dissolved gas analysis for power transformers

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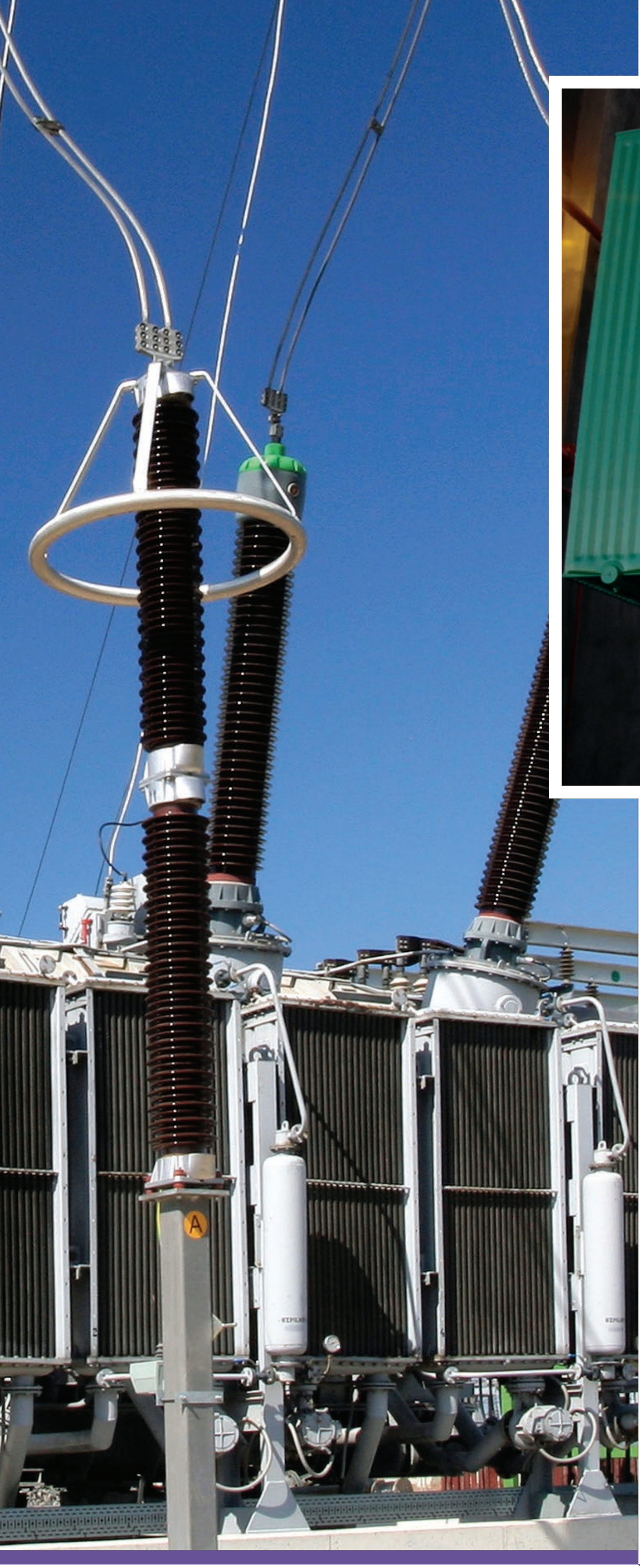

Author: Donal Skelly, GE Digital Energy
Editor: Dominique Legrand, GE Digital Energy

Online management of aging transformers using PHOTO-ACOUSTIC SPECTROSCOPY

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Abstract

Dissolved Gas Analysis (DGA) is recognised as a powerful monitoring technique for the detection of developing faults within transformer main tanks and associated oil filled equipment. The use of extensive historical data, collected by laboratory analysis, allows for accurate fault detection and even fault prediction based on online DGA and this technique has become increasingly relevant with the ageing of the worldwide transformer fleet. Aspects of laboratory DGA are presented to illustrate the evolution from laboratory analysis to on-line DGA. The principles of Gas Chromatography (GC) are outlined together with an analysis of the difficulties associated with the use of this technology in field based on-line instrumentations. An introduction to Photo Acoustic Spectroscopy (PAS) technology employed for online monitoring is presented, together with a description of the significant benefits associated with using this robust technology for the challenging substation environment.

Abbreviations

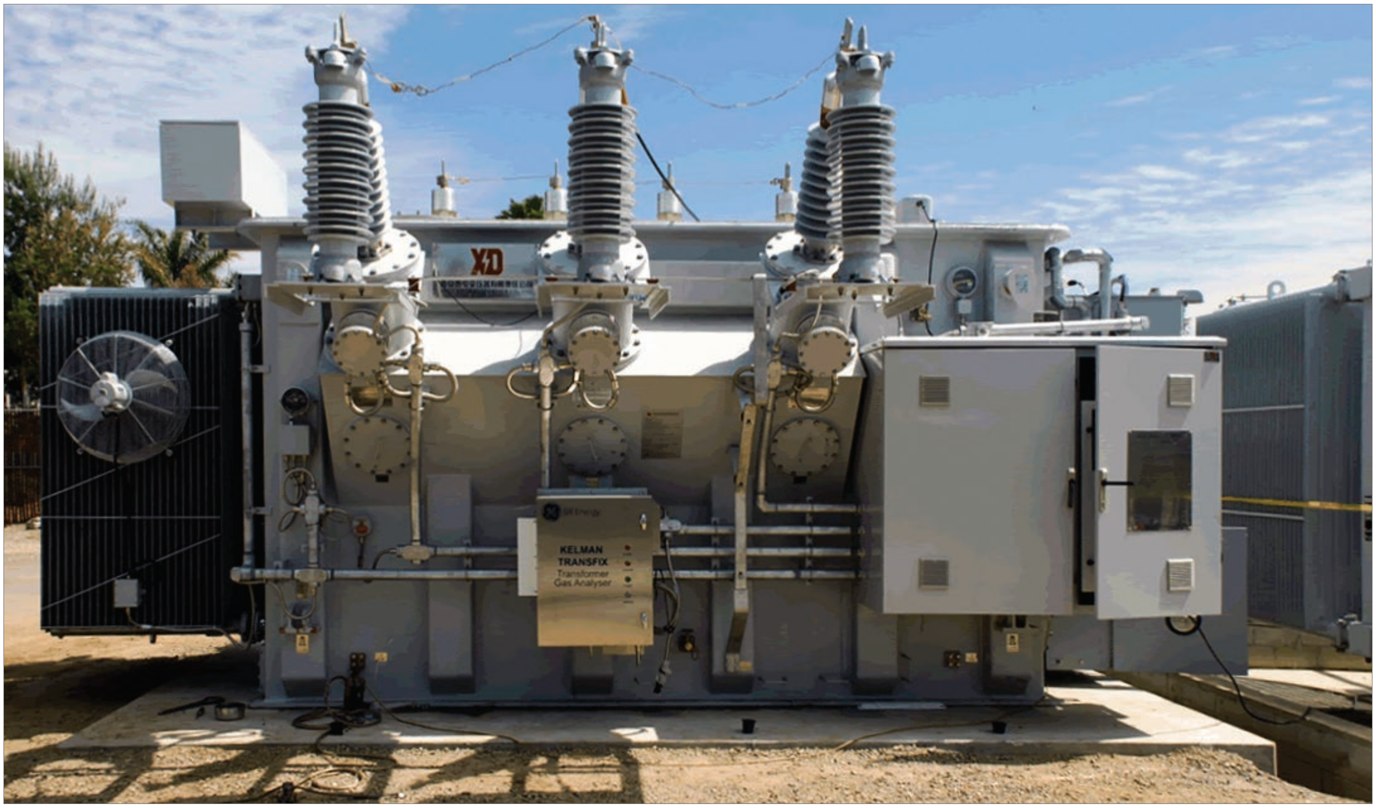
PAS: Photo-Acoustic Spectroscopy **GC:** Gas Chromatography

DGA: Dissolved Gas Analysis

Dissolved Gas Analysis for Power Transformers

Power transformers allow for the transmission of electrical power at efficiently high voltages and the subsequent use of this power at conveniently low voltages. Transformers have been used since the earliest days of electrical generation and transmission and have now become ubiquitous across the world – by some estimation there are greater than 2,000,000 large transformers worldwide (>100kVA). Although thousands of new transformers are being manufactured each year, the vast majority of transformers globally are already in operation and a significant proportion of those have already exceeded or are approaching the end of their design lifetime.

Virtually all large transformers, old or new, have cores and windings immersed in oil, together with input and output electrical connections. The transformer windings will normally be electrically insulated by thick layers of paper insulation wrapped around each part of each winding. The oil acts as both a heat dissipation and an insulating medium. When the oil or paper insulation is stressed, such as under elevated temperature conditions associated with high load and/or fault conditions or even under normal operating conditions, it will break down to form a range of by-products and simple gases. These gases dissolve into the oil immediately following their creation and will remain there indefinitely (if they cannot escape from the electrical equipment via a breather or a leak).



The gases that are associated with specific fault types are Hydrogen (H_2), Carbon Dioxide (CO_2), Carbon Monoxide (CO), Ethane (C_2H_6), Methane (CH_4), Ethylene (C_2H_4) and Acetylene (C_2H_2). They are known collectively as the diagnostic gases.

Analysis of the concentration of these diagnostic gases, called Dissolved Gas Analysis (DGA) has long been recognized as the single most powerful technique for transformer main tank fault detection / prediction. It has been at the forefront of most progressive utilities' monitoring strategy for the last four decades. This is evidenced by very many published papers and by numerous national and international standards relating to how DGA may be performed and how the results can be interpreted. With an aging and expanding transformer fleet and pressures to reduce both capital and operational expenditure, DGA has become even more important to utilities and industries. This trend is set to continue as the global fleet ages and the pressure on utilities to compete intensifies.

KELMAN TRANSFIX AND THE APPLICATION OF PAS TO ONLINE DGA IS A SIGNIFICANT LEAP FORWARD IN THE FIELD OF AUTONOMOUS, STABLE AND ROBUST ONLINE MONITORING.

Manual Samples and Laboratory DGA

Traditionally DGA was limited to a laboratory test because of the complexity of the equipment required to extract and measure gases at quantities as low as one part-per-million (ppm).

Historically gas extraction was normally performed using a strong vacuum pump for degassing a sample of the oil prior to analysis – called a Toepler pump apparatus. More recently, IEC, ASTM and others have published methods describing a gas extraction technique that is suitable for automation. "Headspace Gas Extraction" is now becoming the most common technique employed in laboratories due to its convenience and excellent repeatability at the gas extraction stage of the process.

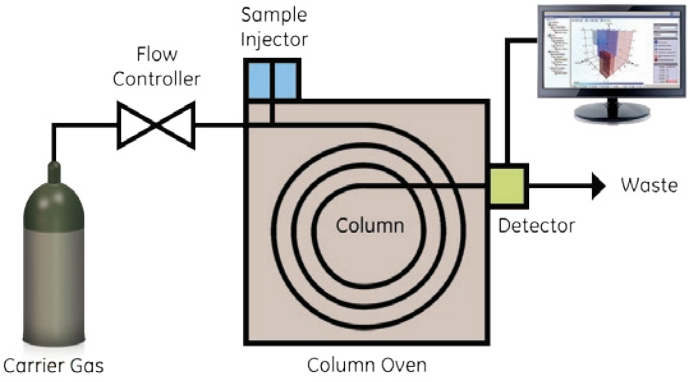


Figure 1. Basic diagram of a Gas Chromatogram showing the major components that go into making such a system. A DGA specified GC will in addition to these basic components require two columns and two detectors to get the required level of sensitivity.

The gas detection technology utilized in the laboratory is based around the separation of each gas in a gas mixture. This is achieved by introducing the gas mix to be analyzed into a constant stream of a "carrier gas" and from there, subsequent detection of the gas on one of several detectors. Called Gas Chromatography (GC) this technique can be designed to be sensitive to each target gas and in fact, can be used to analyze a huge variety of diverse types of samples from oil and gas to water and air pollution.

Each GC is set up for a specific application. A specific carrier gas is chosen to drive the gas sample from its injection point down the length of the column where it will separate as the more mobile molecules in the mixture travel faster. This technique requires very tight control of gas flow rates, temperatures and carrier gas quality. It is a sensitive but unstable technique which has historically been confined to a laboratory environment. This is primarily because GC is sensitive to changing local conditions, e.g. temperature, pressure, movement, continuity of gas flow rates etc. As a result of this high degree of sensitivity to environmental factors, GC requires daily recalibration for continued quality operation. It is for this reason that this technique has remained the exclusive preserve of the laboratory environment for most of the last 50 years. Initial attempts to utilize GC in the field environment have met with limited success - with the single biggest problem being equipment drift, leading to poor repeatability of results from one sample to the next.

With laboratory DGA, oil testing has usually been limited to an annual process. Typically a substation operator would collect a sample of oil into a syringe or bottle, note nameplate information, oil temperatures and other details relating to the transformer, package the sample and ship it to the laboratory. Due to the costs involved (site visit, logistics and laboratory analysis), sampling and analysis would usually be restricted to once per year, with repeated or more frequent samples collected and tested only if significant fault gases were detected in the routine annual sample. As many types of faults can progress significantly in less than one year, this approach often resulted in missed diagnostic opportunities. Faults could occur and progress for up to 12 months before being detected and significant damage caused to the transformer in the mean-time as a result. For this reason, in recent years there has been a dramatic increase in technology companies supplying instrumentation for online, automated DGA on a frequency up to one sample per hour.

On-line, Remote DGA

Recent advances in gas detection technology have seen DGA move out of the laboratory and into the field for the first time. Starting with composite gas detectors capable of passively sampling fault gases through a membrane, (the GE HYDRAN™ - now a byword for transformer monitoring is one such equipment), online DGA has advanced to a point where full, 9 gas analysis can now be performed many times a day according to a pre-programmed schedule, without any user intervention required. Providing unprecedented levels of information, these devices add a whole new dimension to the field of fault detection. By adding communication to the monitoring units, users can remotely track daily, weekly and seasonal gassing trends. These essentially real-time results can be used, not only to detect active faults but even to predict the development of a fault before it becomes a real service issue.

Originally, on-line monitoring devices were based on simple versions of laboratory Gas Chromatography (GC) equipment, packaged in a way so as to allow them to work in a field environment. Accuracy had to be sacrificed for cost and automatic operation purposes (a laboratory GC costs as much as US$100,000!). As these systems have evolved (and stability of GC in the field has been drawn into question), a new technology has emerged to challenge the previously prevalent GC. Developed specifically to address the shortcomings of online GC: Photo Acoustic Spectroscopy (PAS) based DGA instruments entered the market in 2002. Utilizing detection technology normally associated with urban pollution monitoring, PAS based systems have, by 2012, become one of the most trusted technologies for online and portable DGA applications. As such PAS based instruments now have the largest install base of any competing product range worldwide.

GE offers such PAS based monitoring units (in the form of its Kelman TRANSFIX™ range of on-line monitors) and believes that these PAS instruments offer significant advantages over GC technology based units. TRANSFIX is capable of collecting and extracting all diagnostic gases according to the standard principles of headspace extraction and analyzing them at concentrations as low as 0.5ppm. Quantification of the full range of diagnostic gases with a precision and accuracy similar to a laboratory is now possible online on an hourly basis without need for recalibration, consumables or frequent servicing.

PAS Technology

PAS is an old science and was first observed by Alexander Graham Bell in 1880 using the sun as an IR source and the human ear as the detector of the acoustic signal. In the 1970s, with the emergence of modern electronics, interest was renewed in this science since the technique offered a very sensitive method for the identification and quantification of trace amounts of atmospheric gas pollutants without the need for regular recalibration of the detector.

Photo Acoustic Spectroscopy (PAS) works along the following principle: A substance absorbs light energy and converts it to sound energy. The absorbed energy from the light is transformed into local heating and kinetic energy of the sample by the energy exchange processes. This kinetic energy and associated heating results in a pressure wave (sound) that can be picked up by a microphone. By pulsating the light source, repeated measurements can be made on a single sample. A photo acoustic spectrum of a sample can be recorded by measuring the sound intensity at different wavelengths, produced with a combination of a broadband IR source and a diffraction grating . This spectrum can be used to identify the absorbing components of the sample. Photo acoustic spectroscopy has become a powerful technique to study concentrations of gases at the part per billion levels. Modern photo-acoustic detectors still rely on the same principles as Bell's apparatus, however to increase the sensitivity the following modifications have been made:

1. Use of intense IR sources or lasers to excite the sample, since the intensity of the generated sound is proportional to the IR energy intensity (and the gas concentration).

2. The ear has been replaced by sensitive microphones. The microphone signals are further amplified and detected using lock-in amplifiers.

3. By enclosing the gaseous sample in a cylindrical chamber, the sound signal is amplified by tuning the modulation frequency to an acoustic resonance of the sample cell.

In the GE photo-acoustic detector, broadband IR is produced by a black body IR source. IR filters are used to select regions of the infrared spectrum that overlap with particular target gas species. This allows for multiple gas species to be detected without the expense and complexity of multiple lasers while still achieving parts per million gas detection levels.

PAS for DGA

Utilizing a PAS based analyzer for quantification of the transformer fault gases, GE has avoided many of the issues associated with employing a GC for this field application.

Advantages of using PAS over the GC style technology are:

a) Less sensitivity to the environment.

GC systems are very sensitive to environmental conditions (temp, humidity, atmospheric pressure, movement associated with vibration or wind buffeting etc.). While these conditions are perfectly controlled and checked in a laboratory, in the field this is much more challenging, with systems having to cope with day to night changes, winter to summer changes, weather patterns and local shaking from transformer vibration, road traffic and industrial processes. To provide a suitable environment for a field based GC system is costly and complex, but this is the only way to guarantee long term accurate results from a GC based DGA system. Great care must be taken by the utility when assessing the guaranteed specification of operating conditions for the GC system in the field. This is often overlooked by the manufacturer in instrument specifications and only become obvious upon extended operation of the field GC. In contrast, a PAS system is virtually immune to environmental conditions such as temperature, noise and vibration and remains accurate over a very wide range of operating conditions and long duration.

b) No requirement for regular recalibration.

Laboratory based GC systems need to be recalibrated once per day according to recommendation laid out in IEC standard relating to DGA, because they are very sensitive to a range of elements: environmental as discussed above, but also column ageing (which affects the time it takes for the sample to traverse the length of the column, a value which must be known with absolute certainty for qualification and quantification of each gas). While this is possible in a laboratory environment where systems can be maintained with high levels of stability, the same is difficult in the field and so results can vary constantly in a field based system. To perform frequent recalibration, GC systems need a bottle of calibration gas. The more gas they use, the larger the bottle needed or the more often it needs to be replaced. Less calibration gas usage means less frequent recalibration and potentially less accurate results. If the field GC has a suitable supply of calibration gas it must still be calibrated every few days to avoid major drift problems. This constant recalibration gives a discontinuous set of results over time because batches of results are measured off a different recalibrated set-point. This leads to discontinuity in trending charts and makes modeling of trends difficult. To combat this, manufacturers often include an internal smoothing/averaging algorithm to mask these discontinuities but this reduces the sensitivity of the system and provides for the possibility that a real electrical fault will be "smoothed" out in the results displayed for several days. In contrast, PAS systems only need to be recalibrated every 5 years or 10,000 measurements. This means that all measurements, year after year are based on the same calibration set-point. This leads to a more precise instrument that detects minute changes. Because smoothing is not applied to PAS based measurements, normal operating transformer results may appear slightly noisy but in fact the results better reflect the actual changing conditions within the transformer.

c) No requirement for multipoint recalibration in the field.

IEC standards relating to DGA state that a GC system employed for DGA must be calibrated at several different concentrations as the detectors used in GC systems are known to be non-linear in their response over a broad range of concentrations. While common in laboratories where high accuracy is required, no current model of field based GC has this capability. PAS based instruments produce a linear response to changing gas concentrations over a huge range - from approximately 1 ppm to over 30,000 ppm, gas-in-oil.

d) No carrier gases to be connected up, replaced when exhausted or managed in stock.

PAS technology uses atmospheric air as its carrier medium and is immune to changing atmospheric air content for outdoor ambient air. PAS systems measure the background air prior to a gas-in-oil measurement and subtract any effect of this air from the final measurement. By contrast GC systems usually require very high purity (99.999% purity) Argon (use in labs) or Helium (used in field systems due to its lower cost) to operate with good stability. Failure to use these high purity gases in a GC can drastically reduce the lifetime of the column and cause damage to the detectors. As a further benefit, PAS based systems do not require any account keeping about gas usage or logistics surrounding planning gas bottle replacement or delivering them to site in a timely manner and installing them.

e) No safety implications

Use of PAS for DGA avoids the safety implications associated with using and storing potentially hazardous high pressure gas cylinders (hydrogen and calibration gas mixtures required by GCs) beside the instrument in the substation. Also it should be noted that a GC based system operates one of its detectors by maintaining a lit hydrogen flame. This can have obvious safety implication in some environments. Some systems on in the market omit the detector based on a Hydrogen flame and sacrifice some accuracy by doing so.

f) No columns to replace at regular interval

To maintain the levels of accuracy and precision that is possible with a new GC column, replacement is required up to every six months, making this the default service interval (assuming the cylinders of gas are large enough to last at least 6 months). This has to be taken into account over the life of the equipment as 8-gas GC systems use 2 different columns and column replacement is a difficult process normally requiring a specifically trained commissioning engineer. Systems employing only a single column invariable suffer a loss of selectivity in gas measurement associated with using only one column.

The above are just some of the issues associated with using what is essentially a laboratory technology in the field and are the main reasons that GE has developed a system that utilizes PAS gas detection as a preferred alternative for field application. As stated, although the above issues are easy to manage in a laboratory environment where a GC system will be serviced by a technician on a daily basis, they become significant for a system which needs to operate autonomously over long periods of time. Indeed for a technology that requires daily attention in a controlled laboratory environment, a field GC may reasonably be expected to require service visits more often than the transformer or associated substation equipment. Where a primary benefit of online DGA is a reduction in operation expenditure associated with routine scheduled transformer maintenance, the monitoring device should logically require less frequent service visit than the transformer itself.

The TRANSFIX has a default service interval of 5 years (and up to 10 years depending on mode of operation) and this is much more appropriate to a substation environment.

As a result of the above issues TRANSFIX and the application of PAS to online DGA is a significant leap forward in the field of autonomous, stable and robust online monitoring. With the inclusion of a Hydrogen sensor, an Oxygen sensor and a moisture sensor TRANSFIX can perform regular full DGA online, offering as a real practical alternative to laboratory DGA testing.

PAS BASED DGA INSTRUMENTS HAVE BEEN DEVELOPED WITH THE EXPRESS PURPOSE OF ADDRESSING THE SHORTCOMINGS OF ONLINE GC BASED INSTRUMENTS.

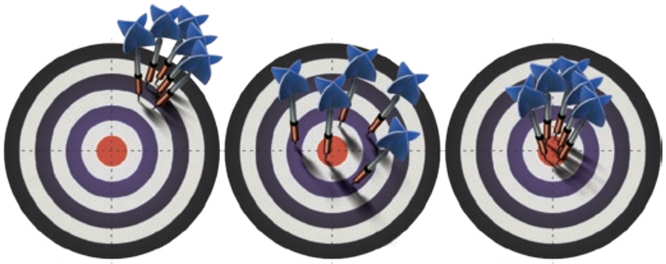
Accuracy versus Precision

To discuss the subject of accuracy and precision for online DGA, we first need to start with a couple of definitions:

"Accuracy" is how close a measured value is to the actual (true) value while

"Precision" is how close the measured values are to each other.

These are well illustrated by the following diagrams:



The diagnostic algorithms for DGA are focused to a large extent on trending changes in gas levels within the transformer rather than absolute quantities of gas-in-oil. For example, a quantity of 100 ppm of ethylene in a transformer main tank may not be of concern if it is known to have been created by a fault in the transformer which has now been repaired. However a quantity of ethylene increasing by 100 ppm over a period of time (weeks or months) probably indicates a serious fault which requires immediate attention. Thus changes and the rate of these changes are more important in DGA results analysis than absolute quantities.

In order to only detect real changes and have meaningful rate of change calculations, the key requirement in DGA is for the unit to be "precise". This is more critical than "accuracy" because an accurate but imprecise system will have poor repeatability and give you variation in the results (indicating changes) when there is really no change. GE has designed TRANSFIX with "precision" as the primary performance characteristic: the ability to have a repeatable value for repeated measurements of the same oil sample. TRANSFIX is capable of precision far in excess of what manual sampling and laboratory testing can achieve.

Clearly accuracy is also useful and TRANSFIX has been developed as a whole analytical system, capable of oil sampling, gas extraction and gas detection. Absolute accuracy of the detector is established by calibration to gas standards with full traceability to international physical standards. During manufacture, standard gas-in-oil samples are prepared and cross instrument verification is used to verify the product's accuracy.

TRANSFIX, a GE product based on PAS technology, is a stable, accurate and very precise instrument capable of autonomous operation over long periods of time without any requirement for consumables. This is a significant advancement in the field of online DGA and offers flexibility of operation not seen before.

Kelman TRANSFIX

Features and Benefits

The TRANSFIX incorporates the following features into its basic architecture:

Full online fault gas DGA using PAS with additional sensors used to provide values for O_2, N_2 and moisture in oil.

Detection of the critical gas acetylene at an impressive 0.5 ppm. Most other diagnostic gases are detected at the recommended 1 ppm.

Load current and ambient temperature recording and tracking to correlate with gas production rates.

Autonomous operation with only oil filters possibly requiring replacement depending on particulate matter loading of the oil.

Multiple alarm relays - programmable caution and alarm options.

Quantitative gas levels and rate of change alarm capability.

Multiple remote communications options.

Multiple communication protocols available.

Wide range of operational environments

- 0 - 2000m altitude.
- -40 ° C to +55 ° C ambient temperature.

The PAS technology and GE's unique approach to online DGA provides the following benefits to the user.

The instrument requires no consumables over a 5 year service interval

- No or very low operational expenditure.
- 5 year interval for service visits.

Stable and repeatable results provided due to the resistance of the detector to drift.

Highly accurate detector, established by calibration to internationally traceable physical standards.

Results and diagnosis of fault conditions available 24/7 via a suite of software capable of collecting and collating data from multiple online units.

Long life, > 15 years is typical.

Full cycle of analysis completed in as little as one hour and at a programmable interval anywhere between 1 hour and 4 weeks.

Interval can be set to automatically increase when caution alarm level has been reached.

Turnkey solutions available to suit individual application requirements.

Additional Benefits of PAS Technology

In addition to the many benefits already discussed, PAS technology has two further unique features that sets it apart from all the competitors for DGA gas detection.

Chief among these is the ability of the PAS detector to transition from measuring very low concentration sample, with just a few ppm of gas-in-oil, to very high concentration samples with

>30,000 ppm gas-in-oil and then back again, without any carryover or fatigue of the detector. This is of particular importance for transformer on-load tap changer (OLTC) monitoring. Analysis has shown that excepting bushing failure, the most common transformer failure mechanism is tap changer failure. Although failure within the main tank can spell the end of life for the transformer and must be guarded against with DGA monitoring, the reality is that over the life of the transformer it is more likely that the tap changer will fail unexpectedly. On critical transformers incorporating an OLTC the tap changer unit needs to be monitored to detect these developing faults.

PAS detectors are perfect for this application. With PAS there is no retention of gases from one analysis to the next and measured gases are simply flushed from the system in an air stream following analysis: all internal surfaces that the gas may come into contact are inert (PTFE, glass, gold and stainless steel) and so there is no gas retention of any sort. On the other hand, using GC based instrumentation for monitoring the main tank and the tap changer would require 2 separate instruments. This is because GC cannot step from low, to high, to low concentration gas-in-oil samples. A GC column is designed to retain gas and only releases it with forced carrier gas and elevated temperature and this feature precludes an application where high concentrations need to be followed by low concentrations.

Finally, and of most significance to portable instrument application, photo acoustic spectroscopy allows for engineering of physically robust instrumentation. PAS systems are extremely rugged and are insensitive to day-to-day mechanical shock and vibration. They are also small and do not require careful temperature control. This allows for the possibility of a small, light, portable DGA instrument suited to transportation, unpackaged, in a maintenance truck with other substation tools and equipment. As a comparison GC requires very careful transportation and is sensitive to all movement, requiring recalibration every time it is moved to a new location.

GE PAS Based Instruments

In addition to the TRANSFIX, GE manufactures a range of DGA equipment to meet all requirements and applications of field DGA. These are:

Kelman TRANSFIX™

Full 9 gas main tank online DGA + H_2O using Photo Acoustic Spectroscopy (PAS) technology.

Kelman TAPTRANS™

Full 9 gas multiple oil sources DGA + H_2O. This product is unique in its ability to sequentially analyse a sample of oil from the main tank as well as from the diverter and selector tanks of the OLTC while avoiding gas or oil carryover from high to low gas in oil sources. This is achieved by the use of two separate oil handing systems built within a single instrument and the fact the PAS systems are immune to gas carry-over. This product is ideally suited to large critical transformers incorporating an OLTC.

Kelman MULTITRANS™

Full 9 gas DGA + H_2O sampling oil from up to three main tanks sequentially. This product is designed for situations where three separate tanks are in the same 3 phase transformer or where three single phase transformers are all within a 50m radius.

Kelman MINITRANS™

This low cost online 3 gases + H_2O device provides many of the benefits associated with the premium Transfix but at a fraction of the cost. MINITRANS is best suited to general deployment in large numbers among smaller or less critical transformers.

Kelman TRANSPORT X™

Full diagnostic gas + H_2O in a self-contained and fully portable robust instrument. Capable of performing a DGA analysis with diagnostics in under ½ hour. Best suited to situations where online DGA is not in place or where quick analysis is required following a single gas online DGA alarm.

Conclusion

PAS based DGA instruments have been developed with the express purpose of addressing the shortcomings of online GC based instruments. They provide a real alternative to GC by employing technology much more suited to long term autonomous operation. Requiring no consumable gases or frequent designed service intervals, the TRANSFIX family of products has revolutionised the landscape of multigas online DGA. Just 10 years after its launch, TRANSFIX has the largest installed base of any multi-gas DGA instrument worldwide.

TRANSFIX provides for monitoring of all the diagnostic gases together with O_2, N_2 and H_2O. By monitoring these parameters up to once per hour while correlating to load and temperature, the amount of data available for trending, analysis and diagnostics is second-to-none. Utilising a technology specifically designed for online application, GE manufactures a very stable and repeatable monitoring instrument perfectly suited for the tough environmental and operational demands often associated with remote substation operation. It has become the new high-end standard for monitoring critical transformers.