Precise DGA measurements are required to look for transformer condition changes


# Dissolved Gas Analysis for transformer health management

## ABSTRACT

Complex studies have led to the development of powerful methods to assess the health of the insulation system, and even the entire transformer, by periodically analyzing samples of the transformer oil. By far the most important of these diagnostic methods is dissolved gas analysis (DGA), which was introduced in the 1960s. Our ability to measure and interpret the dissolved gases has improved tremendously over the last 50 years.

## KEYWORDS

DGA, dissolved gas analysis, monitoring, health

## 1. Introduction

Look at any power transformer today, and one may notice the materials used in its construction remarkably resemble those used 100 years ago. To this day, most power transformer designers continue to prescribe cellulose insulation submerged in mineral oil to achieve a cost-effective and reliable insulation system. One upside to the long history of this design choice is that we have had many years, and many transformers, to study the aging of these materials in service. These studies have led to the development of powerful methods to assess the health of the insulation system, and even the entire transformer, by periodically analyzing samples of the transformer oil. By far the most important of these diagnostic methods is dissolved gas analysis (DGA). Many of the electrical, thermal and chemical problems that may arise during the lifetime of a transformer will leave a signature in the oil. For example, overheating the cellulose insulation tends to generate traces of CO (carbon monoxide) and $CO_2$ (carbon dioxide) gases that become dissolved in the oil. In another case, heat generated by a loose or failing internal electrical connection can cause thermal degradation of the oil as it flows over it. Such oil degradation will generate dissolved $CH_4$ (methane), $C_2H_4$ (ethylene), $C_2H_6$ (ethane) and $C_2H_2$ (acetylene) in proportions that depend on the contact temperature. Partial discharge activity commonly creates a pattern of predominately hydrogen with lesser amounts of methane. Arcing, on the other hand, typically gives rise to similar amounts of dissolved hydrogen and acetylene.

## 2. The critical role of DGA

Our ability to measure and interpret the dissolved gases has improved tremendously over the last 50 years. Today, it is standard practice to draw oil samples from transformers once or more annually, and send these to specialized laboratories to measure the concentrations. When the concentrations are evaluated using DGA interpretation algorithms, the nature of a transformer problem can be determined, or at least narrowed down, and further diagnostic testing or corrective measures can be prioritized with an understanding of the risks and required urgency of response generally associated with such problems.
DGA can detect a wide range of transformer problems. As a result, it has come to play a central role in many transformer asset management programs. The data is quantitative, so each new analysis can be compared to the DGA history of the transformer, to look for changes in the condition. Comparing DGA results with those from other transformers with similar design, age and loading history can reveal gassing behavior that is unusual and warrants investigation. By collaborating with international organizations such as IEEE, CIGRÉ and Doble, DGA experts have compiled guides to help identify and manage concerning DGA conditions. For example, these documents recommend increased DGA sampling frequencies to more closely track the evolution of transformers that may have active faults. Today, most asset managers have policies in place to perform regular DGA analysis and to follow through with the investigation of DGA results that are anomalous. These investigations commonly draw on complementary data from other oil tests, online tests – such as those used to detect partial discharge activity, offline electrical tests, and maintenance and loading history to develop a clearer picture of what may be wrong in the transformer.

## 3. DGA fault diagnosis

As mentioned, DGA can do more than detect changing or anomalous transformer conditions. It can be used to identify the type of fault giving rise to the dissolved gases. The first DGA interpretation algorithms were put forward in the 1960s, and have been improved tremendously through ongoing research. The algorithms were created by correlating the fault types observed inside large numbers of transformers with the dissolved gas concentrations recorded before the fault investigation. Early in the process, it was discovered that the proportions of different gas concentrations show a much closer correlation to fault type than do the absolute gas concentrations. For this reason, DGA interpretation methods today often use ratios of gases, or ratios of gas combinations. Perhaps the most iconic (and graphically intuitive) ratio methods we have today are the triangle and pentagon figures developed by Dr. Michel Duval [1]. In recent years, these algorithms have been extended to allow fault diagnosis when alternative dielectric liquids are used and to evaluate the health of on-load tap changers (OLTCs).
Precise DGA measurements are required to look for transformer condition changes, but precision alone is not adequate for the DGA interpretation methods, which

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require a level of absolute accuracy in the gas readings to calculate gas ratios of acceptable uncertainty (the percentage of uncertainty in the ratio is the sum of the percentage of uncertainty in the individual gas readings). There is some consensus that gas readings should have absolute accuracy of ±15 percent or better for effective use of DGA interpretation tools [1]. To meet this requirement, standardized measurement methods and quality control systems have been widely adopted by DGA laboratories, and these laboratories are able to routinely validate accuracy performance using third party gas-in-oil standards. These gas-in-oil standards are prepared by methods which are more accurate than the test methods for DGA.

Commercial software solutions have simplified the application of DGA, and have made it more accessible to non-specialists. At the most basic level, these tools enable consolidating and visualizing historical DGA data and trends. It is essential that the review of DGA data includes the historic trends to determine gassing rates (which gases are actively changing against the baseline of gases from normal aging) to be able to detect problems in the early stage of evolution. Comparison tools are generally provided to easily identify gassing patterns that stand out as unusual against a selected transformer population, or against published statistical norms. New data can be automatically evaluated to highlight transformer condition changes and DGA interpretation algorithms can be applied with ease. Many of these software solutions provide user-configurable health indexes designed to draw the attention of the asset manager to those transformers at greatest risk of deterioration in condition.

### 4. Online DGA monitoring programs

Transformer faults can evolve slowly over years, or quickly over days or even hours. Faults that emerge suddenly can easily be missed by annual DGA testing regimes. To improve on this, online DGA monitors have been developed to provide DGA measurements every few hours or less. Simpler, lower-cost monitors are optimized for fault detection. These measure the gases generated in most transformer faults, specifically $H_2$ (hydrogen) which forms when faults affect the oil, and CO (carbon monoxide), which forms during degradation of the cellulose insulation. To detect gassing faults as early as possible, it is important to select fault-detection monitors that have the sensitivity and repeatability to detect small changes in gassing behavior. If the gas readings are also accurate, it reduces confusion when comparing the monitor data with laboratory DGA results and allows quantitative rate-of-change monitoring.

Multi-gas DGA monitors report most or all the fault gases commonly analyzed in a DGA laboratory. If the accuracy is good enough, these allow meaningful use of DGA diagnostic algorithms to track the transformer condition in near real-time. This can be particularly useful when an active fault has been identified. If the real-time DGA diagnostics show the fault type is stable (or has potentially been stabilized by reducing the load), it may be possible to continue operating the transformer with acceptable risk of failure, until the next scheduled shutdown. Online comprehensive DGA equipment can provide detailed information that might be missed in

less frequent laboratory tests. Examples include:

- Onset of a fault, or change in the fault condition
- Faults related to loading and operational temperatures
- Voltage dependence of gas generation
- Periodicity of gas generation activity
- Loss of combustible gases, or increase of atmospheric gasses (and in some cases $SF_6$) through leaks
- Oxygen consumption from aging of the insulation system
- Trend of $CO_2$/CO ratio and ethylene/ethane ratios, indicating paper is involved in localized overheating

In the last few years, we have seen the emergence of DGA online monitoring for on-load tap changers, stemming from the recognition that faults in these complex machines account for a significant percentage of all transformer faults. For OLTCs with contacts that are switched under oil, the arcing associated with contact switching leads to high dissolved gas concentrations and carbonate particles, some of which remain suspended in the oil. To slow the buildup of carbonized material and maintain the dielectric properties of the oil, an oil filtration system may be used to constantly clean the oil. The DGA monitor can conveniently draw clean oil from the filtration system, preventing possible buildup of particulate in the monitor. DGA methods are also being developed for vacuum-switching OLTCs, where dissolved gases can highlight anomalous heating of internal components. With these methods, the advantages of DGA monitoring, including early fault detection, can be extended to OLTCs. As for the main tank, DGA diagnostic algorithms for OLTCs can be leveraged to track OLTC health in near real-time.

## 5. The value of DGA for asset management

Figure 1 shows an example of early fault detection using a two-gas DGA monitor on a 23 MVA power transformer in Greece. The hydrogen concentration (left) had been stable for several years at a low level of approximately 15 ppm and suddenly doubled in a few hours, indicating a significant increase in hydrogen generation rate. The carbon


Figure 1. A two-gas DGA monitor detects a step increase in hydrogen at low-concentrations

**DGA methods can detect and diagnose a wide variety of power transformer problems**

monoxide concentration remained low during this event, suggesting the cellulose insulation was not directly involved. Laboratory DGA results confirmed the monitor readings and the Duval triangle method indicated a high temperature thermal fault. The asset manager interchanged the fault detection monitor with a multi-gas DGA monitor to be informed of any deterioration in the fault condition. The transformer was taken out of service at the next opportunity and electrical testing indicated several loose connections on the in-tank OLTC. When the oil was drained, the loose connections were easily located and repaired. The fault detection monitor had played a key role in detecting the fault and addressing the issue before more costly damage incurred.

As another example, Figure 2 shows data recorded by a multi-gas DGA monitor during the first days of service of a new 900 MVA transformer in the southern USA. After installation on site, the unit was filled with new, degassed mineral oil. Within a few hours of being energized, the transformer began to exhibit significant fault gassing. The monitor readings rose steadily over 24 hours, including an increase in acetylene ($C_2H_2$) from zero to six ppm, and the transformer was de-energized later that day after which the gas levels quickly stabilized. A few laboratory DGA samples confirmed the concentrations reported by the monitor. An analysis following Duval methods indicated a "T3" thermal fault with temperature exceeding 700 °C, which could have quickly escalated to a catastrophic failure. The comparatively-constant CO readings suggest the cellulose insulation was not directly involved. The transformer was returned to the manufacturer for root cause analysis and repair under warranty.

## 6. Economic benefits of DGA

Many electrical utilities have deployed condition monitoring programs to reduce the costs associated with operating transformer fleets. DGA monitors commonly play a central role in these programs, alongside systems for monitoring

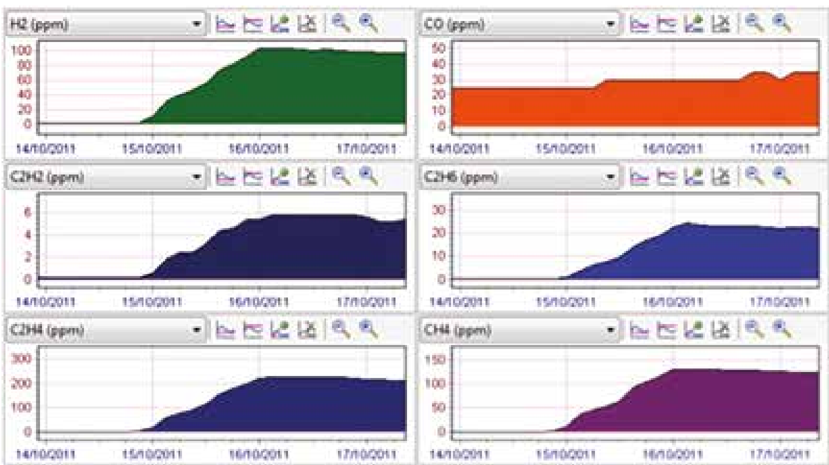


Figure 2. Multi-gas DGA monitoring of a defective new transformer

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temperatures, fans, pumps, bushings and partial discharges. When the data from these systems is used to drive prioritized maintenance actions across the fleet, several primary economic benefits can be realized. First, it is possible to reduce the cost of failure-related repairs by catching issues early, when they are still localized, and repairing them before they grow into more costly problems. Second, monitoring can serve to defer the capital cost of transformer replacement. For example, if monitoring is used to detect excessive temperature, moisture, or oxygen in the system, these conditions can be corrected to avert accelerated and irreversible aging of the cellulose insulation. Capital cost deferral can also be achieved with aged transformers because monitoring allows these to be kept in service until their condition shows actual signs of deterioration, which may be well after the end of their nominal design lifetime. It has been said that extending the transformer lifetime by one year justifies the cost of monitoring a transformer [2]. Other benefits can also be realized. Through improved visibility of the health of the transformer fleet, monitoring can allow more units to remain in service. Financial performance can be improved under performance-based regulation, and in some cases, by minimizing revenue loss due to energy not generated or delivered. Monitoring can also improve environmental performance and personnel safety.

Condition monitoring programs seem to achieve the most benefits when they are carefully planned and actively managed. In planning, monitoring equipment vendors are best selected with a view to a long-term partnership. This helps teams get the best value from the equipment and ensure the availability of product support, repair parts and service throughout the equipment lifetime, which is commonly in the range of 10-15 years. Selecting reliable monitoring equipment is critical to ensure maximum up-time, while controlling costs of responding to false alarms and equipment breakdowns. Consulting with asset managers from other organizations can be a useful way to share experiences, reduce risks and forecast program operating costs. A well-honed response process is necessary to maximize return on the investment in a condition monitoring program. We sometimes see examples where the monitoring system has detected a transformer issue, but the processes in place to interpret the risks and act appropriately are too slow to prevent failure of the transformer. While some of these events are unavoidable, each can be viewed as an opportunity to learn and improve the response process.

## 7. Portable DGA analyzers

Portable DGA equipment allows users to immediately respond to emergencies while on site, without needing to wait for an oil sample to reach a DGA laboratory for analysis and for the report to be returned. Often these emergencies occur when there is an alarm or trip from a protective relay designed to prevent the transformer from failing catastrophically. The issue facing the on-site engineer is to determine if the alarm or trip was due to a transformer fault condition or a false alarm. If there is a gas collection relay for a sealed conservator system, such as a Buchholz relay, a gas sample can usually be drawn from the relay for analysis. This type of relay is placed at the top of the transformer with associated plumbing so that when gases are generated at a rate that exceeds the ability to dissolve in the oil, free gas is formed as bubbles rise in the oil and collect in the relay, which in the normal state is filled with oil. As the free gas in the relay collects, a float switch will activate an alarm or in some cases a trip. However, air can sometimes get trapped in the relay, or vibration can cause false activation of the relay. A portable gas analyzer can be used to quickly determine if the gas in the relay is primarily air, or rather contains high levels of combustible gases, in which case it may be unsafe to put the unit back into service. For a gas blanketed transformer that has an alarm or trip from a protective relay, an oil sample can be quickly analyzed with the portable DGA analyzer to evaluate fault gas concentrations. These readings can then be evaluated by comparing to historical dissolved gas levels and using DGA diagnostic algorithms to determine the best course of action.

Transformers frequently seem to alarm or trip at inconvenient times, like the middle of the night or on holidays, or at far away locations. At these times, it can be particularly valuable to obtain DGA results on site to quickly ascertain if the alarm or trip was based on a real problem in the transformer.

Portable DGA analyzers can be used for routine purposes, too. For example, it can be helpful to test DGA samples on-site immediately before and after doing re-


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pairs, or while performing other test and inspection work. Portable DGA analyzers can also be used to confirm the readings of a DGA monitor, or a suspect DGA laboratory result while on-site. When a transformer has an active fault, a portable DGA analyzer can be used for more frequent sampling to keep the unit in service while following the fault evolution, with the aid of DGA fault diagnostic software. In general, these portable tools are valuable whenever quick DGA results are needed to make timely maintenance decisions.

## 8. DGA leads to confident decisions

DGA methods can detect and diagnose a wide variety of power transformer problems. They have come to play a central role in many asset management programs. The fault types most commonly identified using DGA methods include thermal faults affecting oil, overheating of paper (cellulosic materials), partial discharges and arcing, and more. DGA methods are increasingly capable of diagnosing faults in transformers filled with insulating fluids other than mineral oil and faults in OLTCs of different designs. Portable DGA analyzers can be used routinely to quickly investigate a circuit breaker or gas relay trip, or to manage a unit with an active fault.

**Condition monitoring programs seem to achieve the most benefits when they are carefully planned and actively managed**

Condition monitoring programs using DGA monitors have numerous paybacks. In addition to reducing routine transformer maintenance costs, these programs allow longer transformer service life and the detection and correction of faults before they become too costly. DGA software tools continue to improve and put our collective understanding of DGA interpretation into the hands of the engineers who need it to make timely and informed maintenance decisions.

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