ABSTRACT

Power transformers are one of the most crucial components of any power system network. A new asset management software called APM Edge, based on the reliability centred maintenance (RCM) methodology for the fleet-wide assessment of power transformers that utilises the principle of fault tree analysis is now available. This analytical software is an expert system that incorporates a probabilistic model which always assigns a risk factor to any given transformer – both for long-term reliability and short-term functionality. This paper presents a case study on the utilisation of this expert system and analytical software on a 25 MVA transformer which helped in:

- DGA data quality identification
- Predicting future dissolved gas trends
- Predicting when the DGA abnormal levels would be reached
- Time available before the shutdown
- Determining what investigations are required.

KEYWORDS

analytics, asset management, dissolved gas analysis, expert model

1. Introduction

The CIGRE working groups 12.05 and A 2.37 published the transformer failure survey ELT 088 [1] first in 1983 and the latest version 642 [2] in 2015, respectively. Based on these surveys, failure modes, failure causes (based on kV) and position of failures for power transformers were identified. Key findings included:

- **Failure mode:** based on 964 transformers, the dielectric failure mode was the predominant with 36.62 %, followed by the mechanical failure at 20.02 %.
- **Failure causes:** failure causes include ageing (12.34 %), external short circuit (11.62 %), improper repair (6.02 %), etc.
- **Failure position:** the three most common failure positions include winding (47.4 %), bushing (14.4 %) and tap changer (23.2 %), while other positions contributed to the failure as well, but the percentages were minor.

Based on the above, different models have been formulated to determine the 'health index' of power transformers [3, 4]. Some of the common parameters used in these models include dissolved

Bhaba P. DAS

It is very hard to manage the fleet of transformers and to estimate their reliability, probability of failure, and to plan activities accordingly without the aid of modern calculation methods and algorithms

Advanced analytics for transformer asset management

Case study on 25 MVA transformer

gas analysis (DGA), oil quality parameters (dielectric strength, dissipation factor, acidity, moisture, colour, and interfacial tension of the oil), furans, transformer age, loading history, tap changer and bushing data, maintenance data, etc.

A new decoupled approach was presented in [5, 6] which forms the backbone of **APM Edge** software [7]. The procedure developed selected those failure modes and brought to the 'analysis matrix' those operational parameters that play a role in that specific failure mode. It is very important to note that the parameters that are not correlated or those that do not contribute to a given failure mode, are not analysed together with those directly associated to a failure mode to enable decoupled analysis. This decoupled failure mode approach based on reliability centred maintenance philosophy is illustrated in Fig. 1.

For example, a bushing may fail due to several reasons, such as design and manufacturing issues, storage, maintenance and operations, external causes, etc. Each of these possible failures may require different data inputs in order to be properly assessed, such as:

- Bushing installation date
- Bushing power factor and capacitance
- Bushing reference power factor and capacitance as per manufacturer
- Bushing voltage class
- Bushing construction type
- Bushing inspection results - hot spots, cracked, oil, oil leakage, dirty bushings, etc.
- Bushing maintenance date.

The above data is used to calculate the risk posed by the bushing for the over-

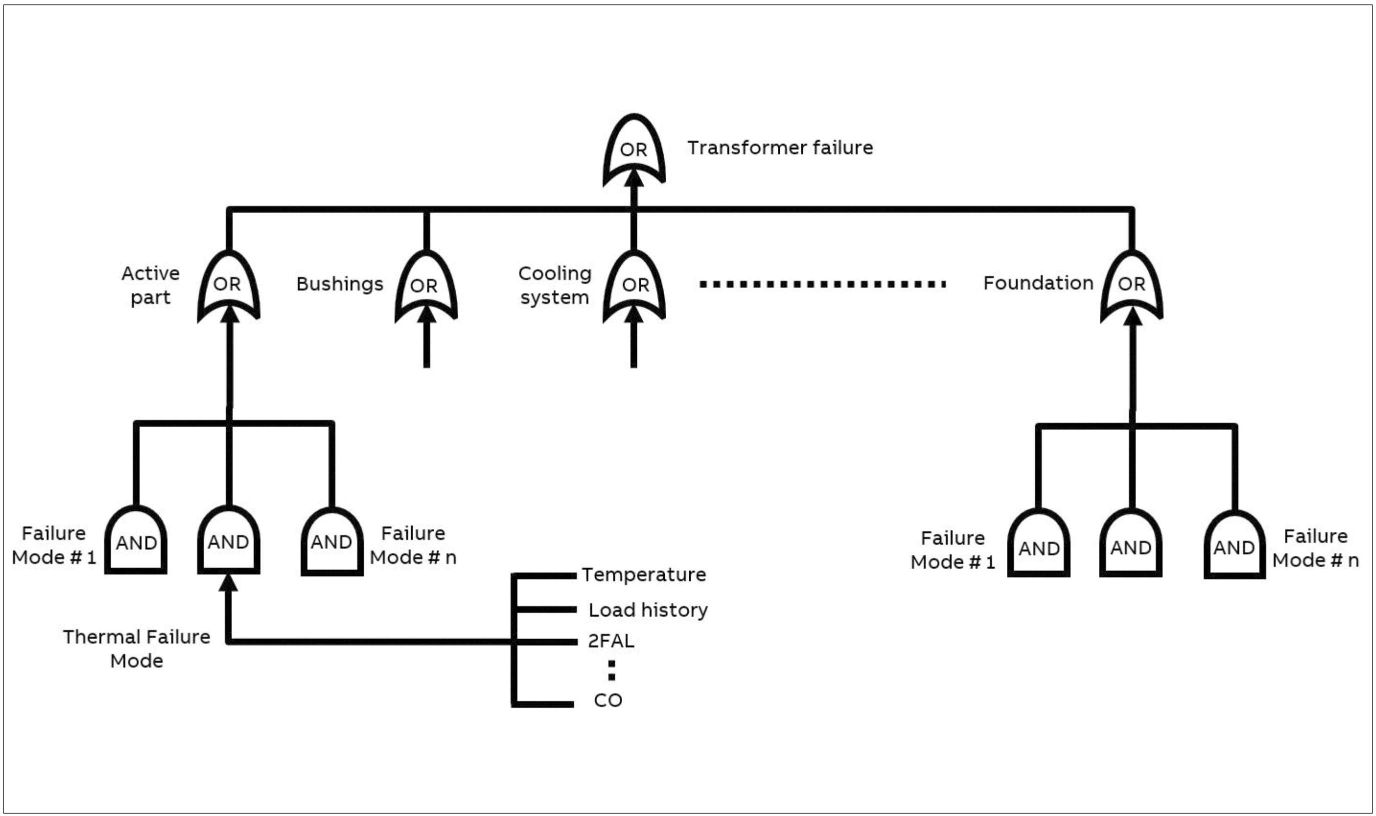

Figure 1. Decoupled transformer failure analysis, the backbone of APM Edge

APM Edge is a risk assessment software for power transformers based on the reliability centred maintenance methodology that utilises the principle of fault tree analysis

all transformer assessment. The CIGRE Working Group A 2.49 published the brochure 761 [8], which laid down the general guidelines for transformer assessment scoring development, including the advantages / disadvantages of different aggregation methods, such as:

- Weighted sum
- Sum of non-linear scores
- Worst case
- Statistical regression
- Artificial intelligence.

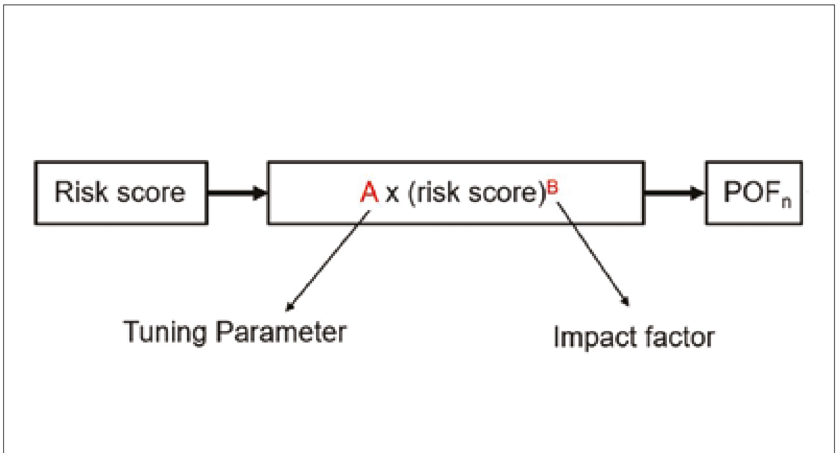

Figure 2. Individual POF calculation based on non-linear scoring

APM Edge utilises the sum of the non-linear score method (Fig. 2) for each component, which can contribute to transformer failure. All major components and their failure modes are duly evaluated, and a global associated probability of failure (POF) score is produced out of the individual scores of each component. The procedure is done for the active parts, bushings, cooling system, on-load tap changer or off-circuit tap changer, oil preservation system, etc.

This score is mapped in a criticality index matrix, designed to map the POF score against the importance of the transformer. The importance is assigned by the customer, usually based on:

- Criticality index established via a reliability maintenance score
- Cost of the replacement of a transformer
- Cost of energy not served due to the failure of a transformer.

APM Edge also incorporates the 'expert system' within the software. The expert system is a comprehensive rule-based system designed to perform different tasks. One such example of the expert system is the data quality check and management by employing statistical packages. As data is generated every few minutes / hours from technology deployed within a smart grid, such as online DGA equipment or other online devices, assessment of data quality by manual methods becomes tedious. Statistical packages, such as outlier identification, box plots, piecewise linear approximation, normal data distribution, etc., are inbuilt in this model to automatically process data and perform data quality checks. In CIGRE Brochure 761 [8] and the recent IEEE standard C 57.104 (2019) [9], the importance of data quality has been given its due credit. The quality of health assessment ultimately depends on the incoming data quality - be it the accuracy of data or completeness of data. For example, sometimes the DGA data for the main tank is available, whereas from the OLTC compartment it is not available. It is paramount to understand what it means not to have data or below-par data. The expert system within APM Edge performs this check automatically.

APM Edge utilises the sum of the non-linear score method for each component (active parts, bushings, cooling system, etc.) to determine the probability of failure of the transformer

As of today, APM Edge contains a set of comprehensive algorithms that are parameter specific. In addition, they are enriched with the readings of the online sensors (when available), such as:

- Inspection data
- Bushings, cooling and oil preservation system data
- Maintenance data
- DGA offline data, including laboratory accuracy for the trend calculation
- DGA online data (multiple types of sensors supported)
- Standard oil tests data (moisture, dielectric strength, power factor, interfacial tension, acidity)
- Thermal profile data (dynamic hot-spot calculation), and others.

Based on the availability of the inputs above, APM Edge performs the following tasks:

Result	Description
Calculations	Values resulting from the calculations performed as part of the analysis
Expert system flags	Indications of issues discovered by the analysis that will be used by the expert system **Examples of issues** – Any DGA level or a trending issue, hot spot temperature issue, oil preservation system issue, sum of the current level or a trending issue, insulation resistance issue, among many others
Messages	Textual findings of the analysis, possibly including diagnoses, causes and recommendations **Example of recommendation upon finding a conflict between offline and online DGA data** – Combustible gases obtained from manual oil and a sample measured in the lab showed a significant difference (greater than 15 %) to the data obtained from the online sensor. This conflict cannot be solved without further action. To solve the conflict: a) Repeat the manual oil sampling strictly following the sampling and lab recommendation procedures b) Send the samples to two different labs, annotating lab accuracy c) Compare the new results, between the two labs and the previous lab d) All the relative differences in (c) must not be higher than 15 %; larger variations indicate lab calibration / accuracy issues; these must be addressed before repeating the results. e) If the lab results confirm one another within acceptable tolerances, then the sensor must be completely checked for calibration, power supply, wiring, communication and other issues, as indicated by the vendor.

APM Edge also incorporates the 'expert system' within the software; the expert system is a comprehensive rule-based system which can provide input data quality check, and give recommendations accordingly

2. Chronological order of events: Application of APM Edge

The events that are included in the article are given in chronological order as follows: an offline DGA test, the application of advanced analytical software to predict gas trends and future course of action on an 11 kV / 6.6 kV 25 MVA transformer.

2.1. Offline DGA testing by an independent laboratory

To ensure reliable operation, various strategies have been adopted by the utilities, such as monthly visual inspections, routine oil sampling (usually once a year), mechanical or electrical checks to ensure normal operation, among others. As part of this routine plan, an oil sample was taken from this 25 MVA transformer in July 2019. The results reported by the laboratory are shown in Table 1.

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 ^oC
- Test results are marginal (gases)
- Recommend further monitoring to establish trends
- Resample in 6 months.

This data was shared with the author as advice. Based on experience, the gas level comparisons were made as shown in Table 2.

According to Table 2, only the C_2H_6 gas levels are above the typical 90 % gas PPM levels observed in power transformers, with all other gases below the IEC limits. It is also observed that the laboratory accuracy values are above the typically recommended values as listed in Table 3 [10]. Hence, extra caution is needed when validating both gas levels and gas trends.

Based on the data in Table 3, the recommendation from the laboratory indicates –**thermal fault (T1) at a temperature of < 300 ^oC (Fig. 3).**

Fig. 3 shows a basic application of the Duval Triangle #1 [11, 12]. However, one needs to remember that in the Duval Triangle #1, the key gases are **CH_4, C_2H_4 and C_2H_2**. None of these gases are above the IEC typical 90 % gas PPM level limits, ***hence the application of the Duval Triangle # 1 is not applicable.*** The Duval Triangle needs to be used carefully, as it always produces results of irrespective gas ppm values.

2.2. DGA results from 2016 - 2019

The author requested the previous offline DGA test results to determine the trends. The physical reality in case of a fault is in the production of gases. It is ***very important*** to follow the temporal

Table 1. DGA laboratory results

Date	H_2 Hydrogen	CH_4 Methane	C_2H_2 Acetylene	C_2H_4 Ethylene	C_2H_6 Ethane	CO Carbon monoxide	CO_2 Carbon dioxide
July 2019 (ppm)	10	100	0	11	170	300	1800

Table 2. DGA laboratory results with lab ± % accuracy

Date	H_2 Hydrogen	CH_4 Methane	C_2H_2 Acetylene	C_2H_4 Ethylene	C_2H_6 Ethane	CO Carbon monoxide	CO_2 Carbon dioxide
July 2019 (ppm)	10	100	0	11	170	300	1800
Lab accuracy (1)	± 18 %	± 16 %	± 22 %	± 18 %	± 16 %	± 15 %	± 17 %
July 2019 (ppm) High	11.8	116	0	12.98	197.2	345	2106
IEC limits (2) (ppm)	< 150	< 130	< 20	< 280	< 90	< 600	< 14000

(1) The laboratory accuracy values are obtained from the lab test certificate.
(2) The IEC limits are based on the IEC 60599 2015 standard [10], the higher end of 90th percentile values are used.

Table 3. Recommended lab ± % accuracy values

Gases	H_2 Hydrogen
Hydrocarbons	± 15 % or 1 ppm, whichever is greater
Hydrogen	± 15 % or 5 ppm, whichever is greater
Carbon monoxide	± 15 % or 25 ppm, whichever is greater

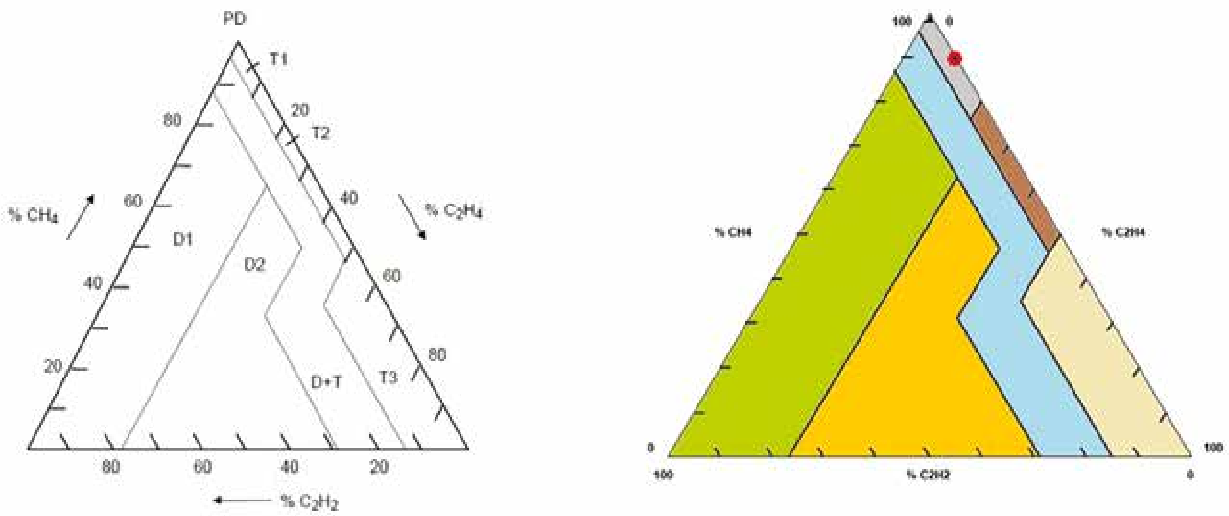

Figure 3. Duval Triangle #1: Application shows fault classified as Fault T1

evolution of the gasses, i.e., to have several DGA samples and study the trends. The DGA results from 2016 to 2019 are listed in Table 4.

From Fig. 4, C_2H_6 is showing an increasing upward trend along with CH_4. How-

APM Edge contains a set of comprehensive algorithms, and they are enriched with the readings of the online sensors when available

Table 4. DGA laboratory results (2016 - 2017)

Date	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2
July 2016 (ppm)	8	19	0	2	0	166	167
June 2017 (ppm)	6	40	0	3	13	283	684
July 2018 (ppm)	3	52	0	6	38	200	658
July 2019 (ppm)	10	100	0	11	170	300	1800

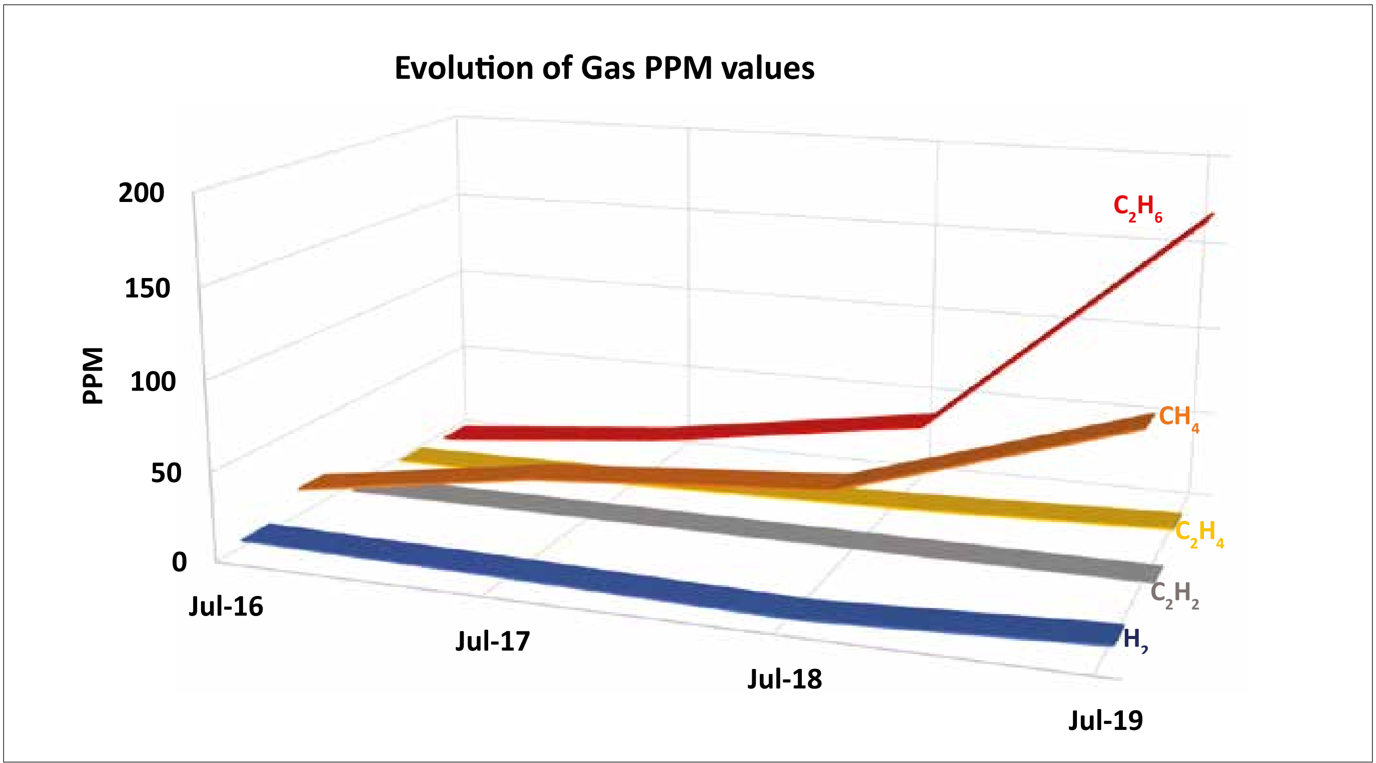

Figure 4. Gas evolution trend (25 MVA, 11 kV / 6.6 kV)

A case study of assessing the risks for 25 MVA transformer has been carried out using APM Edge

ever, from 2016 - 2018, the tests were carried out by a different laboratory to the one test carried out in 2019. Also, the test laboratory used from 2016 - 2018 did not report its gas PPM accuracy ± % figures. *To maintain the consistency and give the benefit of the doubt to the two different laboratories of meeting the recommended accuracy, APM Edge is set to perform calculations at ± 10 %*. This data is uploaded to APM Edge to answer the following questions:

a. Is the latest DGA data 'normal'?
b. Is the latest DGA data a statistical outlier?
c. Why is it important to know if it is an outlier?
d. Is there a trend? Is there a sudden trend?
e. How critical / significant is the trend?
f. What should be the frequency for the manual oil sampling? Are the recommended 6 months by oil laboratory reliable?
g. Is there a need to go online, i.e., to do continuous monitoring?
h. Should the user be informed? When? How? What should the user do to investigate the causes?

2.3. Application of APM Edge for offline DGA results (manual sampling)

To assess gas levels, the 4-level criteria[1] has been developed for the IEC specification, as shown in Fig. 5.

These criteria are similar to the 4-level criteria developed in the CIGRE brochure 443 [13]. Based on the Fig. 5, the Ethane PPM levels are shown in Fig. 6.

IEC typical 90 % limits (ppm) Level 1	**PPM** < typical IEC region (values higher than 90 %)
Level 2	Typical IEC region < **PPM** < 50 % above typical IEC
Level 3	50 % above typical IEC < **PPM** < 100 % above typical IEC
Level 4	**PPM** > 100 % above typical IEC

Figure 5. 4-level criteria developed used to determine DGA levels

[1] The new IEEE standard [9] has changed the 4-level criteria for three DGA status values, this is planned for future APM Edge release.

Level 1 limits (ppm)	Typical IEC region	20 - 90
Level 2 limits (ppm)	Typical IEC region – 50 % above typical IEC	90 - 135
Level 3 limits (ppm)	50 % above typical IEC – 100 % above typical IEC	135 - 180
Level 4 limits (ppm)	100 % above typical IEC	> 180

Figure 6. Ethane PPM values based on the 4-level criteria

To assess the gas trends, the best linear fit of the last three to six valid DGA points is used in APM Edge.

2.3.1 APM Edge recommendation (July 2019)

Based on the recommendation, another oil sample was taken in September 2019.

After feeding data from few offline DGA tests into APM Edge, due to inconsistency in input data, AMP Edge recommended to double-check the data and to take another verification sample for testing

Result	Description
Offline DGA recommendations	The latest DGA lab sample of ethane (170 ppm) is a statistical outlier - showing a continued increase (above 447 %) from the previous level. The statistical outlier ethane is 170 ppm – 189 % above the IEC typical maximum level of 90 ppm. NOTE: Considering the current lab accuracy (± 10 %), the current ethane level may be in the 50 % above IEC typical range or 100 % above IEC typical range.
Expert system recommendations	The statistical outliers may be caused by the mistaken input data, inadequate test or sampling procedure, sample contamination, loss of test equipment calibration or real issues inside the transformer, which might have to be identified. Recommended double-checking input, procedure and calibration. Also, taking another sample to verify the outlier is recommended. Recommended actions should be taken as soon as possible.

Table 5. 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	1800
September 2019 (ppm)	10	100	0	11	180	310	1790

This confirmed that C_2H_6 gas is showing an upward trend and is not an outlier result. The new data set was uploaded to APM Edge, and the following outputs were generated.

After uploading new data from DGA test into APM Edge, the detailed report with the overall risk estimation was generated

2.3.2 APM Edge recommendation (Sep 2019)

Result	Description
Offline DGA recommendations	The latest DGA lab sample of ethane (180 ± 18 ppm) is 50 % above the IEC typical gas concentration level of 135 ppm. This requires high caution. NOTE: Considering the current lab accuracy (± 10 %), the current ethane level may be 50 % above the IEC typical range or 100 % above IEC typical range. Based on the full dataset of 5 offline samples, ethane shows the rate of increase of 59.9 ppm per year. If the current offline trend is maintained, the linear approximation indicates that ethane will reach 100 % above IEC typical gas concentration in less than a month.
Expert system recommendations	Hot metal gases indicate an estimated fault temperature of about 156 °C. This can be caused by several issues, including poor connections (check bushing and LTC connections, check for an increase in LTC contact resistance), shorted turns and broken winding strands. These gases may also appear with an inadvertent core grounding which may be produced by a number of factors including core-ground insulation deteriorating to the point where the insulation becomes resistive; core-ground insulation damage during transportation or a through fault; core bolts and plates unduly grounding multiple parts due to manufacturing or design issues. In all these cases, there will likely be the circulating currents in the core, resulting in the hot-spots in the core and the surrounding structures.
Risk	Low

Afterwards an online monitoring system with 9-gas DGA was installed to monitor the rising ethane trends continuously

Main inferences from APM Edge are as follows:

- The expert system clearly indicates that ethane comes from localised (rather than general) overheating in the transformer, and the risk associated with it is still low (green).
- The expert system indicates the source of localised heating may be LTC contact resistance, inadvertent core grounding or even core bolts.
- Fault temperature calculated is based on [14].
- The ethane PPM / year was calculated at 60 ppm / year. This was based on the linear trending for full 5 sets of the manual DGA samples.
- Comparing it with the IEC [10] 90th percentile ethane values: (5 ppm / year – 90 ppm / year), 59.9 ppm / year is on the higher side.
- Comparing it with the IEEE [9] 90th percentile ethane values: 7 ppm / year, 59.9 ppm / year is on the very higher side.
- Based on the above, the need for online monitoring was very evident.

As the risk (POF) calculated was still low (Fig. 7), it was recommended by the

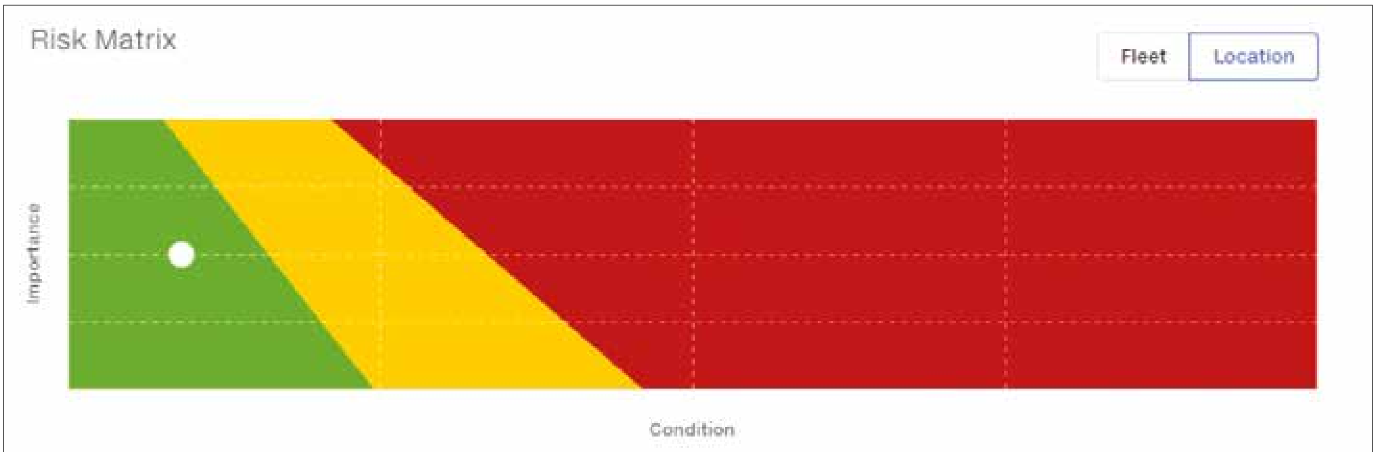

Figure 7. The risk matrix for 25 MVA transformer with 50 % importance

author to install an online **9-gas DGA monitor** to continuously monitor the rising ethane trends. Selection of the correct online DGA device is very crucial. In this case, the author advised installing a 9-gas DGA device. With a 9-gas DGA device, it is possible to identify most of the fault cases [15].

The initial assumption was that this transformer had a 50 % importance, assuming (N-1) criteria.

2.3.3 Excel fit of online ethane gas data

The online DGA data for ethane gas is shown in Fig. 8. Excel was used to do a straight-line fit of the data. Based on the 4 months data, the ppm / year is calculated from the slope as = 0.2 x 365 = 73 ppm / year. This is comparable to the offline sample ppm / year calculated as 60 ppm / year.

Based on the four months data of ethane monitoring, the increase in ppm / year was calculated, which was 73 ppm / year, while the total ethane levels exceeded more than 200 ppm

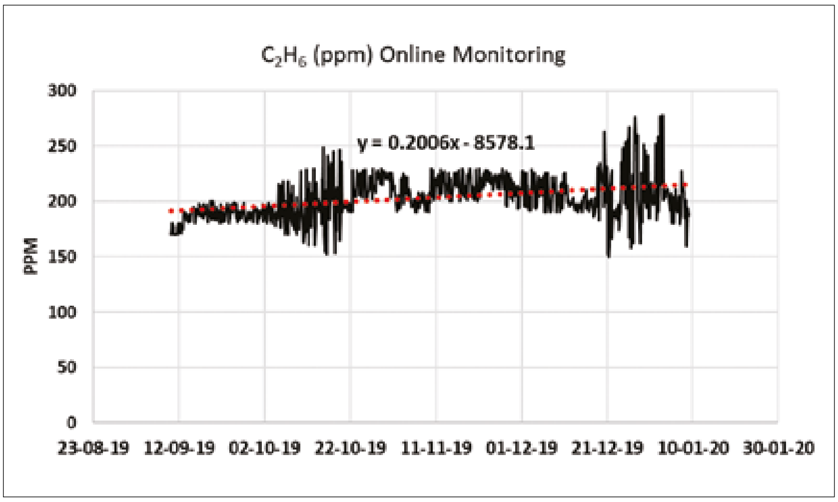

Figure 8. Gas evolution trend (using online DGA monitoring, Sep 2019 - Jan 2020)

From this, it was clear that there is an increasing trend, and as predicted by the expert system in Sep 2019, the PPM values did cross 100 % above the IEC threshold within a month. As of January 2020, the C_2H_6 ppm levels have increased above 200 ppm.

As the evolution of CO (and CO_2) was stable, unlike C_2H_6, the risk assessment by the expert system was spot on. This was further confirmed as per CIGRE 771 brochure [16] (Fig. 9), which gave typical values of around 550 ppm for C_2H_6 without failure.

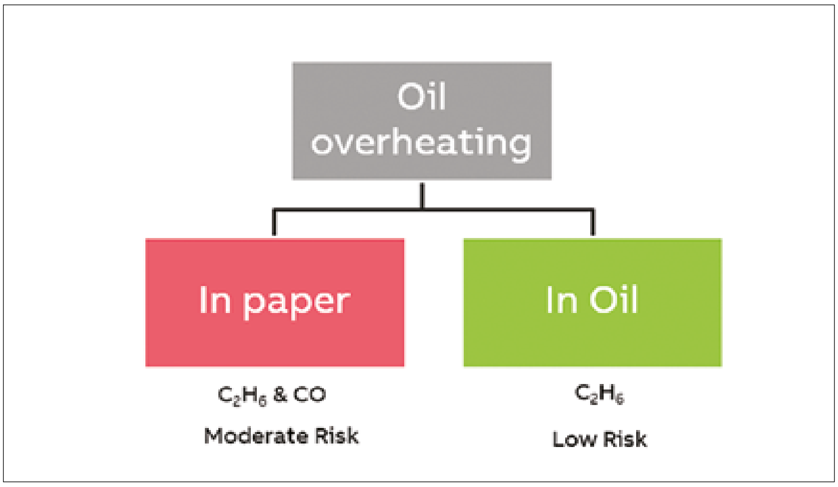

Figure 9. Risk assessment for oil overheating (CIGRE 771)

However, the customer requested to change the importance to 100 % due to a scheduled shutdown of the other N-1 transformer. The revised POF matrix is shown in Fig. 10, changing the unit of importance increased the **priority of action** by increasing the risk (POF) from the green zone to the yellow zone.

2.4. Final recommendation

Based on the application of the analytical software, the final recommendations were as follows:

- Ethane comes from localised (rather than general) overheating in the transformer. This is usually due to a 'hot spot'. It is not as 'hot' as arcing under the oil, which tends to produce C_2H_4 and C_2H_2 but is still a problem.
- As inferred by the expert model, the cause is that somewhere there is a poor mechanical connection, such as a bolted connection (cable to bushing or tap changer, etc.).
- The way forward is to conduct the recommended tests and finally an internal inspection to try and find the location of the heating.
- As ethane by itself will not deteriorate the oil, and C_2H_6 levels of 550 ppm have been reported by CIGRE, it is better to find the cause and rectify it.
- Oil filtering is not an option as the baseline DGA will be lost without treating the cause of high C_2H_6 levels.
- Continuous online DGA monitoring is recommended until refurbishment / maintenance is carried out, which is planned in June 2020.
- Expected (extrapolated) C_2H_6 ppm levels around 250 ppm by June 2020. An offline DGA test has been recommended to confirm online DGA results and trends.

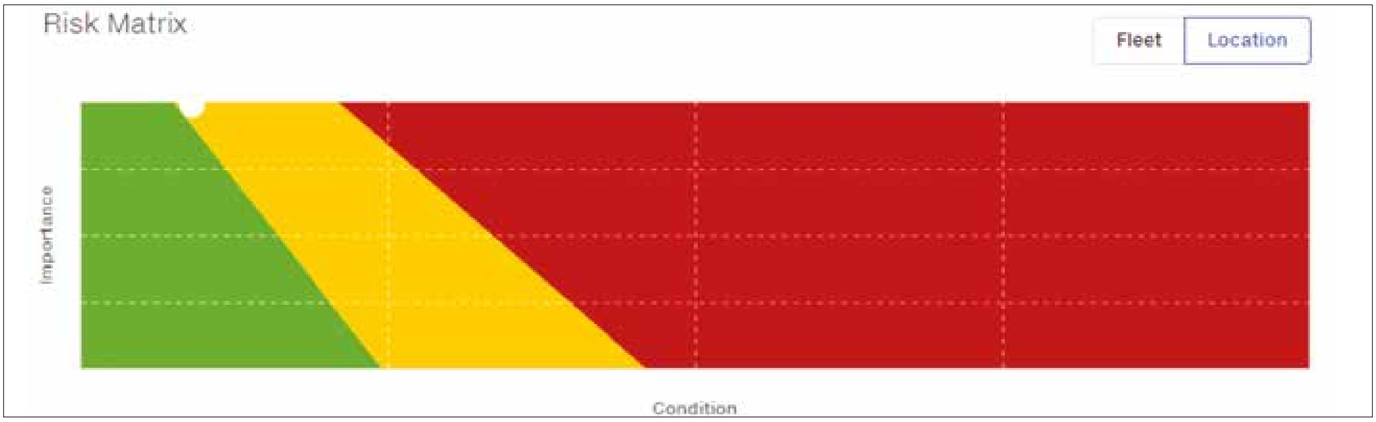

Figure 10. The risk matrix for 25 MVA transformer with 100 % importance

Conclusion

The ability to plan maintenance almost half a year in advance indicates the impact this platform will bring in terms of cost savings, resource allocation, planning, and maintenance execution. An offline DGA laboratory recommendation to resample in 6 months to establish a trend versus using the software to perform maintenance with the knowledge of what to look for inside the transformer in the same timeframe, demonstrates the impact this kind of asset management strategy (the use of APM Edge) will bring to any customer. A subsequent article on the cost savings is planned based on the replacement versus refurbishment scoring calculated in APM Edge.

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Author

Bhaba P. Das is the Lead Digital Business Developer for Transformers Business Line, HUB (Asia-Pacific, Middle East and Africa), ABB Power Grids, based in Singapore. He is part of the Application Engineering Team and spearheads the digital transformation efforts of transformers in the Asia Pacific region. Prior to ABB Power Grids, he worked as the R&D engineer for a major transformer manufacturer in New Zealand. He was awarded the Young Engineer of the Year 2017 by the Electricity Engineers Association of New Zealand for his work on the design and development of smart distribution transformers, fibre optics-based sensors for transformers, and diagnostic software for fleet condition monitoring. He is a Senior Member of IEEE and Young Professional of IEC. He completed his PhD in Electrical Engineering from the University of Canterbury, New Zealand.