DGA is one of the best methods to detect internal faults within power transformers

ABSTRACT

The value of Digitalization is the marriage of domain knowledge and digitized sources of important information, to provide insight and create business value.

For many years, the power industry has had various options for Online Dissolved Gas Monitors. There are many different vendors providing different options – in terms of the number of gases measured and different measurement technologies. The specifications differ from monitor to monitor, so it is very important to understand online Dissolved Gas Analysis (DGA) specifications. The TXpert™ Ecosystem supports best in class TXpert™ Ready DGA solutions from both Hitachi ABB Power Grids and leading 3rd party suppliers.

KEYWORDS

detection, DGA, diagnostics, monitoring, parameters, specifications

Demystifying online DGA monitor specification

Introduction

It has now been firmly established that dissolved gas analysis (DGA) is one of the best methods to detect internal faults within power transformers. DGA can be applied to transformers with mineral oil, ester oil, etc. In the latest IEEE C57.104-2019 standard [1] it states that voltage class, MVA, and volume of mineral oil in the transformer do not significantly contribute to the determination of 90th percentile values of dissolved gas levels. This has been a significant change from earlier standards such as IEC 60599 – 2015 [2], where it stated that oil volume did affect DGA 90th percentile values. However, it is to be noted that IEC 60599 – 2015 used around 20,000 DGA samples, whereas IEEE c57.104-2019 used 1,391,436 samples. Thus, the statistical analysis is bound to be different. It is also to be remembered that both standards are written for manual oil sampling and offline DGA analysis in a laboratory. On the other hand, online DGA has gained popularity over the years, and statistical fitting techniques applied for offline DGA can be theoretically applied to online DGA as well, albeit considering different trend periods –1 day or 10 days or 1 month or 6 months or 1 year, etc., depending on the capability of the used online DGA monitor.

Nevertheless, online DGA monitoring makes it possible to detect or diagnose, nearly in real-time, any incipient failure occurring in a transformer, thereby giving the operator time to intervene and avoid a major failure. However, the operator must choose the right online DGA monitor to be able to take correct decisions, but there are always some "budget" constraints. Many vendors come around the end-user budget constraints by offering 3/4/5 gas online DGA monitors instead of a 9-gas monitor or equivalent and sell them as online DGA monitors. This article is an attempt to address some of the practical experiences gained by the author while talking about online DGA monitors to end-users. This article discusses the following – **choice of DGA monitor, confidence in the DGA monitor, important specifications to consider while choosing a DGA monitors and avoiding false positives while setting gas alarm levels.**

1. Choice of DGA monitor

In October 2019, CIGRE released technical brochure 783 – 2019 [3], which illustrated in-depth the difference between "detection" and "diagnostic" online DGA monitors. Some of the important points are re-emphasised for completeness of this article.

Duval triangles and Duval pentagons fault interpretation techniques for mineral oil are now a part of IEC 60599 – 2015 & IEEE c57.104-2019 standards. Using fault categories of Duval triangles and Duval pentagons, the six basic types of faults (PD, D1, D2, T3, T2 T1) are detectable with Duval triangle 1 and pentagon 1, and the five sub-types of faults (T3-H, C, O, S, PD) are detectable with Duval triangles 4, 5 and pentagon 2, as listed in Table 1.

Table 2 indicates faults possible to identify in transformers with different types of online DGA monitors. Online DGA monitors are labelled as M1, M2, and up to M9. As per CIGRE [3], number Mx indicates the number of gases monitored minus moisture measurement. For example, M9 equates to 9 fault gases plus moisture measurement. Table 2 also indicates six basic types of faults (PD, D1, D2, T1, T2, T3) and five sub-types of faults (T3-H, C, O, S, PD) which can be identified by different online DGA monitors.

An example is provided to illustrate why it is important to choose a correct online DGA monitor – manual oil sampling was done on a 25 MVA transformer. The following results (Table 3) were reported by the laboratory:

The laboratory recommendations were as follows:

- Test result(s) indicate a problem(s) requiring further action.
- Total combustible gases are low.
- DGA gas ratios indicate a thermal fault at a temperature of < 300°C.
- Test results are marginal (gases).
- Recommend further monitoring to establish trends.
- Resample in 6 months.

The end-user was unsure about the laboratory recommendations and decided to install an online DGA monitor. However, the vendor recommended inadequate 5-gas online DGA equipment to the end-user, based on the price, and it was installed to establish trends measuring - H_2, CH_4, C_2H_2, C_2H_4, CO, contradictory to DGA results in Table 3. End users are encouraged to verify vendor recommendations.

> **Online DGA monitoring makes it possible to detect or diagnose, nearly in real-time, any incipient failure occurring in a transformer, thereby giving the operator time to intervene and avoid a major failure**

For detecting desired faults it is essential to combine the right types of the online DGA monitors

Fig. 1 shows data for the 5-gas online DGA equipment. As C_2H_2 values are < LDL (lower detection limit), the data is not plotted in Fig. 1.

From 5-gas online DGA data (Fig. 1) and Table 4 (IEC 60599:2015 typical DGA 90 % limits), as CH4 > exceeds the IEC limit, Duval triangle T1 is used to identify the issue. However, all the standards, using either Duval triangle or pentagon, are based on offline DGA oil laboratory test results and not online DGA data. There will be confusion as to which date to choose from for further analysis. To identify trends or any gas level issue using online DGA requires a certain time duration. To do this, the box and whiskers plot is used for the last 30-day data obtained from the 5-gas online DGA monitor. The box plot shows there are no outliers for this 30-day period, and the CH4 mean value is 146 ppm.

To use this data for Duval triangle T1, the following values are used:

- CH_4: 146 ppm (mean from box and whiskers plot, no outliers)
- C_2H_4: 14 ppm (mean from box and whiskers plot, including outliers)
- C_2H_2: 0.2 ppm (LDL of online DGA monitor)

Using this data, Duval triangle T1 can be used to identify fault T1: thermal fault < 300°C, but Duval triangle T4 cannot be used to identify the sub-fault as C_2H_6 is not measured by this 5-gas online DGA monitor. If a sub-fault cannot be identified, then the risk associated with this transformer cannot be fully evaluated. If the risk cannot be fully identified, it is not possible to make the necessary asset management decisions correctly, and the whole point of installing an online DGA monitor capable of properly diagnosing the issue inside the transformer becomes contentious. Similarly, neither Duval pentagon P1 nor P2 can be used.

At this point in time, another manual oil sample is taken and analysed with the following results in Table 5. The end-user realised that 5-gas online DGA is not enough in this case!

This manual result is used to identify the sub-fault using Duval pentagon P1 and P2, as shown in Fig. 3. Both Duval triangle and pentagon indicate oil overheating < 250°C.

The risk classification for fault O is shown in Fig. 4. If fault O is in the paper, rising levels of C_2H_6 and CO should be observed and if fault O is in oil, only rising C_2H_6 will show (please refer to Section 2, Fig. 5). The risk assessment is directly linked to the "customer confidence" in the DGA monitor, meaning how the online DGA monitor performs in relation to the laboratory DGA results.

2. Confidence in DGA monitor

To take an appropriate refurbishment / replacement decision based on an online DGA, customer confidence in the data from the online DGA monitor is a must. Carrying forward the discussion from

Table 1. Definition of the types and sub-types of faults

Faults	Definition
T3	THERMAL FAULT T > 700°C
T2	THERMAL FAULT 300°C < T < 700°C
T1	THERMAL FAULT < 300°C
PD	PARTIAL DISCHARGE OF CORONA TYPE
D1	LOW ENERGY DISCHARGE
D2	HIGH ENERGY DISCHARGE
S	STRAY GASSING OF OIL < 200°C
O	OVERHEATING < 250°C
C	PAPER CARBONISATION > 300°C
T3-H	T3 IN OIL ONLY

Table 2. Faults possible to identify in transformers with online gas monitors

Application	Type of monitor	Gases measured	Faults possible to identify	Faults not possible to identify
Fault diagnostics	M8/(M9)	H_2, CH_4, C_2H_6, C_2H_4, C_2H_2, CO, CO_2, O_2, (N_2)	All faults are possible to identify.	None
	M6/(M7)	H_2, CH_4, C_2H_6, C_2H_4, C_2H_2, CO, (CO_2)		Faults in the paper very often are not detected correctly with CO only with M6, M5 and M2.
	M5	H_2, CH_4, C_2H_4, C_2H_2, CO	Only the 6 basic fault types.	The 5 sub–fault types cannot be detected.
	M3	CH_4, C_2H_4, C_2H_2		
Fault detection	M2	H_2, CO	None of the faults can be identified, but trending can be observed.	May not detect faults D1, D2 in their early stages, only in their late, sometimes catastrophic stages.
	M1	H_2		
	M1*	Composite reading of H_2		

the previous section, prior laboratory test results for this transformer were investigated.

The rate of change observed between offline and online results immediately led to figuring out the difference between offline and online values. The difference between offline and online DGA values was calculated as – offline DGA = 305 ppm (average of July 2019 and September 2019), online DGA (average, using box & whisker method) = 500 ppm. Percentage (%) difference is calculated as approximately +57 %, which is much higher than recommended ± 15 % [4]. These performance characteristics, along with the inability to measure C_2H_6 diminished the confidence in this 5-gas online DGA monitor and led to switching to a 9-gas DGA monitor.

Fig. 5 shows the following 30-days data for CO and C_2H_6, using the 9-gas DGA monitor along with the trend lines. It is apparent that CO is not increasing and has a "fairly" straight (slightly decreasing) trendline. The per cent accuracy with respect to the laboratory result is now +13.7 %. Similarly, C_2H_6 has a 30-day slope of 13 ppm/month for September - October 2019. Using the minimum 4-month of IEEE C57.104-2019 analogy to compute the ppm/year rate of increase, C_2H_6 slope is calculated as 72 ppm/year. Based on the full dataset of 3 offline samples, the rate of increase is 60 ppm/year, which indicates offline and online results are showing similar values.

Periodic accuracy check as per [3] is carried out for all the gases at the end of one month, as listed in Table 8. However, this check needs to be repeated (at least yearly) as gas chromatography (GC) based systems require calibration gas, while other infra-red (IR) based systems claim no maintenance-free features. Periodic accuracy check will help to quantify *"drift with time"*. The accuracy calculations depend on the lower detection limit (LDL) of the online monitors. LDL is explained in Section 3.2.

Based on the above, the "customer confidence" on online DGA data is regained, and it is established that fault O is occurring in oil and paper is not involved at present. This was further confirmed as per

Table 3. DGA laboratory results

Date	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2
July 2019 (ppm)	10	100	0	11	170	300	1,800

When the offline detection methods are applied together with the online DGA monitors then the question that arises is which date to choose for the further analysis

Table 4. IEC 60599:2015 Typical DGA 90 % limits

Date	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2
IEC limits	< 150	< 130	< 20	< 280	< 90	< 600	< 14,000
IEC limits are based on the IEC 60599 2015 standard [2], the higher end of 90th percentile values are used.							

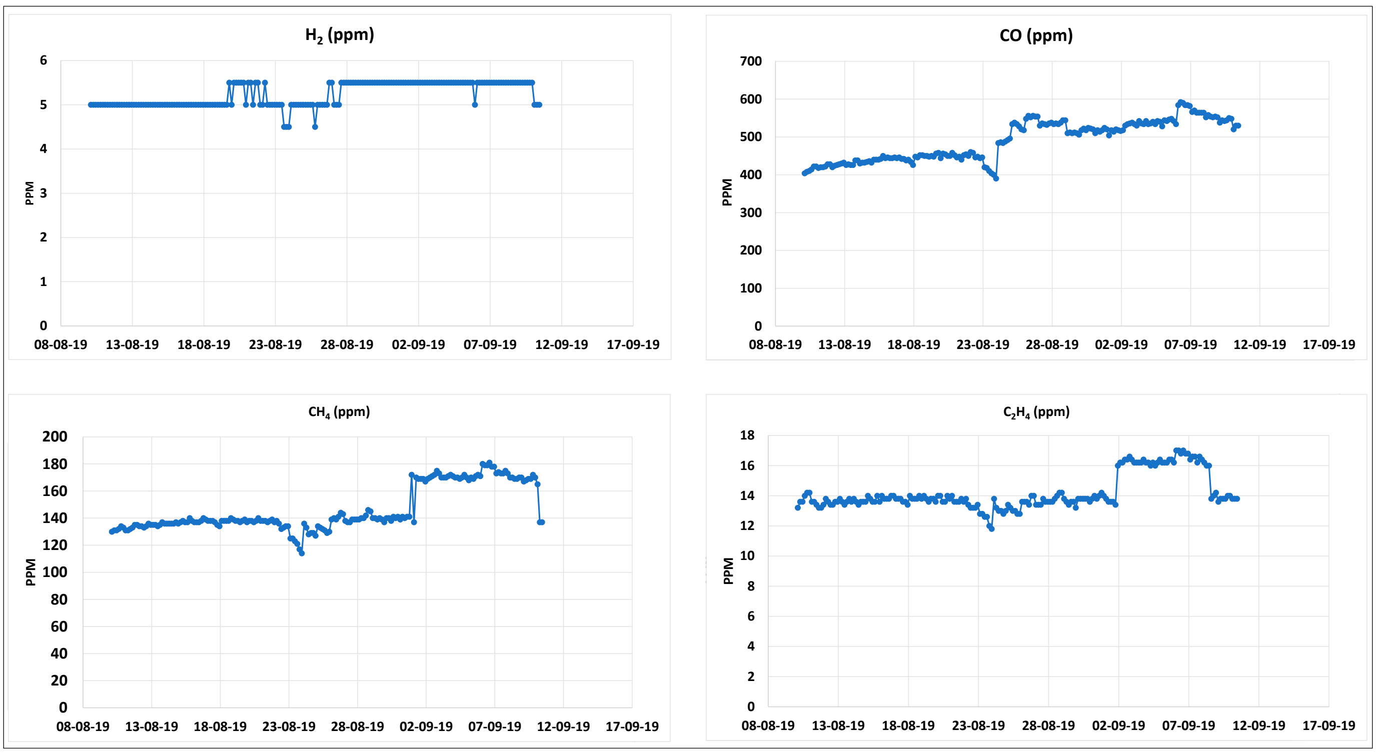


Figure 1. 5-gas online DGA monitoring: August 2019 – September 2019

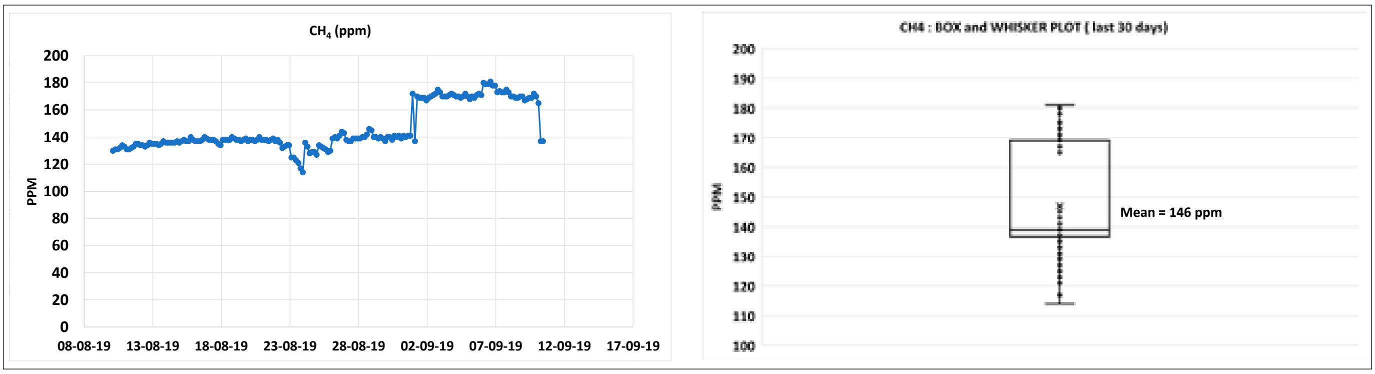


Figure 2. CH4 online DGA and corresponding box plot

With the online DGA monitors and with the use of simple statistics, it is possible to detect the trends in the concentration of the gasses, which can be useful in detecting the faults in the early stage

Table 5. Laboratory results – verification sample

Date	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2
July 2019 (ppm)	10	100	0	11	170	300	1,800
Sept. 2019 (ppm)	10	100	0	11	180	310	1,790

CIGRE 771 brochure Table 3.4 [5], which gave typical values of around 550 ppm for C_2H_6 without failure for fault O.

Based on data analysis of C_2H_6 real-time data, time for C_2H_6 to reach pre-failure values can be estimated (please refer to Fig. 9). Hence it can be safely assumed that monitoring evolution of C_2H_6 would give time until shutdown can be planned and resources allocated. Thus, the selection of the proper DGA monitor with confidence in DGA monitor is key for correct assessment, thus for success.

3. Specifications of DGA monitor

Various online DGA monitors are available to choose from. Fig. 6 shows categories of commercial online DGA monitors categorised from M1 to M9 as per CIGRE nomenclature [3]. With such a wide variation, there are certain aspects one needs to be aware of – first and foremost the type of technology used, second specification parameters, third operational parameters, fourth regulatory test performance and finally mechanical features.

3.1 Type of technology

The main manufacturers use predominantly gas chromatography (GC), photoacoustic spectroscopy (PAS), forms of infra-red (IR) spectroscopy, such as non-dispersive infrared (NDIR), near-infrared (NIR), and Fourier transform infrared (FTIR), as shown in Fig. 7.

It is to be noted that GC has been used

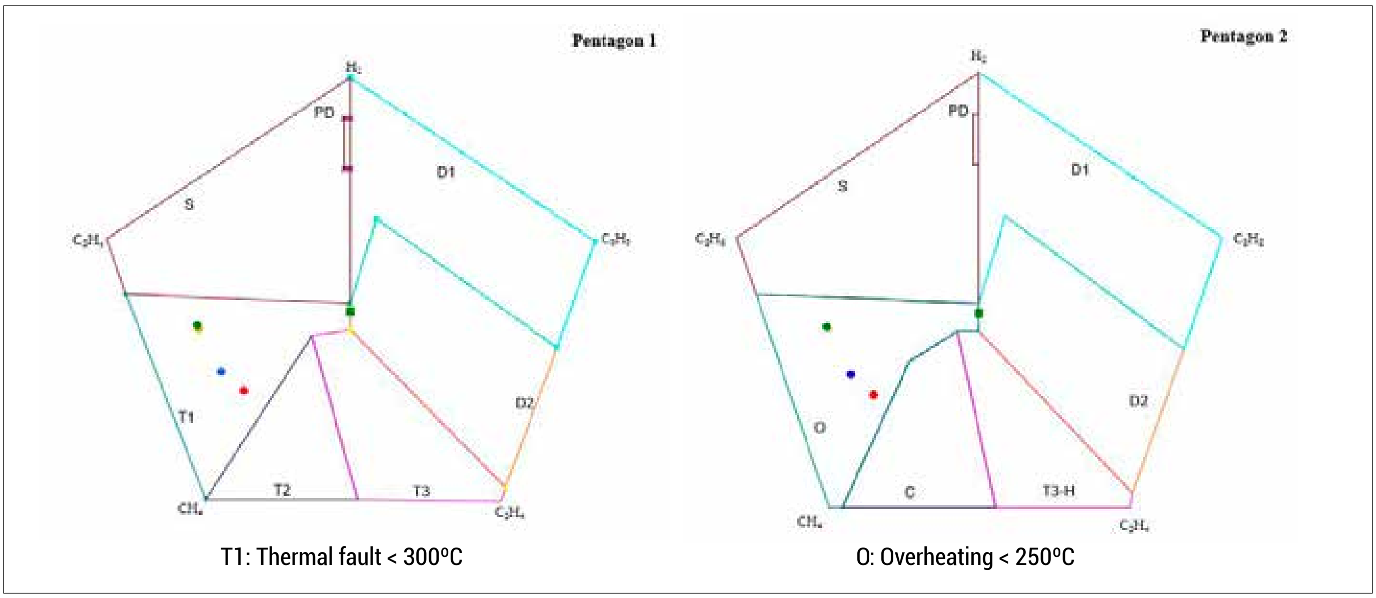


Figure 3. Sub-fault identification using laboratory results

by most oil laboratories over many years as the leading test to assess a transformer condition.

All the IR techniques come in combination with either solid-state sensor, micro-electronic sensor or electrochemical cell, usually to detect H_2 or O_2 or H_2O. In general, gas extraction is based on headspace or vacuum extraction principle, and it is performed:

- either by direct contact between the oil and a small gas phase above it, or through a membrane separating the two phases (membrane or tube of semipermeable PTFE or another polymer),
- at atmospheric pressure, or under partial vacuum,
- at the temperature of oil coming from the transformer tank, at ambient temperature, or at a fixed temperature,
- with equilibrium obtained without agitation, or by gas bubbling,
- with or without continuously pumping the oil into the monitor.

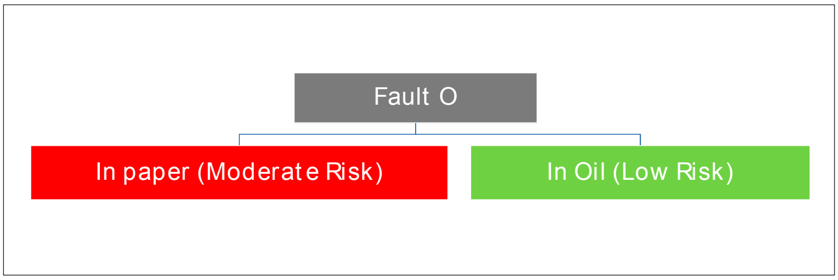


Figure 4. Risk identification based on the severity of faults

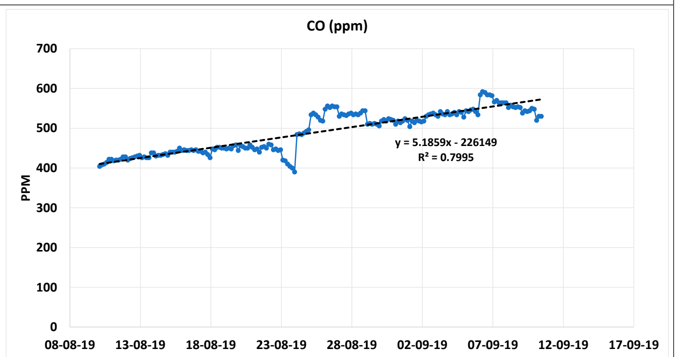
The selection of the proper DGA monitor with the confidence in DGA monitor is key for correct assessment and for the success

Table 6. DGA laboratory results (2018-2019)

Date	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2
July 2018	3	52	0	6	38	200	658
July 2019	10	100	0	11	170	300	1,800
September 2019	10	100	0	11	180	310	1,790

Table 7. The rate of change in CO (for offline and online) was calculated as below:

<table>
<tr><th>PPM/year (offline, manual sampling)</th><th>PPM/year (online DGA data)</th></tr>
<tr><td>Absolute change July 2018 – July 2019: 100 ppm

Based on a full dataset of 3 offline samples, the rate of increase is 94 ppm/year.</td><td>

From 30 days of online data, the slope is calculated as = 5.185 x 30 = 155 ppm/month, much higher than 94 ppm/year</td></tr>
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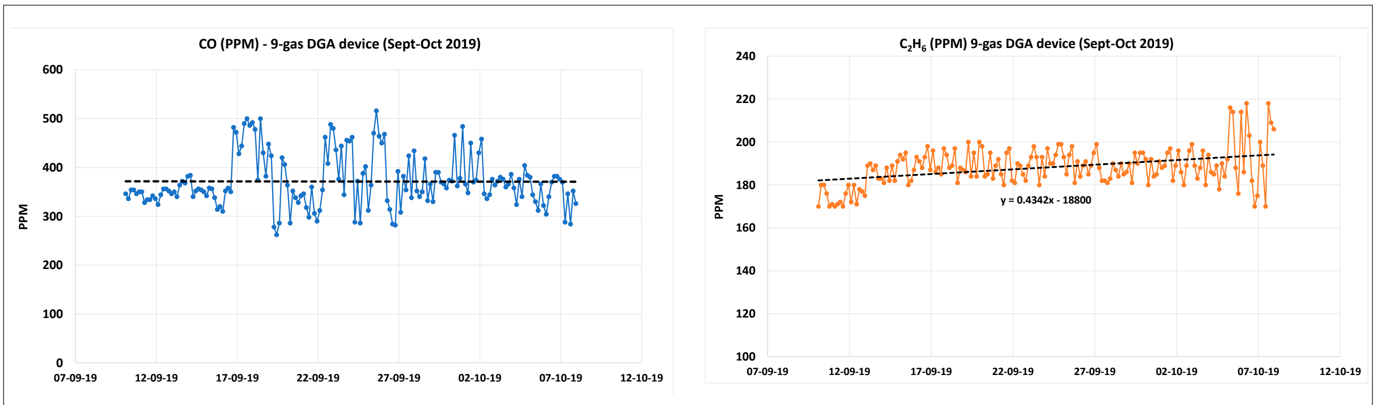

Figure 5. CO and C2H6 30-days data using the 9-gas DGA monitor

When selecting the DGA monitors, it is necessary to pay attention to the type of technology used, specification and operational parameters, regulatory test performance and mechanical features

Table 8. Per cent accuracy table for 9-gas online DGA monitor after 30 days of installation

COMPONENT	ACCURACY	TARGET
Hydrogen (H_2)	Not computed	± 15 %
Carbon monoxide (CO)	13.7 %	± 15 %
Carbon dioxide (CO_2)	-8.05 %	± 15 %
Methane (CH_4)	9.66 %	± 15 %
Ethane (C_2H_6)	4.6 %	± 15 %
Ethylene (C_2H_4)	8.81 %	± 15 %
Acetylene (C_2H_2)	Not detected	± 15 %

Table 3.4 of CIGRE 771 Concentration levels of fault O

C_2H_6	Typical	Intermediate 1	Intermediate 2	Pre-failure
ppm	550	1,000	1,500	4,460

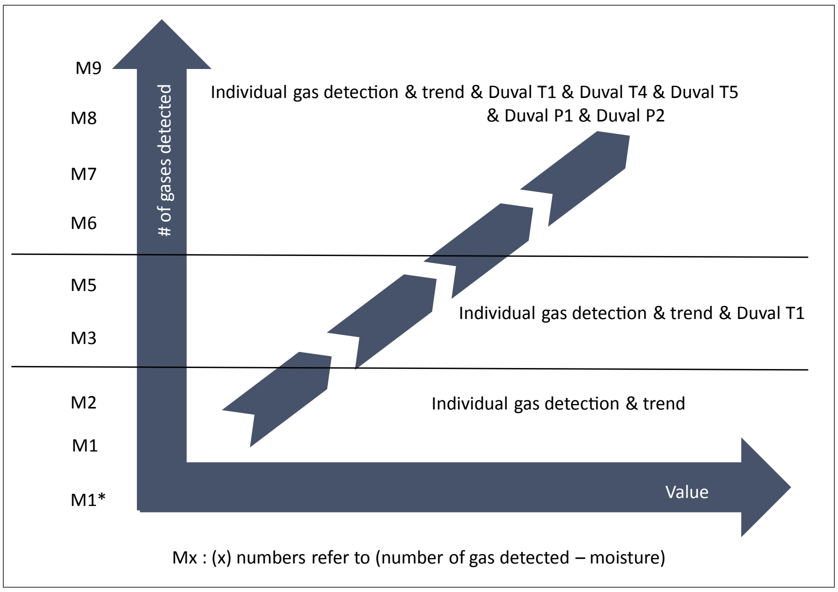

Figure 6. Commercial online DGA monitors categorised from M1 to M9 as per CIGRE nomenclature

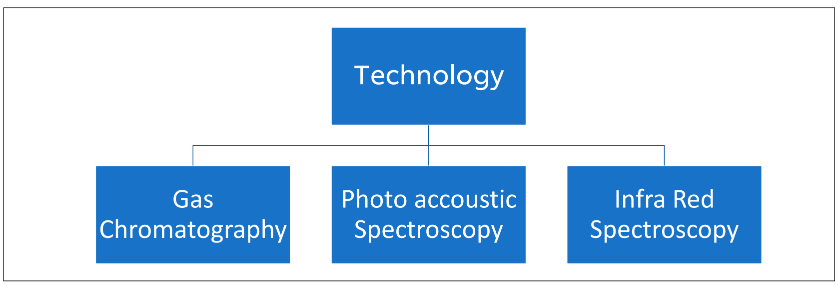

Figure 7. Types of technology employed for online DGA monitors

Several studies [6-8] present a review of these gas-sensor technologies for detection of different gases, so that topic will not be elaborated further here. It is for end-users to decide, based on the pros and cons of each technology.

3.2 Important Parameters

Some of the common parameters (Fig. 8) that can be seen in different specification document have been listed here:

- **Detection Range** - The measurement range indicates the lower detection limit (LDL) and the higher detection limit (HDL) in parts per million (ppm) that the monitor measures. Table 9 shows common LDL-HDL combination for different technologies. Customers specifying technology A and rejecting technology B and C were observed in many instances by the author.
- In CIGRE brochure 771, typical and pre-failure values observed are listed in Table 10. CIGRE brochure 771 also lists typical values and pre-failure values (Table 11) for different types of identified faults.

As shown in, Table 10 and Table 11, pre-failure values (the highest) are in most cases under 10,000 ppm for most faults. The detection range of the selected online DGA monitor should be checked regarding its intended use. For example, wind-farm transformers are well-known to generate high to very high levels of hydrogen due to stray gassing of oil and partial discharges of corona-type PD, with 90 % typical H2 levels observed close to 5,000 ppm. In such cases, technology A is better suited, whereas, for all other cases, all three technologies are well above the required HDL limit.

Table 12 shows IEEE c57.104-2019, 90th percentile and 95th percentile values for transformers with O_2 / N_2 < 0.2* and unknown age. These values should be considered when checking for online DGA specification compliance, along with Table 10 and Table 11. Setting correct gas concentration limits helps to avoid false-positive alarms from online DGA monitors.

*All nitrogen-blanketed transformers and about 60 % of the membrane-sealed types in DGA databases of IEEE 2019 standard have oxygen / nitrogen ratio <= 0.2, while

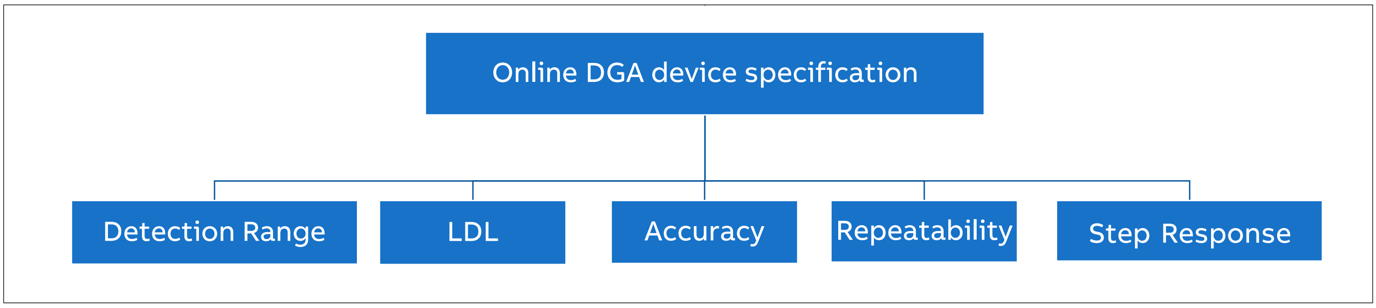

Figure 8. Major specifications of online DGA monitors

all air-breathing transformers and about 40 % of the membrane-sealed types have oxygen / nitrogen ratio > 0.2. That is why this ratio has been brought in to differentiate between the transformer types.

Several important parameters have to be carefully considered when selecting the online DGA monitor

- **The lowest detection limit (LDL)** - The LDL is the minimum gas concentration that the monitor is able to measure; cases in which the manufacturers indicate a lower measurement range equal to 0 ppm do not indicate that LDL is 0 ppm, only that measurements below LDL will be considered to be 0 ppm. Table 13 shows some common LDL available from different technologies.

Let us take H_2 LDL for the above 3 technologies as an example. For correct application of fault detection or diagnosis (whether it is Duval triangle or Duval pentagon) any gas ppm value lower than LDL must be replaced by the LDL value, i.e. 10 ppm of H_2 is to be replaced by 25 ppm when analysing for technology C, while 10 ppm can be 10 ppm for technology A and B (without considering the accuracy).

If we use the IEEE percentile numbers of 80 ppm (90th percentile) or 200 ppm (95th percentile), 25 ppm is well below the thresholds. Therefore, all three technologies are well suited. LDL values for each gas must be considered against the 90th or 95th percentile values. What is important to consider is LDL + accuracy. As reported by CIGRE, laboratory readings for H_2 around 5 ppm can be out by almost 100 %, while at 10 ppm readings may differ by 50 %!

- **Accuracy** - The accuracy of DGA readings is a very critical specification. Poor accuracy is likely to affect trending analysis based on which repair and maintenance decisions are made. Inaccurate DGA readings may result in the wrong diagnosis, increasing maintenance and repair costs. Common accuracies listed in Table 14 are around ± 5 %, but these are reported during the monitor calibration. Thus, it is paramount to perform a field accuracy check [3].

An example using forward linear straight-line approximation is shown in Fig. 9 for ease of understanding. Suppose 220 ppm is an unacceptable level of C_2H_6 gas for a customer. From Fig. 11, if error = true value + x %, the 220 ppm will be reached earlier, while if error = true value – x %, the unacceptable level would be reached later. Faster means less reaction time to rectify / refurbish / replace, slower may mean a delay in planning or even worse, that a failure has already occurred. Higher the value of ± x %, the worse is the case for subsequent action – be it inspect / repair / refurbish or even replace.

For accurate trending, step response to a change in gas concentration is very important. This is discussed in the following text.

- **Step response** – This parameter is the most crucial one for online trending. However, it is the least discussed. In almost all of the specifications observed by the authors, over 90 % of customers have never specified step response as a requirement. The step response is the ability of the online DGA monitor to respond to changes in actual gas levels within a certain time duration. Example of response time specifications from various vendors is shown in Fig. 10.

How is T33 / 50 / 63 / 66 / 90 / 95 defined – basically it is the time required by the online DGA monitor to jump to say 90 % (T90) of the final value of the gas which has had a change in its gas levels.

How is measurement cycle defined – time required to perform analysis on the extracted gas sample by the online DGA monitor.

Consider Table 15, if there is a steep jump in hydrogen (as an example) for

Table 9. Common detection range for different technologies

Gases Detected	Technology A	Technology B	Technology C
Hydrogen (H_2)	0 - 20,000	0 - 5,000	0 - 5,000
Methane (CH_4)	0 - 100,000	0 - 50,000	0 - 10,000
Acetylene (C_2H_2)	0 - 100,000	0 - 50,000	0 - 10,000
Ethylene (C_2H_4)	0 - 200,000	0 - 50,000	0 - 10,000
Ethane (C_2H_6)	0 - 200,000	0 - 50,000	0 - 10,000
Carbon Monoxide (CO)	0 - 30,000	0 - 50,000	0 - 5,000
Carbon Dioxide (CO_2)	0 - 100,000	0 - 50,000	0 - 20,000

Table 10. CIGRE Gas concentration levels above typical values, in ppm [5]

Condition	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2
Typical	118	85	56	111	5	700	6,300
Intermediate L1	200	135	120	210	19	970	11,600
Intermediate L2	280	180	200	300	40	1,180	16,700
Pre-failure	725	400	800	900	450	2,100	50,000

Table 11. Gas concentration above typical values for different faults, in ppm [5]

Fault	Major gas	Typical	Intermediate L1	Intermediate L2	Pre-failure
S	H_2	460	800	1,100	2,480*
O	C_2H_6	550	1,000	1,500	4,460
T3-H	C_2H_4	126	270	450	1,800
D1 in oil	C_2H_2	25	60	100	1,400
D1 in paper	C_2H_2	1	3	6	45
C (leads)	C_2H_4	200	440	700	2,900
C (windings)	C_2H_4	68	150	240	970
C (between turns)	C_2H_4	2	4	7	25

Table 12. IEEE gas concentration levels above typical values, in ppm

Condition	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2
90th percentile	80	90	50	90	1	900	9,000
95th percentile	200	150	100	175	2	1,100	12,500

The detection range of the selected online DGA monitor should be checked regarding its intended use

technology A – it would take almost 4-5 hours to register the jump, for technology B – it would be 2-3 hours whereas for technology C it would be almost 30 minutes. The slope will be very different for the three technologies, and as mentioned previously, response to such step jumps will vastly differ, even leading to catastrophic failure if the reaction to fast faults is slow.

- **Repeatability** – Repeatability is a measure of how consistently an online DGA monitor will read the same gas level. If the repeatability is higher, the online DGA monitor is less stable. If the monitor is less stable, accurate statistical fitting is an issue. In the case that is an issue, accurate slope calculation becomes problematic. Fig. 11 shows the DGA data for the same transformer with 2 online DGA monitors, one with repeatability (relative standard deviation) of 15 % and the other with repeatability of 2.3 %, offline DGA test indicate actual gas CO ppm results are 347 ppm ± 11 %.

Apart from the above, other key specifications to be considered are:

3.3 Life cycle costs

Life cycle costing is an important specification which must be considered after considering the typical specifications. In the case of different online DGA monitors, early user experience has revealed that maintenance and operational costs are significant and must be considered in the selection process. Typical factors which should be considered include:

1. Consumable costs – carrier gas / calibration gas,
2. Spare parts and repair time costs – parts such as field repair of IR analysers, electronics repairs,
3. Site visit and requirements for annual inspection costs,
4. Oil piping system maintenance – oil leaks, pump failures, oil line pipe filters,
5. Remote communication requirements,
6. Typical expected life of the monitor and the warranty offered,
7. Is the software supplied capable of performing both gas level and gas trend analysis? Will further subject matter expertise be required to analyse online DGA data?

Once these factors are incorporated, an economic evaluation must be made as decisions based on economics are the most unbiased and the least controversial since everybody understands in terms of dollars and cents. Very specific and detailed investment calculations should be done in terms of the following:

- net present value
- internal rate of return
- payback period

The comparison of different technologies is meaningless unless the costs are brought to the same common economic basis!

3.4 Installation and oil piping system

The installation of the online DGA monitors depends on the type of technology used and the transformer construction. Typically, the installation of monitors is using either one or two different valves on the transformer.

- For single valve systems, the monitor is mounted directly on the valve using a thread or a flange.
- For dual valve systems, two values are required – one is the supply valve and one return valve. This creates a closed-loop system for oil flow using the oil lines. Supply valve is to take an oil sample and return valve is to return the representative oil sample.

However, there are some field issues with oil lines:

- reduction in flow rate due to sludge formation or oil line deformation,
- sludge filters replacement in oil lines,
- high criticality of no stainless-steel fittings - galvanised steel, copper or plastic fittings as these materials can negatively affect gas concentrations in the sample line,
- installation of a heat trace cable for low ambient temperatures,
- oil leaks at various points.

Apart from that, the flexibility to move an online DGA unit from one transformer to another becomes difficult with the oil piping system. These are some points which the end-user should be aware of with regards to mechanical installation complexities.

Finally, a comparison between offline DGA and online DGA result is discussed next.

Table 13. Common LDL of different technologies

Gases Detected	Technology A	Technology B	Technology C
Hydrogen (H_2)	0.5	5	25
Methane (CH_4)	0.2	2	1
Acetylene (C_2H_2)	0.2	0.5	0.5
Ethylene (C_2H_4)	0.2	1	2
Ethane (C_2H_6)	0.2	1	2
Carbon monoxide (CO)	10	1	2
Carbon dioxide (CO_2)	15	20	5

Table 14. Common accuracy different technologies

Gases Detected	Technology A	Technology B	Technology C
Hydrogen (H_2)	± 5 % + LDL	± 5 %+ LDL	± 20 % or LDL
Methane (CH_4)	± 5 % + LDL	± 5 %+ LDL	± 5 %+ LDL
Acetylene (C_2H_2)	± 5 % + LDL	± 5 %+ LDL	± 5 %+ LDL
Ethylene (C_2H_4)	± 5 % + LDL	± 5 %+ LDL	± 5 %+ LDL
Ethane (C_2H_6)	± 6 %+ LDL	± 5 %+ LDL	± 5 %+ LDL
Carbon monoxide (CO)	± 5 % + LDL	± 5 %+ LDL	± 5 %+ LDL
Carbon dioxide (CO_2)	± 5 %+ LDL	± 5 %+ LDL	± 5 %+ LDL

For correct application of fault detection or diagnosis, any gas ppm value lower than LDL must be replaced by the LDL values

4. Comparison with oil lab results

The physical reality of DGA, whether offline or online is that differences are

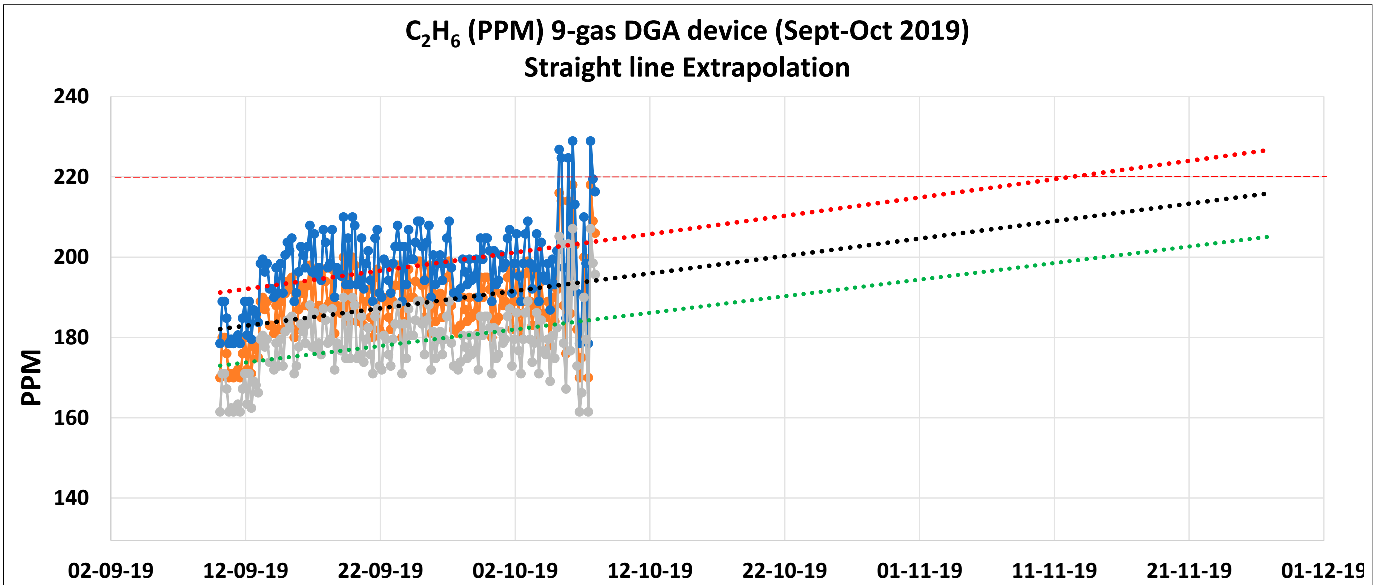

Figure 9. Forward linear straight-line approximation of 30-day C_2H_6 data

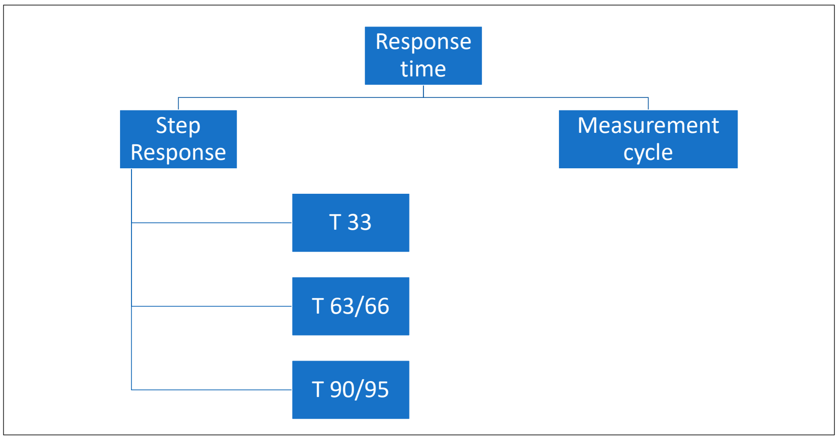

Figure 10. Response time specifications

Repeatability is a measure of how consistently an online DGA monitor will read the same gas level, the lower values are better

bound to happen. Reference [3] is currently the most comprehensive evaluation method published by CIGRE. It mentions that laboratory accuracy must be considered when comparing offline DGA results with online DGA monitors. An example is shown in Fig. 14, where a DGA monitor was installed and while in operation, four identical offline DGA samples were taken four times over a period from February 2020 until May 2020. The average offline DGA value is plotted against online DGA data. Each oil laboratory has its own accuracy values (± 3 % to ± 65 % [4]), and end-users must insist that accuracy values are always provided in the laboratory report. However, this is seldom the case. For our comparison purposes, laboratory accuracy values of ± 30 % are considered.

As shown in Fig. 12, there is broad agreement between online DGA trend and offline DGA trend. Similarly, values for online DGA are well within the uncertainty range of the laboratory DGA results, i.e. within ± 30 % accuracy zone. Calculations as per CIGRE 783 [3] have been carried out for the four offline DGA conducted and the online DGA monitor field accuracy evaluated (similar to Table 8). This procedure of trend check and field accuracy evaluation is a current method for determination of field acceptability of online DGA monitors. The need to establish a standard for this purpose is rather evident.

5. Conclusion

CIGRE 783 brochure published in 2019 clearly states there are two types of online DGA monitors which can be evaluated - fault detection monitors and fault diagnosis monitors:

- M1, M2 type of monitors are used for fault detection only,
- M3 and M5 type monitors can be used for fault detection and diagnosis using Duval triangle 1 only,
- M7, M8 and M9 type of monitors are capable of both detection and diagnosis,

where x in M_x refers to the number of gases detected.

While it was shown in [3] that majority of the online DGA monitor on the market meet the accuracy requirements of IEC 60567:2011, a minority of them do not, with accuracies as bad as ± 50 %. Some online DGA specifications are listed under ideal factory conditions. Some online DGA monitors are designed in a way that as part of the installation procedure, transformer-specific values are needed to align the readings with recent laboratory DGA results. Online DGA users should be aware of these caveats and arm themselves with adequate questions.

Some main specifications points which end users must consider / include:

- suitability to insulating oil used in transformer,
- accuracy in the field,
- repeatability in the field,

Table 15. Common response time for different technologies

Gases Detected	Technology A	Technology B	Technology C
Hydrogen (H_2)	Typical measurement cycle: 1-1.5 hours 95 % in 3 hours Frequency (fast): 1 reading per hour	Typical measurement cycle: 1-1.5 hours 95 % in 1 hour Frequency (fast): 1 reading per hour	Typical measurement cycle: 10 min averaging 90 % in 30 min Frequency: 1 reading per 10 min

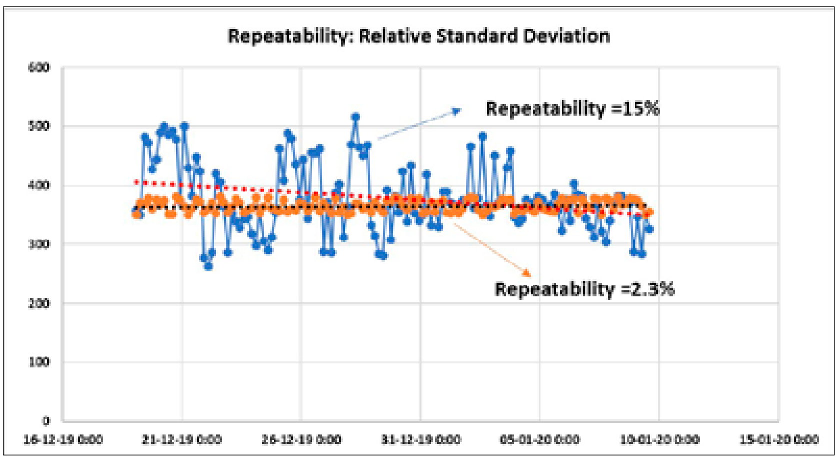

Figure 11. DGA results from 2 online DGA monitors in the same transformer for carbon monoxide

- speed of response to gas ppm changes,
- recurring life cycle costing costs – maintenance costs, carrier / calibration gas costs,
- number of connection valves and piping requirements required which increase chances of the oil leak and introduction of air bubbles,
- typical manufacturer expected life of the monitor and the warranty offered,
- is the software supplied capable of performing both gas level and gas trend analysis?

The key takeaway is that the field accuracy must be proven for the whole integrated monitor in a transformer since this is what will generate the gas ppm values which will then be used in subsequent asset management decisions.

The accuracy for DGA monitor must be at an acceptable level since that is what will generate the gas ppm values and which will then be used for subsequent asset management decisions

Table 16. Common repeatability listed for different technologies

Gases Detected	Technology A	Technology B	Technology C
Hydrogen (H_2)	LDL + 3 %	< 3 %	< 10 %
Methane (CH_4)	LDL + 3 %	< 2 %	< 0.5 %
Acetylene (C_2H_2)	LDL + 3 %	< 2 %	< 0.5 %
Ethylene (C_2H_4)	LDL + 3 %	< 2 %	< 0.5 %
Ethane (C_2H_6)	LDL + 4 %	< 2 %	< 0.5 %
Carbon monoxide (CO)	LDL + 3 %	< 2 %	< 0.5 %
Carbon dioxide (CO_2)	LDL + 3 %	< 3 %	< 0.5 %

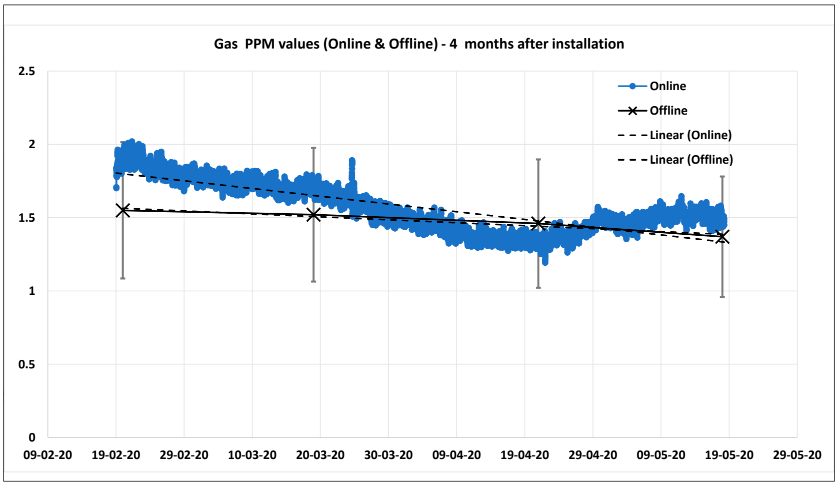

Figure 12. DGA data comparison – online and offline for acetylene gas

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