TRANSFORMER SERVICE

Online dissolved gas monitoring
Introducing the CoreSense™ family
Today’s electrical grids are comprised of millions of transformers that interconnect power generation, transmission and distribution. These transformers are critical assets that require proper maintenance in order to provide long uninterrupted electrical service.

In this white paper, we look at the typical structure of an oil-filled power transformer and explain why it is important to monitor dissolved gases. We then look at the characteristics of online sensors and introduce the ABB CoreSense™ family of online dissolved gas analyzers.
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Transformer insulation degradation
Monitoring through gas formation

The three main components subject to deterioration and contamination in a transformer are:
• Paper, which is used for conductor insulation;
• Pressboard, which is used for the major insulation and winding support; and
• Insulating oil. [1][2]

Both mineral oil and cellulose have carbon based molecular structures that are rich in hydrogen as illustrated below. The decomposition of oil and cellulose forms a large number of byproducts, including combustible and non-combustible gases.

Cellulose is sensitive to heat, oxygen and moisture. The higher the temperature, the faster the paper ages (thermal aging). In the presence of higher amounts of oxygen and moisture, the paper breaks down through oxidation and hydrolytic processes, which generate additional moisture, acids and other components that accelerate the aging process even further.

The molecular structure of the insulating fluid also breaks down in the presence of higher temperatures and electrical faults such as partial discharges and arcing. Both cellulose and insulating oil may also degrade in the presence of contaminants, such as moisture and oxygen introduced through leaks and/or maintenance activities.

The formation of gases is common to almost all types of insulation degradation. These gases then dissolve in the oil, allowing detection and analysis of the defect through adequate monitoring. This procedure is called Dissolved Gas Analysis (DGA).

For many years, the method of analyzing gases dissolved in oil (DGA) has been used as a tool for transformer diagnostics. The method has several purposes:
• to detect incipient faults;
• to supervise suspect transformers;
• to test a hypothesis or explanation for the probable cause of failures or disturbances which have already occurred; and
• to ensure that new transformers are healthy.

DGA can also be used as part of a scoring system in a strategic ranking of a transformer population.

Industry standards dictate DGA measurements be done on a defined schedule that depends on the criticality of the transformer, the gas levels and their production rates. This practice of regular measurements leads to blind periods ranging from several months to several years inside of which significant thermal or electrical events can go undetected. Online DGA sensors allow continuous measurement, thus bridging the gap in the analysis done by conventional methods.
DGA Theory from the IEEE C57.104/2008 [3]

4: The two principal causes of gas formation within an operating transformer are thermal and electrical disturbances. 4.1 Cellulose Decomposition – The thermal decomposition of oil-impregnated cellulose insulation produces carbon oxides (CO, CO$_2$) and some hydrogen and methane (H$_2$, CH$_4$) due to the oil...

4.2 Oil Decomposition – Mineral transformer oils are mixtures of many different hydrocarbon molecules and the decomposition processes for these hydrocarbons in thermal or electrical faults are complex. The fundamental steps are the breaking of carbon–hydrogen and carbon–carbon bonds.

Active hydrogen atoms and hydrocarbon fragments are formed. These free radicals can combine with each other to form gases, molecular hydrogen, methane, ethane, etc., or they can recombine to form new, condensable molecules. Further decomposition and rearrangement processes lead to the formation of products such as ethylene and acetylene and, in the extreme, to modestly hydrogenated carbon in particulate form. 4.3 Application to Equipment – ... Internal faults in oil produce the gaseous byproducts hydrogen (H$_2$), methane (CH$_4$), acetylene (C$_2$H$_2$), ethylene (C$_2$H$_4$), and ethane (C$_2$H$_6$).

When cellulose is involved, the faults produce methane (CH$_4$), hydrogen (H$_2$), carbon monoxide (CO) and carbon dioxide (CO$_2$). Each of these types of faults produces certain gases that are generally combustible.

DGA Theory from the IEC60599:2015 [4]

4.1 Decomposition of oil – ... Scission of some of the C-H and C-C bonds may occur as a result of electrical and thermal faults, with the formation of small unstable fragments, in radical or ionic form, such as H•, CH$_3$•, CH$_2$•, CH• or C• (among many other more complex forms), which recombine rapidly, through complex reactions, into gas molecules such as hydrogen (H-H), methane (CH$_3$-H), ethane (CH$_3$-CH$_2$), ethylene (CH$_2$ = CH$_2$) or acetylene (CH≡CH) ... Low-energy faults, such as partial discharges of the cold plasma type (corona discharges), favor the scission of the weakest C-H bonds (338 kJ/ mole) through ionization reactions and the accumulation of hydrogen as the main recombination gas.
Online DGA sensors
Continuously monitoring the health of your assets

Online gas monitors are installed on transformers at the factory or in service and provide frequent readings (typically several readings per day) of gas concentrations dissolved in the transformer’s oil without the need for manual sampling.

A major advantage of continuous gas monitoring, as compared to laboratory analysis, is the capability to reduce the risk of an unplanned incident or failure and costly consequences of the related outage. It also provides valuable input to plan for maintenance, repair or replacement. For regular supervision with laboratory analysis, manual samples are typically taken every year or every 6 months. With online gas monitors, gas analysis is performed much more frequently, thus providing a powerful early detection system. This practice avoids the need for excessive site visits and manual samplings. Finally, if a transformer is located in a very remote area, the cost savings of sending a person to obtain DGA samples less often could easily justify installing an online sensor.

Three types of DGA sensors are currently available on the market to continuously observe the status of a transformer:

**Single gas sensors**
Hydrogen sensors or single gas sensors measure hydrogen gas in oil due to its central role in the detection of abnormal operation of transformers. Most serious fault conditions cause significant hydrogen production, and it can even be the dominant gas formed, such as in cases of partial discharges. This sensor acts as a watchdog by giving an alarm when hydrogen content in a transformer rises, triggering an unplanned lab DGA in order to perform a root cause analysis.

**Multi-gas sensors**
Multi-gas sensors give a more complete view of a transformer’s health by providing individual readouts for up to 12 gases, similarly to a laboratory DGA analysis but continuously. They can also be installed as an upgrade to single gas sensors once a transformer starts to show signs of repeated thermal faults. This constitutes an alternative to frequent lab DGA analyses and helps keep the unit in service until the next maintenance or repair.

**Gas Combination Monitors**
Gas combination sensors, sometimes called Total Combustible (oxidizable) Gas sensors are another common type of online gas monitor usually deployed on transformers for early fault warning purposes. These devices use sensors that give a single readout in response to a combination of oxidizable gases. Their typical response may look something like

\[ \text{Readout} = A \times \text{H}_2 + B \times \text{CO} + C \times \text{CH}_4 + D \times \text{C}_2\text{H}_2 + E \times \text{C}_2\text{H}_4 + F \times \text{C}_2\text{H}_6 \]

The readout is dependent on the concentrations of all the gases with different relative sensitivities for each gas. The idea is that the readout will provide an early warning of gas formation regardless of what gas is actually being formed.

The main issue with this type of sensor is that the interpretation of the readout can be very difficult because a perfectly normal transformer always has some background gas present in its oil.

It may be seen as an advantage that the monitor reacts also to changes in CO content, for example. However, in the case of high background levels of interfering gases, the detection of H\textsubscript{2} content trending becomes more difficult. Finally, combination monitors incorporating membranes are also less robust and require more care.

Considering the above arguments for Gas Combination Monitors, this paper will focus on the comparison between single and multi-gas analyzers.

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How to choose between a single or a multi-gas sensor

Multiple factors play a role in choosing a DGA sensor for an oil-filled transformer

Asset criticality and size
Transformers vary widely in criticality and size. It can be as important to monitor a small power transformer feeding a hospital as to monitor a medium power transformer at an industrial installation. In the first case, a power interruption to critical life-support or surgical equipment can cost lives, while in the second case, the shutdown of an industrial plant can cause millions of dollars in revenue losses.

As a general rule, adding monitoring to a transformer should represent a small percentage of the overall value of the asset. This usually implies that smaller critical units are equipped with single gas monitoring sensors whereas larger critical transformers tend to be equipped with multi-gas sensors.

Total cost of monitoring
Beyond simply choosing a sensor, installation and maintenance costs associated with a specific measurement technology need to be considered in the overall assessment of a solution. For example, some gas sensors, like gas chromatographs, require expensive repetitive maintenance procedures. This technology generally requires a continuous supply of helium carrier gas and calibration gases as well as regular maintenance for the chromatography columns.

Transformer health
Once a critical transformer is identified as having a type of fault that causes gassing, an online sensor (either single or multi-gas) can be used to tightly monitor the situation as it evolves. In some cases, the remaining life of the asset can be considerably extended by adjusting operating parameters to slow down development of the fault; a practice called transformer nursing.

Central data acquisition system
Finally, the value of the data from single or multi-gas sensors can be greatly enhanced if the data is centralized and correlated for a whole fleet of transformers. Indeed, fleet-wide data acquisition software, like ABB’s AssetHealth solution, allows large scale operators to use the data from sensors to classify transformers according to their relative health and probability of failure. This allows resources to be optimally allocated to the most important problems on the network. The more data available, the better the assessment and recommendations made by the software. It follows that multi-gas sensors enable a better overall view, however budget constraints limit their widespread use.

The bottom line is that for a given finite maintenance budget, a risk-based approach should be used to optimize technology choices in order to minimize overall expenditures to keep the network up and running. This usually entails installing both types of sensors and possibly interchanging single-gas with multi-gas units after gases are first detected.
3. The gas-sensing elements in the monitor must exhibit long-term stability under real world transformer conditions. Indeed the same conditions that lead to the aging of the transformer itself can age and/or deteriorate the electronics and sensors present in the monitoring system. Some of the conditions that must be accounted for are:
   a. Temperature cycling
   b. Inherent drift of the sensor elements over time
   c. Presence of moisture and oxygen dissolved in the transformer oil
   d. Presence of reactive chemicals in the transformer oil generated by the aging and breakdown of the cellulose insulation and the oil itself; e.g., carbon monoxide, organic acids, alcohols, furans...
   e. Pressure variations
   f. Vibrations

4. The gas-sensing elements should not exhibit cross interference; e.g., react to other gases that may be present in the transformer or in the atmosphere and provide an incorrect reading.

5. The monitoring system should not consume the gas in order to measure it as this can lead to a depletion in the oil sample and to false trends in the gas levels.

6. The monitoring system needs to exhibit long term reliability and should diagnose itself to avoid having a dead sensor be interpreted as “condition normal, no gas detected”.

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**Sensor interchangeability**

In the context of transformer nursing, it often makes economic and technical sense to upgrade from a single-gas sensor to a multi-gas sensor once a specific transformer has been clearly identified as having issues.

Having a common interface design provides significant added value by making such upgrades quick and easy.

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**Challenges of online DGA sensors**

A number of challenges must be addressed when installing, commissioning and operating gas monitoring systems in order to avoid undetected fault conditions (false negatives) and also to avoid false alarms in the absence of real transformer issues (false positives with no actual fault).

Some of the parameters that need to be carefully addressed are:

1. The oil sampled by the monitor must be representative. If the monitor is installed so that it is always sampling the same pocket of stagnant oil, there is a high probability that a developing fault condition will go undetected and create a false sense of security.

2. The monitoring system oil sampling mechanism must be designed in a fail-safe manner to reduce the likelihood of oil leaks. Over time, even a small leak can lead to a ground contamination and to a drop in the oil level of the main transformer tank. If the oil drops below a critical threshold, either safety shut down of the transformer will be initiated automatically or the transformer will fail catastrophically in the absence of a safety system.
Introducing the CoreSense™ Family
Engineered simplicity and robustness

ABB is introducing a new line of DGA sensors called CoreSense™. This new offering represents ABB’s answer to the challenges of designing cost effective, robust and low-maintenance oil-gas analyzers.

In the past few years many utilities and industries around the world voiced their concerns about DGA sensors. These devices were either costly to operate and maintain or simply failing.

The CoreSense™ family is the result of ABB’s combined expertise in transformer and sensor technologies.

ABB’s answer to the challenges presented in this paper is the CoreSense™ family:

1. CoreSense™ - Single-gas sensor
2. CoreSense™ M10 - Multi-gas sensor
CoreSense™
Single gas sensor

CoreSense™ is a hydrogen and moisture sensor. It utilizes two solid-state sensors to measure hydrogen and moisture directly in transformer insulating oil. This is accomplished without the need for complex sample handling, including the use of membranes to separate the dissolved gas from the oil.

The solid-state sensors used in CoreSense™ are designed for long-term stability and reliability. They have been extensively tested and characterized both in the laboratory and in the field for these properties. Both sensors rely on a reversible change in electrical properties to detect concentrations without actually consuming the hydrogen or the water. (See operating principles below).

CoreSense™ is designed for durability and long life with no moving parts and no consumables.

1. It avoids pumps and other mechanical parts by the use of an ultra-reliable thermal element. It induces forced convection to move oil in and out of the sensing chamber, thus avoiding issues related to stagnant oil. This enables easy and safe mounting on any type of valve since it does not create an intrusion into the transformer. In fact, CoreSense™ can easily be installed by users and requires no special protective actions prior to oil treatment activities, a great plus over membrane based systems that can easily be damaged by pressure fluctuations.

   It is equipped with a robust all metal IP67/C4 rated submersible waterproof enclosure. This makes CoreSense™ perfect for flood-prone areas or remote locations with potential weather extremes and access difficulties.

2. It replaces batteries with super capacitors to keep time in the event of a power interruption.

CoreSense™ has a built-in embedded computer that continuously monitors all of its functions. It provides status-at-a-glance capability with three super bright LEDs:
- one for system self-diagnostics,
- one for hydrogen levels, and
- one for moisture levels.

CoreSense™ also has a built-in web server that publishes a simple Human Machine Interface (HMI) to enable local and remote network access to the gas and moisture levels as well as the current status of the monitoring system. The interface is very intuitive, easy to read and efficient. Web pages are accessible from modern internet browsers (Internet Explorer, Chrome, Safari, Edge) and do not require installation of any specific software.

CoreSense™ accurately measures hydrogen in oil with a response time of under one hour and a detection limit of 25 ppm with an error of ±25 ppm or 20%, whichever is greater. It is designed to provide accurate readings for 10 to 15 years with no calibration or routine maintenance requirements and no consumables.

These characteristics make CoreSense™ ideal for large-scale cost-effective deployments that enable continuous monitoring of transformer fleets.
Operating principles

Solid state hydrogen sensor
CoreSense™ uses an oil-immersed palladium element that is sensitive to hydrogen. Hydrogen will split and lodge into the palladium lattice, thus changing the electrical potential of the material. This reversible reaction is proportional to the hydrogen levels in oil. The sensor thus measures the change in resistance and capacitance of the palladium and is calibrated to provide a hydrogen concentration in ppm.

Solid state moisture sensor
CoreSense™ is equipped with an oil-immersed capacitive sensor that is sensitive to moisture. The sensor is made out of two capacitor plates separated by the transformer oil that acts as dielectric insulation. Dissolved moisture in oil will change the dielectric properties of the oil, effectively changing the capacitance between the two plates. The sensor measures the changes in capacitance and is calibrated depending on the oil type to provide moisture concentration in relative percentage or ppm.
CoreSense™ M10
Multi-gas analyzer

ABB has relied on proven in-house technology to re-invent the way we look at multi-gas DGA sensors. The CoreSense™ M10 Multi-gas analyzer is a dissolved gas monitoring system that addresses the challenges of easy installation, robust design and low maintenance cost.

CoreSense™ M10 utilizes Fourier Transform Infra-Red (FTIR) technology combined with solid-state hydrogen and moisture sensors to measure moisture and nine gases: hydrogen (H₂), methane (CH₄), acetylene (C₂H₂), ethylene (C₂H₄), ethane (C₂H₆), propene (C₃H₆), propane (C₃H₈), carbon monoxide (CO) and carbon dioxide (CO₂).

CoreSense™ M10 is comprised of two enclosures:
• a measurement head that has the same dimensions as a CoreSense™ single-gas sensor, and
• a wall mounted analytical unit that can be installed on the transformer, on a firewall or on a pedestal.

The measurement head contains a patent-pending continuous gas extraction system based on gas permeation through a gas permeable capillary. A 10 m flexible protective conduit carries gases, communications and power between the measurement head and the analytical unit. The measurement head uses the same thermal element as the single-gas CoreSense™ to induce convective oil circulation in the head, eliminating the need for external oil circuits that are complicated, expensive and prone to leaks.

A small gas pumping stage made up of three redundant gas pumps ensures gas circulation to the analytical unit containing the FTIR spectrometer. The FTIR spectrometer continuously measures the transformer gases on one channel and the atmospheric background on a second channel. This allows any background fluctuations to be eliminated from the actual DGA results and ensures long-term stable and interference-free DGA measurements with no calibration requirements. In order to ensure maintenance free operation for 10 years, the FTIR spectrometer uses a redundant infra-red source.
CORESENSE M10

Easy to install right out of the box, with no external oil circuit and with reduced maintenance cycles
ABB FTIR technology: a historical perspective

The gas measuring FTIR module in the CoreSense™ M10 is based on the same technology manufactured by ABB and deployed in space by multiple national space agencies and in industrial settings on factory chimneys. ABB’s FTIR is also used in other process applications such as refineries, semiconductor factories and chemical plants to measure chemical compounds in liquids.

Space-borne ABB FTIR technology is used in satellites to analyze Earth’s atmosphere for greenhouse gas monitoring and meteorological applications. It is sought after for its high reliability, accuracy and stability in harsh environments. In addition, the calibration-free nature of the technology saves millions in maintenance or replacement costs. The longest serving space ABB FTIR equipment has been orbiting the Earth since 2005.

Continuous Emissions Monitoring Systems (CEMS) are another proven application of ABB’s FTIR technology that has been available on the market for more than 25 years. In developed countries, toxic emissions from factories are strictly regulated, with some countries imposing a mandatory sensor uptime of 99%. FTIR-based CEMS devices can meet these reliability requirements and provide stable measurements over extended periods of time, allowing identification of long-term trends.

Applying proven and robust FTIR technology to transformer assures that a DGA sensor is accurate, reliable and calibration-free.

Principle of the interferometer

Fourier Transform Infrared Spectrometers (FTIR) selectively modulate an incoming infrared beam by means of optical interference. The intensity of the incoming light [a] is split in two parts by a half-mirror beamsplitter [b].

The reflected part travels the d1 distance twice (separating the moving mirror [c] from the beamsplitter). Similarly, the transmitted part travels the d2 distance twice (separating the fixed mirror [d] from the beamsplitter). The two parts interfere with each other [e] in either a constructive or destructive way depending on the wavelength and the d1 and d2 distances (see “From waves to data: a quick guide to Fourier Transform Spectroscopy” on page 60).

The intensity at the interferometer output is a function of the position of the moving mirror [c], because the interference patterns vary from completely constructive to completely destructive. In fact, the intensity of the modulated output, also called the interferogram, for a monochromatic light at wavelength λ (or frequency ν = c/λ) entering the interferometer is given by where x = 2(d1 – d2) is the optical path difference

\[ I(x,ν) = \frac{I_0}{2} \left\{ 1 + \cos \left\{ 2\pi ν \frac{x}{c} \right\} \right\} \]

between the two arms of the interferometer and I0 is the intensity of the incoming monochromatic light. For a polychromatic input, the total interferogram is simply the sum of the monochromatic interferograms, i.e.:

\[ I(x) = \int I_0(ν) \left\{ \frac{1}{2} \left( 1 + \cos \left\{ 2\pi ν \frac{x}{c} \right\} \right) \right\} dν \]
10 Industrial chimneys equipped with a continuous emission monitoring system

11 ACE (Atmospheric Chemistry Experiment) satellite incorporating ABB FTIR technology

12 Image taken from space during meteorological event
FTIR spectroscopy has a number of advantages over other spectroscopic methods such as filter based photoacoustic spectrometers:
- Stable frequency reference laser to ensure no drift over wide temperature ranges and over multiple years. In fact, the CoreSense™ M10 will never require any recalibration over its entire lifetime
- Very high resolution over a wide spectral range allows unambiguous identification of each gas fingerprint and avoids false readings from interfering gases or cross interference between DGA gases
- Complete spectrum acquisition as opposed to a few spectral windows allows prediction of all gases including heavier constituents propene (C\textsubscript{3}H\textsubscript{6}) and propane (C\textsubscript{3}H\textsubscript{8})

Robustness was a key design parameter during the product development process. We eliminated weak points such as the external oil circulation circuit, carrier gases, active cooling, batteries and other high maintenance components. The CoreSense™ M10 was designed from the ground up for low maintenance by minimizing complex moving parts and using redundancy where necessary. The result is a multi-gas DGA analyzer that can run continuously for 10 years with no maintenance or support.

CoreSense™ M10 is equipped with multiple communication options to suit varying needs. From classic 4-20 mA analog and digital relay outputs to the latest fiber optic, cybersecurity hardened Ethernet connectivity. Each unit can be equipped with a SIM card slot to enable global cellular network connectivity used:
- for remote locations lacking wired infrastructure;
- to avoid expensive wire trenching;
- to fully benefit from the ease of moving CoreSense™ M10 within a fleet; or
- to get ABB transformer experts following your assets when subscribing to a service contract.

CoreSense™ M10 provides the user both local quick and in-depth visibility. LEDs integrated in both the measurement and analytical unit provide status-at-a-glance for gases, moisture and system. In-depth analysis is also provided locally through a color touch screen inside the cabinet of the analytical unit and a built-in web interface to display gas levels and trends.

The CoreSense™ M10 is also provided with a local version of AssetHealth, ABB’s asset management solution, called AHT DGA. It employs a number of algorithms in a sequential mode to establish first if there is any abnormality, then if positive assess the seriousness of the event and subsequently make adequate recommendations for action. The main steps followed by AHT DGA are summarized here:
1. Identify if the current DGA levels are within acceptable limits
2. Identify statistical abnormalities (historical statistical distributions, outliers, etc.)
3. Identify significant trends – short term (last 10 days) and mid/long term (10-30 days) or latest 5 years (user may select longer periods for trend calculation)
4. If issues are detected in 1, 2 or 3 above then run the diagnostic tool (by default run Duval Triangles 1, 4 and 5 when indicated but customizable to IEC 60599)
5. Once a diagnosis of an apparent abnormal condition is identified then run the Expert System that will analyze the issue using the following, but not limited to:
   - transformer age
   - if recent maintenance has been performed
   - if the issue is only related to CO and CO2
   - if the issue is thermal
   - if the transformer has an OLTC (or a communicating LTC)
   - if the issue is dielectric

For each of these issues, or perhaps a combination, the Expert System will make appropriate recommendations regarding actions, and indicate an adequate time frame based on the serious nature of the issue.

6. The Expert System will also try to establish eventual relationships between the evolving DGA issue and other parameters such as load increase (dynamic load data must be provided), ambient temperature, etc., depending on data availability. If data is not available for the correlations the Expert System will make recommendations to look for those correlations since they may provide a good indication with respect to possible means of mitigating the issue.
Bibliography

Additional information

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