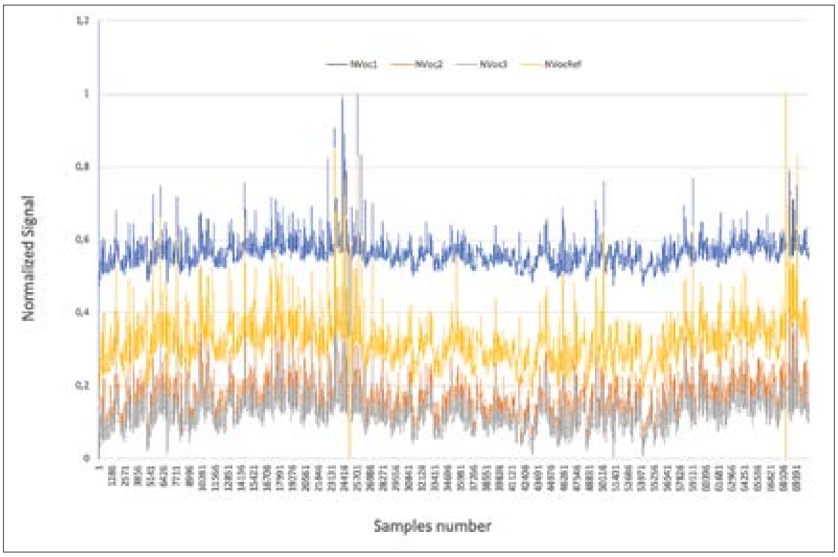

Fig. 7. Normalized signals of four equivalent MOS sensors

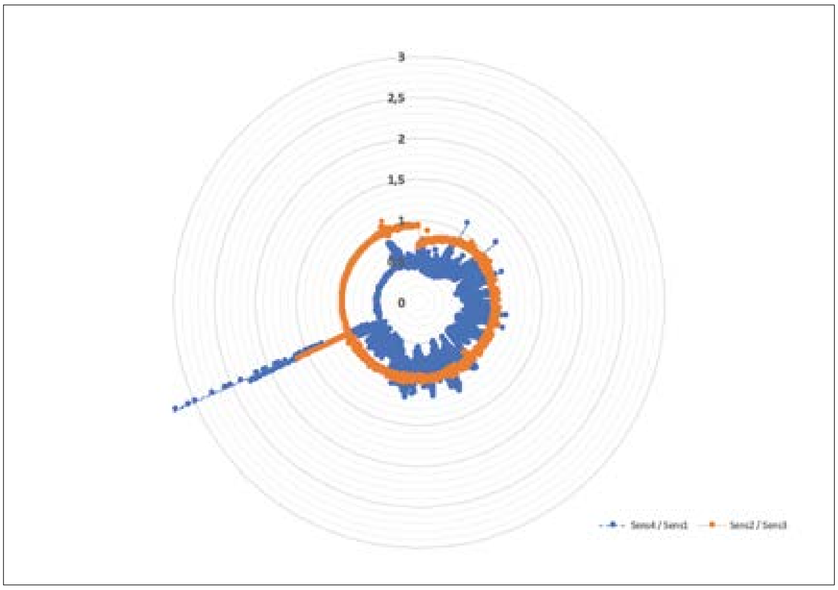

Fig. 8. Ratios between signals of a 4-MOS cluster for transformer #2 (see Table 2). The inner curve is the ratio between sensor 4 and sensor 1 (abbreviated as the reciprocal), and the outer curve is the ratio between sensors 3 and 2 (abbreviated as the reciprocal).

In Fig. 7 a comparison of signals from four equivalent MOS sensors positioned in different places is shown. Regardless of placement right above a phase, at a certain distance, or even outside the room, information is the same. It follows that the air inside and outside the room is similar and marked by a high level of external pollution, which is recognized to contribute to failures as it can create carbon deposits on accessible parts and lead to tracking and potential failure [14]. Consequently, sensors that monitor contamination levels are useful and necessary.

In Fig. 7 sensors 1-3 were placed one at each phase of transformer #2 (see Table 2). The fourth is the external reference positioned in different places inside the room. The profiles do not vary from curve to curve, and only the relative intensities are different. Normalization was performed according to the following calculation: (average – min)/(max-min). This was a posteriori signal analysis, which cannot be employed in real-time.

Nonetheless, an additional goal was to differentiate between molecules that can be released by a transformer from those that can sneak in from outside. Consequently, other models of sensors (for instance, with higher hydrocarbon sensitivity) were selected and installed with the intention of creating a selective sensor cluster. To characterize the in-field behavior of a 4-MOS cluster, some volatile chemicals (pentane, acetone, isopropyl alcohol, and an industrial degreasing mixture) were released in the air inside a transformer's room. In Fig. 8, a radar chart is displayed where two curves are visible. The data cover a four-month sampling period and are plotted in cumulative daily aggregations (binning). One represents the normalization ratio between the signals of sensors 1 and 4 and the other between sensors 3 and 2. Sensors 4 and 1 are quite similar concerning the type of gas to which they show affinity, but their sensitivity is quite different. Sensor 1 is much more sensitive. The signal of sensor 4 can be used to compensate for humidity and temperature variations. A similar approach holds for the other two sensors, which interact more with hydrocarbons. The reciprocal ratio is shown to accentuate results. Both signal ratios normally ripple within two given values, but when sensors are exposed to chemicals, a spike appears. The peak of the ratio between sensor 3 and sensor 2 is less prominent because of an almost exclusive responsiveness to aliphatic and aromatic hydrocarbons.

Figure 9 shows a radar chart that displays the same ratios as Fig. 8, but for transformer #7 (the one that suffered damage to its sealing ends), Here again, the signal ratios oscillate inside a given annulus and exhibit a peak at a given time unmistakably associated with the presence of organic molecules, either from the transformer or from outside the room.

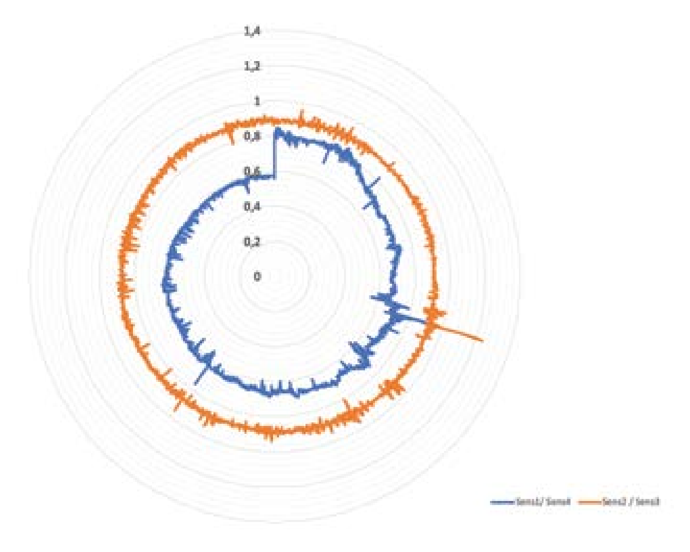

Fig. 9. Ratios between signals of a 4-MOS cluster for transformer #7. The inner curve is the ratio between sensor 4 and sensor 1 (abbreviated as the reciprocal), and the outer curve is the ratio between sensors 3 and 2 (abbreviated as the reciprocal).

> **Inside each transformer's room, an air sampling device equipped with an adsorbing cartridge was installed to understand if any molecule could be released by the polymeric parts while the transformer was running**

Adsorbing cartridges

Inside each transformer's room, an air sampling device equipped with an adsorbing cartridge was also installed. Every six months since the beginning of the experimental campaign, the cartridges were replaced with fresh ones and subjected a few days later (allowing the time for delivery and processing) to GC-MS (Gas Chromatography coupled with Mass Spectrometry) analyses after adequate extraction and purification. The purpose was to understand if any molecule could be released by the polymeric parts while the transformer was running. Unfortunately, the air pervading an industrial site like a steel plant can be rich in organic molecules that compete with those allegedly set off by epoxy resin (and other polymeric components). The analyses revealed the presence of some compounds that have a high probability of originating from polymeric material for electrical applications [17]. In Table 3,

Table 3. List of molecules trapped by the adsorbing cartridge and detected through the GC-MS/MS technique.

# Trafo	Compound	Uses
3	Isopropyl Lactate	Solvent
	Xylene	
6	Unknown compound. Chemical formula: $C_8H_{11}N$	
8	Isopropyl Lactate	Solvent
	Xylene	
	Unknown compound. Chemical formula: $C_8H_{11}N$	
7	Acetophenone	Possibly from the degradation of XLPE-insulated cable
	Phenylmaleic anhydride	Possible curing agent for epoxy resin
	Benzoic acid	Possibly from the insulating coating of cables

> **Temperature is a key feature to be monitored since it can be an important source of damage and failure, and it is not a coincidence that a good deal of the literature addresses temperature-related phenomena and behavior**

the detected compounds, their use and possible origin, and respective transformers are listed.

Temperature profile

Temperature is a key feature to be monitored since it can be an important source of damage and failure. It is not a coincidence that a good deal of the literature addresses temperature-related phenomena and behavior. Often, each transformer's phase is equipped with a temperature probe. Unfortunately, a single sensor can read the temperature in the immediate surroundings of its housing but cannot deliver knowledge about the presence of hot spots or temperatures at distant points.

As can be inferred by looking at a transformer's specification and the standard IEC 60076-12, three temperature-related aspects are fundamental: the environmental temperature, a transformer's temperature, and their difference.

Regarding the transformer which suffered a destructive failure, the difference between the environmental temperature and the maximum superficial temperature measured on the side "seen" by the thermal camera is shown in Fig. 10. Such difference oscillated between 40°C and 50°C on average, which is far below the acceptable maximum overtemperature (100°C), as declared by the manufacturer. Obviously, the internal temperature was higher, and the presence of hot spots could not be excluded.

The max temperature and overtemperature values for the remaining transformers are collected in Table 4. The highest numbers pertain to transformer #6, which failed. All others did not show particularly high temperatures or overtemperatures.

> **Not only temperature and humidity but also the presence of polluted air (from chemicals, brine, or conductive particles) must be considered**

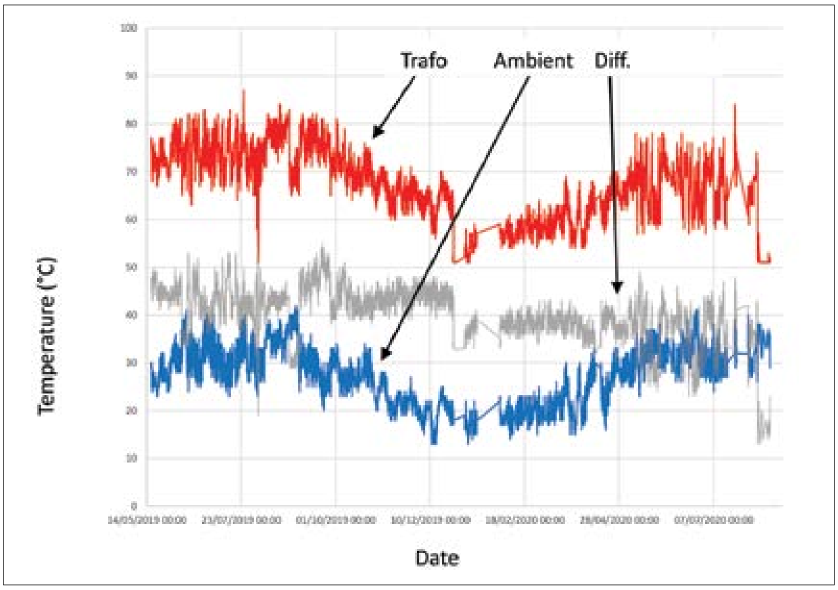

Fig. 10. Difference in temperature between the room environment and the transformer.

External factors profile

The nature of the environment surrounding and inside the transformer's room is a vital factor. Not only temperature and humidity but also the presence of polluted air (from chemicals, brine, or conductive particles) must be considered. The transformers monitored in the steel plant were exposed to a massive buildup of dust, which originated from steel production activities and had a high metal content. Fig. 11 shows a typical situation after a few months of testing. The accumulation of large amounts of particles did not impair the correct functioning of the devices. All transformers from #1 to #8 worked in this highly polluted environment (steel plant). Transformer #9 was immersed in less dusty air, although the concentration of pollutants deriving from hydrocarbon combustion was typical of environments close to motorways and thermal power plants. Cases of failures caused by pollution and high concentrations of particles are reported. IEC 60076-11 [18] advises against keeping transformers in dusty or polluted environments.

Table 4 lists the maximum environmental temperatures and the yes-no temperatures exceeding the classification chart. In fact, according to IEC 60076-11 [18], the cooling air inside the room should not exceed "40°C at any time; 30°C monthly average of the hottest month; 20°C yearly average". The highest temperature values are read in the summertime and coincide with those of the indoor air when no forced cooling is provided. The temperature of the air conveyed from the outside may be equal or a little lower or higher depending on the location and activities around the room.

Relative humidity never exceeded 93% and thus did not represent a threat. In IEC 60076-11, that is the limit value for a warning signal.

> **Mechanical vibration and acoustic sound monitoring are important because they can be linked to loads, operating conditions, and mechanical problems**

Sound and vibration (vibration profile)

Mechanical vibration and acoustic sound monitoring are important because they can be linked to loads, operating conditions, and mechanical problems [19]. Therefore, all devices were equipped with microphones for fundamental frequency detection. Only one was provided with a vibrometer. The most common frequencies found by microphones were 100 Hz and 300 Hz. A transformer fundamentally vibrates at 100 Hz and shows harmonics at higher frequencies.

Concerning vibrations, the most common value was 200 Hz. This observation complies with literature information that

Fig. 11. Data acquisition device after a few months in a dirty room.

Table 4. Maximum temperatures and yes-no temperatures exceeding the classification chart.

# Trafo	Cooling	Max Env. Temp. (°C)	40°C exceeding	30°C monthly average exceeding	20°C yearly average exceeding	Max Trafo Temp. (°C)	Max Overtemp. (°C)
1	AN/AF	38	no	yes	No	65	30
2	AN/AF	42	yes	yes	No	47	10
3	AN	44	yes	yes	Yes	70	30
4	AN	39	no	no	No	40	5
5	AN	40	yes	yes	Yes	60	20
6	AN	46	yes	yes	Yes	100	60
7	AN/AF	50	yes	yes	Yes	80	50
8	AN	49	yes	yes	Yes	70	20
9	AN/AF	37	no	yes	No	70	35

The ultimate objective of the study is to realize an integrated diagnostic and prognostic system that comprises not only an evolved version of an innovative device but also all state-of-the-art data analysis techniques

90% of the 100 Hz frequency is quenched in the lower part of the transformer where the sensor was attached, but only 20% of that for the 200 Hz component [20]. It is also reported that a prevalence of 200Hz can be linked to a slacking of windings [21].

However, being in a real-world industrial noisy environment, work needs to be done to process signals and unmistakably link vibration frequencies to transformer operating conditions.

Conclusions

The pathway opened by two years of tests and monitoring is discernible. Unfortunately, a much longer time is required to achieve robust and strongly significative results that could lead to the creation of a prognosis tool. However, during the experimental period, one fatal failure and one case of damage occurred. The former event was marked by harsh operating conditions, high ambient temperatures, ozone formation from electrical discharges (or the presence of high concentrations of nitric oxide, i.e., corrosive pollution), and the presence of conductive dust. The latter occurred to a machine working in a relatively hot environment, full of dust, with continuous inductive cycles. However, the damage was not diagnosed on the machine itself but on accessory parts (namely, on the low-voltage sealing ends).

Thanks to chemical analyses of adsorbing cartridges, a few molecules have been isolated and attributed to thermal or electrical events occurring in the transformer. Not only the epoxy coating of a transformer but also polymeric interconnecting parts contribute to the generation and release of compounds. Also, solid-state VOC sensors help to understand the level of pollution in which transformers operate. The construction of a suitable sensor array enables the evaluation of which molecule emits from thermally or electrically degraded polymeric parts.

Even though monitoring sound and vibration is not easy in an industrial environment contaminated by spurious vibration, some useful information can be retrieved.

The main properties and related profiles are:

1. Transformer temperature:
   Pathologies (type): overheating, quick temperature drops, degradation of polymeric parts, cracking of resin coatings.
   Associated Profile: *Temperature* and *Operative*
2. Environmental temperature, humidity, particles, and pollutants:
   Pathologies (type): formation of conductive bridges, diminished cooling capability, ease of discharge, corrosion.
   Associated Profile: *External Factors Profile*
3. Formation of organic compounds and ozone:
   Pathologies (type): electrical and thermal degradation.
   Associated Profile: *Degradation*
4. Sound and vibration:
   Pathologies (type): mechanical problems, intensity of use, variable loads.
   Associated profile: *Vibration* and *Operative*

Partial Discharge (PD) was not included in monitoring activities because of the complexity of measurement in an industrial environment and associated costs. As a matter of fact, the interpretation of PD measurement results requires expertise. This becomes even more profound in an industrial environment, which is more complicated compared to laboratory offline testing chambers (accessibility problems, noise, and connections) [22].

As previously mentioned, the ultimate objective of the study is to realize an integrated diagnostic and prognostic system that comprises not only an evolved version of an innovative device but also all state-of-the-art data analysis techniques. As such, experimental activities are still underway and are included in a regionally (Piedmont) financed project named Transfoclean4OT (code 337-285) dedicated to the development of integrated systems for diagnosis and prognosis of pathologies in transformers (both oil immersed and dry). Among the partners of the project, Reply (an Italian consulting company) and Polytechnic of Turin are included and appointed to analyze and interpret all data collected through artificial generative intelligence (AGI). Derived analytical models will be used to scale up the technology to a readiness level close to 9 (TRL 9 - *Actual system proven in the operational environment, competitive manufacturing in the case of key enabling technologies; or in space.* [23]).

Accordingly, future results and conclusions will be presented in due course.

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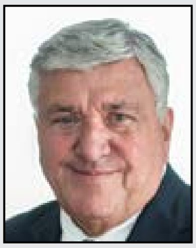

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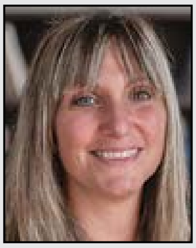

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