It is firmly established that DGA is one of the best methods for detecting internal faults of the power transformers

ABSTRACT

Over the years, online dissolved gas analysis (O-DGA) has gained traction with power transformer asset managers. Many asset engineers have realized the technical benefits of the shift from traditional laboratory-based DGA to O-DGA. However, the main stumbling block in widespread O-DGA usage is convincing the commercial team members of the economic benefits gained by installing an O-DGA device. Usually, with an O-DGA device, there are different costs associated - the upfront purchase cost, usage costs over O-DGA monitor lifetime, and O-DGA maintenance costs. In this case study, an investigation is carried out on the return of investment for an O-DGA monitor for a service-aged power transformer, utilizing the principles presented in IEEE c57.143. Two monitors – a higher-priced O-DGA monitor with minor maintenance versus a lower-priced O-DGA with regular maintenance requirements are compared.

KEYWORDS

cost-benefit, monitoring systems, online DGA, return on investment

Investigating return on online DGA investments for service aged power transformer

I. Introduction

Power transformers are critical assets that ensure successful operation of many different applications - commercial plants, data centers, oil and gas plants, renewable plants, and utilities, among many. During their operational years, these transformers are subjected to stress, which can be categorized as thermal, mechanical, and electrical. Each of these stresses contributes to transformer aging. To maintain reliable operation, different strategies have been adopted by asset managers - visual inspections, routine oil sampling, mechanical or electrical tests, refurbishment (oil filtering, etc.), and replacements (when necessary) to ensure continued operation of these transformers.

It is now firmly established that dissolved gas analysis (DGA) is one of the best methods for detecting internal faults of the power transformers shortly after it was introduced [1]. There are international standards / technical brochures from IEC [2], IEEE [3], and CIGRE [4] providing background and assistance in interpreting DGA results. Traditionally, the gas chromatography (GC) [5] based DGA has been performed in oil laboratories all over the world. It is very common to perform offline DGA once or twice a year. This is due to different reasons: operational costs, lack of experienced staff, the complexity of standards [6] that must be applied to the extraction, storage, and transportation of oil samples to laboratories.

There are certain fundamental issues related to offline DGA analysis:

- Yearly DGA sampling only provides a snapshot of the transformer's condition at that time-point.
- There are issues related to laboratory accuracy and repeatability.
- Contamination (air bubble) of an oil sample during and / or after sampling.
- Lack of trained sampling staff.
- Degradation of the sample between the time of analysis and time of sampling.
- Manual sampling in remote locations is costly.
- The sample verification concept is hardly followed.

To overcome some of these issues, online DGA (O-DGA) is now becoming popular. A major benefit of O-DGA monitoring is its ability to detect failures that are evolving faster than the usual yearly sampling interval and which would otherwise remain undetected. O-DGA monitors can pick up and alert about changes in the gas production rates at an early stage of an incipient fault in near real-time. O-DGA monitors are especially beneficial when "sick" or "remote" transformers need to be sampled at regular intervals when the significant dissolved gas levels have already been identified, which otherwise would not be viable for regular manual sampling.

Although the advantages of O-DGA are recognized, many end users are reluctant to adopt it. Early O-DGA adapters have tried to resolve the high operational costs of O-DGA monitors, and some of them have switched back to the traditional manual DGA. A local survey was carried out by the author, involving 11 different end-users of O-DGA monitors to investigate the decision-making process in the procurement of O-DGA monitors and to understand the discontinuation of using O-DGA monitors in some cases. In the majority of cases (70 %), the decision has been made by the purchasing / commercial teams, while in only 19 %, it has been the decision of the engineering team. The engineering team would evaluate various solutions, and most of the time, the purchasing team would pick the lower-priced O-DGA monitor.

With the availability of new O-DGA technology launched almost every year, specific and detailed investment calculations are required. Decisions based on economics are unbiased and least controversial since everybody understands dollars and cents.

A major benefit of O-DGA monitoring is its ability to detect failures that are evolving faster than the usual yearly sampling interval and which would otherwise remain undetected

In this case study, an investigation on the return on investment in an O-DGA monitor for a service aged power transformer is carried out, utilizing the principles presented in IEEE c57.143

This means assigning the dollar value to all benefits, even to some intangible ones, which is very relevant in the current business environment as cost optimization and using assets for a longer lifetime is required.

A very useful guide is the IEEE C57.143.2012 [7], presenting a comprehensive cost-benefit analysis method to evaluate the economic benefits of online monitoring. In this case study, an investigation on the return on investment in an O-DGA monitor for a service aged power transformer is carried out, utilizing the principles presented in IEEE c57.143. The 40 / 63 MVA transformer manufactured in 2007 is investigated to determine if it is economically worth investing in an O-DGA monitor, where the transformer showed significant 2-FAL values along with an increasing concentration of CO_2/CO ratio. An unbiased investigation method based on IEEE c57.143 was used to evaluate and compare different O-DGA monitors in terms of the net present value, internal rate of return, and payback period.

Table 1. Determining critical 2-FAL limits based on different furan-DP models [9]

DP = 400	2-FAL (ppm)
Chengdong	1,29
Burton	3,16
De Pablo	8,87
Vuarchex	4,37
Average	4.42 ≈ 5 (approx.)

II. TRANSFORMER UNDER INVESTIGATION

The basic details of the investigated transformer are the following:

- rating = 40 / 63 MVA,
- voltage = 150 kV / 21 kV,
- oil type = mineral,
- paper type = kraft,
- year of manufacture = 2007,
- cooling = ONAN / ONAF,
- conservator = free breathing with air bladder.

Standard oil test, together with the offline DGA analysis tests, are routinely performed once a year, and the data has been recorded regularly for this transformer. Furan measurements have not been performed routinely. Over the service age of 13 years for this transformer, furans have

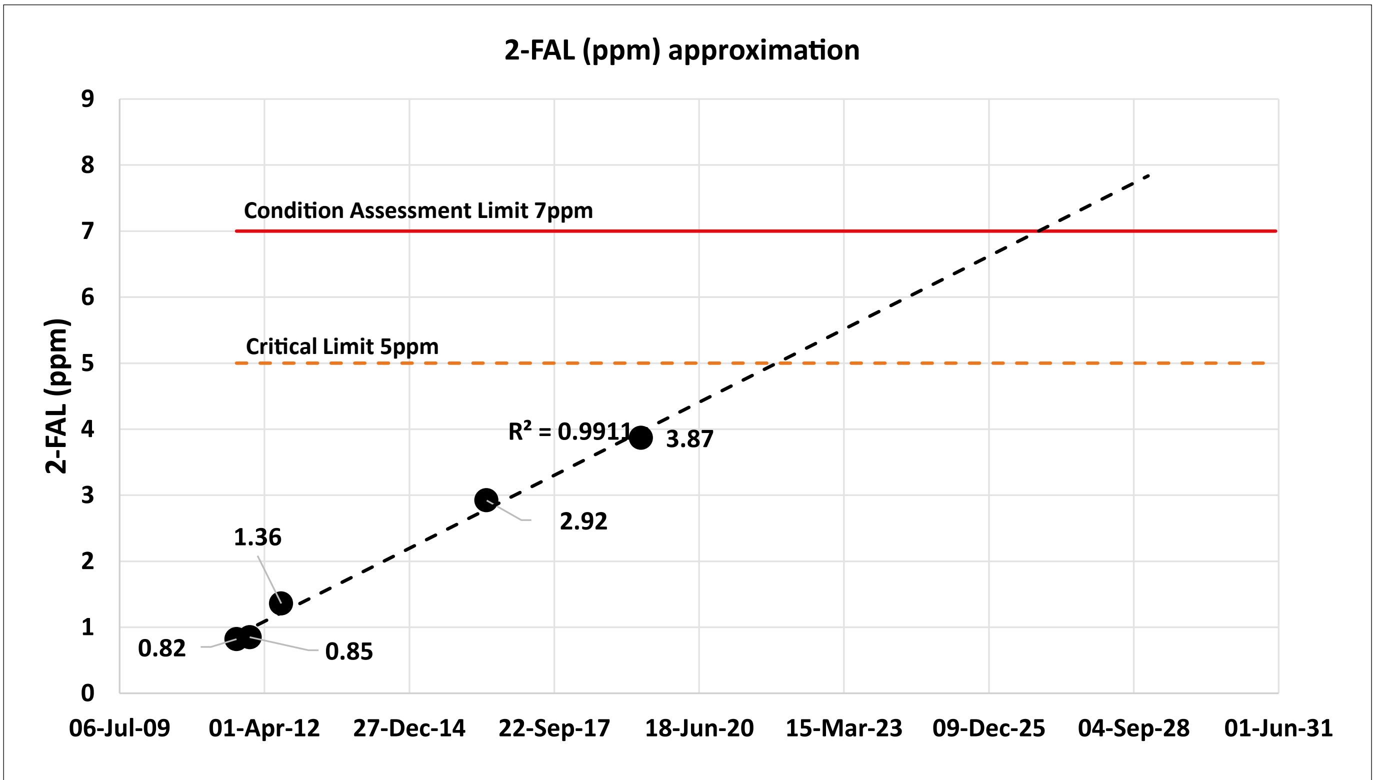

Figure 1. Straight-line trending of 2-FAL over time to estimate transformer retirement age

been measured five times. A straight-line extrapolation plot of 2-FAL values is shown in Fig. 1, to estimate when 2-FAL values of 5 ppm (critical) and 7 ppm (condition assessment required) will be breached.

Furan measurements have gained popularity in the past 20 years because they offer measurements of specific chemical compounds such as 2-FAL, which can be directly correlated with the aging of the transformer's paper insulation [8]. Several equations describing a degree of polymerization (DP) as a function of $\log_{10}$ (2-FAL) for kraft paper have been developed, and it is shown in [9] that accurate DP estimation is not always possible. It is advisable not to apply any furan-DP correlation without proper analysis directly. Additionally, certain actions may affect the furan concentration in the oil, such as oil reclamation and oil treatment, among others.

Typically, a DP = 200 is the end of life. As such, DP = 400 can be considered as moderate paper deterioration. A 2-FAL > 5 ppm can be considered critical as per Table 1, where the average 2-FAL value is determined using different DP models [9] with DP = 400.

As such, and considering the logarithm relationship, a 2-FAL ≥ 7 ppm would require a complete condition assessment of the transformer. As listed in Table 2 and Fig. 2, the average DP would be around 331, which indicates a considerable paper degradation.

Furan measurement is popular because it offers the measurements of specific chemical compounds such as 2-FAL, which is directly correlated with the aging of the transformer's paper insulation

A decision for replacement will be required at this point. As no oil treatment has been carried out for this 40 / 63 MVA transformer and by analyzing the rate of furan production, a reasonable estimate on 2-FAL values crossing 7 ppm can be made. Utilizing the five furan measurement results, a rate of furan generation is plotted in Fig. 1, and it can be estimated that the transformer

Table 2. Determining average DP @ 2-FAL = 7 ppm using furan-DP models [9]

2-FAL = 7 ppm	DP
Chengdong	189.9
Burton	330.8
De Pablo	358.1
Vuarchex	447.38
Average	331

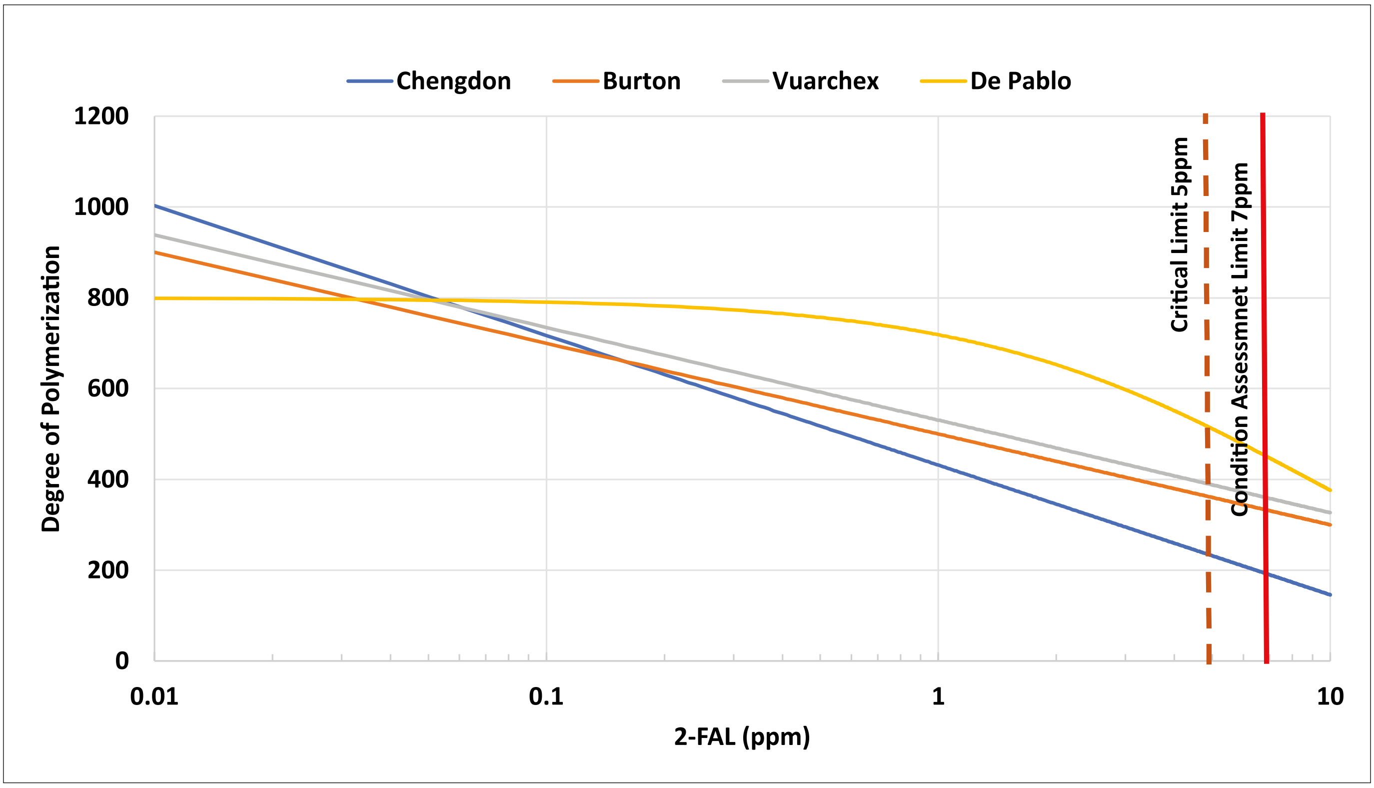

Figure 2. Critical and condition assessment limits based on different DP models [9]

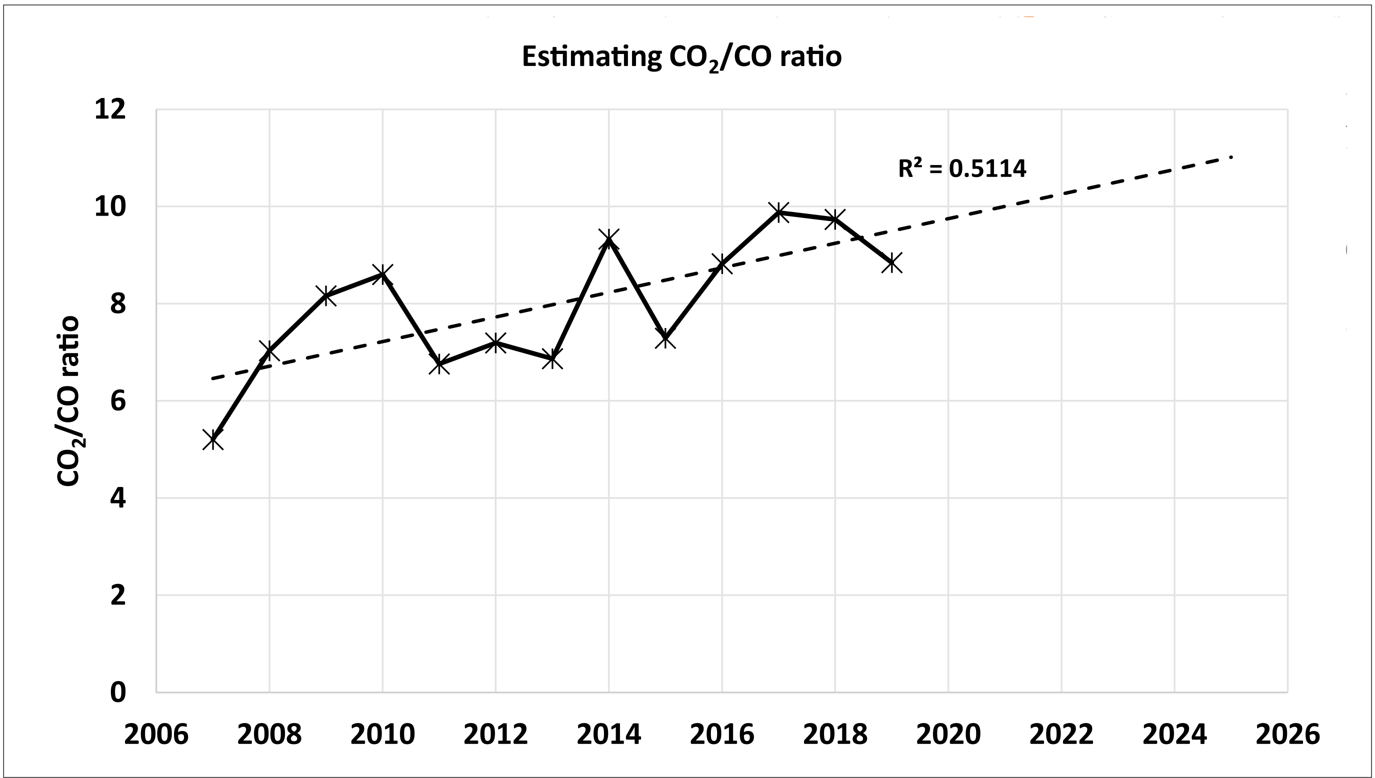

Figure 3. A straight-line trending of CO2/CO ratio over the time

With the increasing rate of gas production, it is easier to install an O-DGA monitor rather than increase the frequency of manual oil sampling

replacement may be required by 2027 (2-FAL ≥ 7 ppm).

A similar estimation can be obtained by plotting the CO_2/CO ratio. Fig. 3 shows that the CO_2/CO ratio is also increasing with the service age along with both individual gas ppm values crossing 7000 ppm and 800 ppm in 2019, whereas the CO_2/CO is almost 9 on average, still below 11, indicating aging due to thermal heating. A straight-line approximation shows that by 2025 $CO_2/CO \geq 11$ (Fig. 3). This is an indication of cellulose aging, which points towards the transformer's end of life. Installing an O-DGA monitor capable of correlating other gases such as H_2, CH_4, C_2H_4, C_2H_6 would be ideal at this point.

Hence, any O-DGA monitor that is installed in this transformer must have a payback period of less than approximately 5-7 years. Also, with the increasing rate of gas production, it will be easier to install an O-DGA monitor rather than increase the frequency of manual oil sampling.

Table 3. O-DGA probability of detection calculation

Component	Average CIGRE failure location % (CIGRE 642:2015)	O-DGA detection likelihood
Winding	42%	50%
Bushing	17%	0%
OLTC	22%	0%
Lead exit	10%	25%
Core & magnetic circuit	9%	25%
Others	0%	0%
Overall probability		25.7%

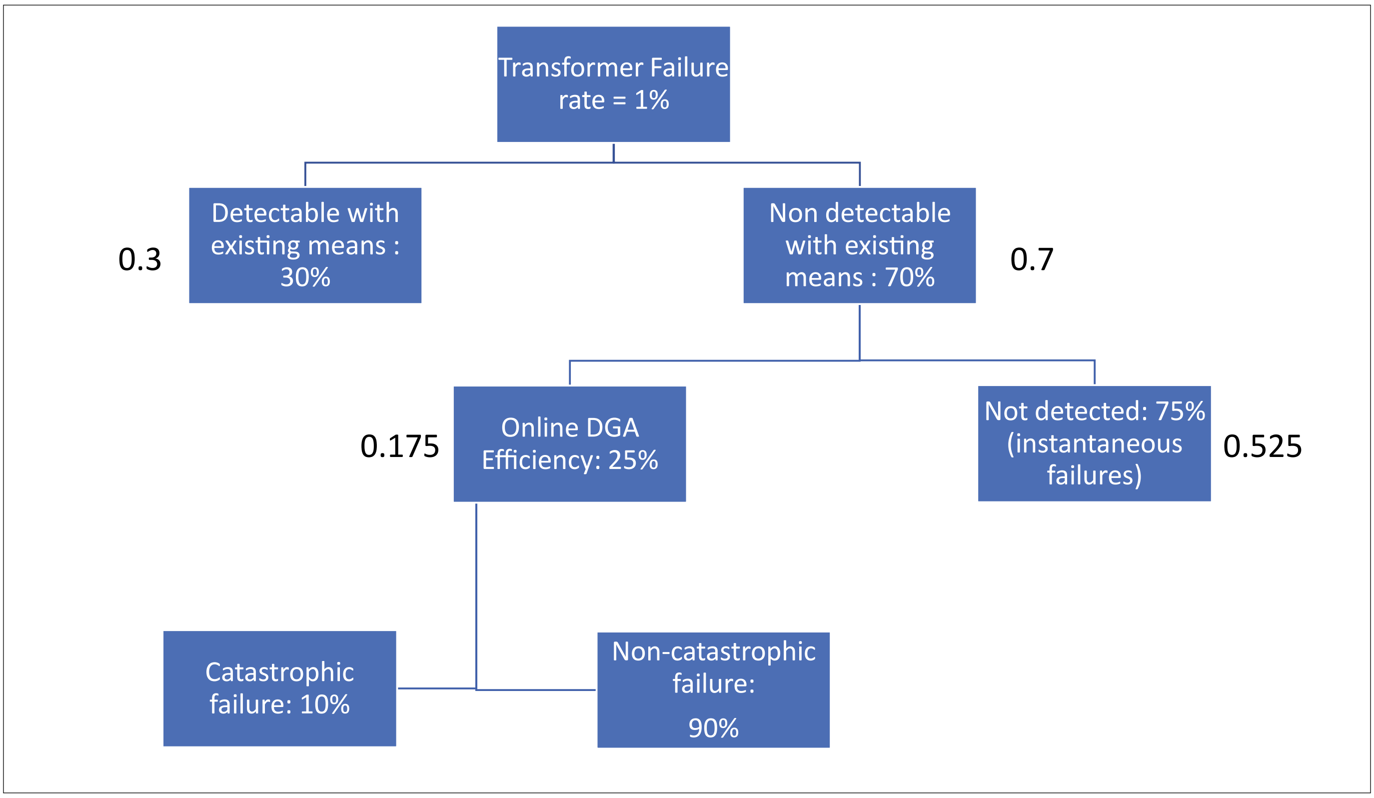

Figure 4. Breakdown of failure probabilities as per IEEE c57.143-2012.

III. UTILIZATION OF IEEE C57.143

IEEE c57.143 guide describes the transformer's operational parameters that can be monitored, and it provides a cost-benefit method to evaluate the application of transformer monitoring. The fundamental economics used to calculate any benefit are based on the equation:

Risk = Consequence x Probability

Probability is defined by a transformer failure rate, whereas a consequence can be the cost of major failure, cost of lost production, cost of early detection of fault (failure avoidance), etc. The failure rate (λ) is calculated as:

$$\lambda = \frac{No\ of\ units\ failed}{Operating\ unit\ years} \ x\ 100\%$$

There are 14 transformers in this plant, with combined operating unit years of 303 years, with 3 failures due to which production had to be stopped. This gives an average failure rate of 0.99 % (1 % approximately).

The detection rate having installed only an O-DGA device (in the main tank) can be evaluated as below – the average failure location numbers from CIGRE 642:2015 brochure is used in Table 3 to calculate the O-DGA probability of detection, i.e., O-DGA monitoring efficiency.

IEEE c57.143 guide describes the transformer's operational parameters that can be monitored, and it provides a cost-benefit method to evaluate the application of transformer monitoring

As per IEEE c57.143-2012, existing devices such as gas accumulation relays, top oil temperature indicators, and winding temperature simulators can provide a warning about developing faults along with periodic oil sampling. The proportion of faults that can be detected by these means is estimated at 30 % out of the calculated average failure rate of 1 %. The impact of O-DGA monitoring to reduce the failure rate can be evaluated as below (as shown in Fig. 4):

- Yearly manual DGA can detect 30 %, while 70 % of the failures cannot be detected.
- O-DGA monitor can detect 25 % (Table 3) from the rest of the undetected 70 % failures.
- 75 % of the undetected 70 % failure cannot be detected with O-DGA only. It is unrealistic to expect 100 % coverage.
- The catastrophic failure rate is 10 % of the total failures, and the non-catastrophic failures form 90 % of the total failures. Although no catastrophic failure has been observed in this plant, a 10 % likelihood is assumed.

Failure reduction calculations show that with the O-DGA monitor, it is possible to prevent 47.5 % of all potential failures, while without the online monitoring, the number is 30 %

Table 4. Benefits of O-DGA

	With offline DGA	With O-DGA	Relative improvement
Failure occurring	70%	52.5%	Decrease by 28.5 %
Failure prevented	30%	47.5%	Increases by 45 %

IEEE c57.143 states that a transformer is normally retired if the failure rate is assumed to be higher than the acceptable failure level

Failure reduction calculations (Table 4 and Fig. 4) show that with the O-DGA monitor, it is possible to prevent 47.5 % of all potential failures, while without the online monitoring, the number is 30 %. The result is that the O-DGA monitor improves the failure rate by 45 % (absolute difference), which can be considered as a remarkable improvement.

The cost / benefit analysis of the transformer monitoring is a difficult undertaking. Calculating the cost is relatively straight-forward, taking into account equipment purchase, installation, training, and maintenance costs, etc. The benefits, however, are more difficult to assess as the evaluation relies partly on factors dictated by experience. Some tangible events that can be quantified are the following:

- reduced inspection and maintenance costs,
- reduced failure-related repair or replacement costs,
- improved real-time transformer loading capability,
- deferred upgrade capital costs due to load growth,
- deferred replacement capital costs due to equipment age or condition,
- reduced cost of lost production.

In this example, the following benefits are calculated:

A) Deferred replacement capital costs due to equipment age

IEEE c57.143 states that a transformer is normally retired if the failure rate is assumed to be higher than the acceptable failure level. For an aging transformer, the risk is not so much the residual value of the transformer but the inconvenience (maintenance / lost production) caused by an unplanned outage. The benefit from a deferred replacement is directly proportional to the current interest rate and the capital cost of a new unit.

- Transformer costs usually vary due to many factors, a generalized estimate is $8 k ≤ per MVA ≤ $12 k.
- For a 63 MVA transformer, an approximate cost is around $500,000.
- Current interest rate = 4 %

Another recognized benefit from IEEE C57.143 consists of the savings generated from reduced repair / maintenance costs

Table 5. Annual benefits due to deferred replacement

Year	Extension	End balance	Annual benefit
2020	0	$500,000.00	
2021	1	$520,000.00	$20,000.00
2022	2	$540,800.00	$20,800.00
2023	3	$562,432.00	$21,632.00
2024	4	$584,929.28	$22,497.28
2025	5	$608,326.45	$23,397.17
2026	6	$632,659.51	$24,333.06
2027	7	$657,965.89	$25,306.38

Table 6. Annual benefits due to reduced failure rate - normal stage

Parameters	Values
Transformer cost (TC)	$500,000
Predictive repair costs (PRC)	20 %
Failure rate (λ %)	1 %
Non-detectable failure %	70 %
O-DGA efficiency (η %)	25 %
X (repair cost – non-catastrophic)	7.5
Y (repair cost - catastrophic)	25
Non-catastrophic failure %	90 %
Catastrophic failure %	10 %
Reduced failure rate cost	$1443.75

- Based on extrapolated 2-FAL ppm value ≥ 5 ppm, life extension can be considered from 2021 as listed in Table 5.

B) Reduced failure-related repair or replacement costs

Another recognized benefit from IEEE C57.143 consists of the savings generated from reduced repair / maintenance costs. The benefit is calculated by considering the repair cost for a major failure with and without O-DGA, replacement, and collateral damage costs with and without O-DGA. A multiplier X = 7.5 has been used to reflect that the repair cost for a major failure, while a multiplier Y = 25 has been used to reflect the replacement cost and collateral damage resulting from a catastrophic failure as per [7].

The annual benefit of reduced failure-related repair or replacement costs can be calculated as listed in Table 6.

The "normal life" stage of industrial transformers is around 16 years [10], after which the failure rate starts to increase, as calculated in Table 7. Typical failure rates are extracted based on a failure rate = 12 % at 35 years [10].

Based on Table 7, the annual benefit can be calculated and listed in Table 8.

C. Reduced manual oil sampling costs

In many cases, additional monitoring can reduce the frequency of manual inspections. Direct time savings are achieved during site visits, manual oil sampling, laboratory costs, and reporting. The annual benefit of reduced manual oil sampling costs can be calculated from a decreased offline oil sampling frequency as shown in Table 9 below – with an O-DGA monitor. Manual offline oil sampling can be carried out once, instead of 12 x offline DGA samples in a year. In the case of offline DGA sampling, the approximate total costs are around $100.

Total offline DGA costs, if the transformer is retired at the age of 20 years (i.e., the year 2027 from today, 2020) is $9600. If an O-DGA monitor is installed, the offline DGA costs are $300. Total savings per year = $1162.50.

If the O-DGA monitor is installed, the savings are also achieved by the reduction of manual oil sampling

Table 7. A typical failure rate increases with age

Period	Failure rate
Normal stage	2nd to 16th year, λ = 1 %
Wear-out stage	17th year, λ = 1.06 %
Wear-out stage	18th year, λ = 1.34 %
Wear-out stage	19th year, λ = 1.55 %
Wear-out stage	20th year, λ = 1.66 %

Table 8. Annual benefit earned with respect to the failure rate

Year	Age	Failure Rate	Annual Benefit Earned
2020	13	1 %	$1443.75
2021	14	1 %	$1443.75
2022	15	1 %	$1443.75
2023	16	1 %	$1443.75
2024	17	1 .06%	$1530.38
2025	18	1.34 %	$1934.62
2026	19	1.55 %	$2237.81
2027	20	1.66 %	$2396.62

The comparison of different O-DGA monitors is meaningless unless the costs are brought to the same common economic basis - calculating the net present value and payback period

IV. INVESTMENT INTO AN O-DGA MONITOR

In the previous section, the benefits of installing an O-DGA monitor were calculated. However, when purchasing an O-DGA monitor, there will always be additional costs over the actual purchase price. The highest upfront cost will be the cost price of the unit. However, there will be indirect costs such as:

- consumable costs – carrier gas / calibration gas,
- spare parts and repair time costs – parts such as field repair of IR analyzers, electronics repairs, site-visits, and annual inspection costs,
- oil piping system maintenance – oil leaks, pump failures,
- oil line pipe filters,
- remote communication requirements, etc.

Table 9. Annual benefit earned with reduced manual oil sampling

Year	Yearly DGA costs	Extended with O-DGA
2020	$1200	$100
2021	$1200	$000
2022	$1200	$000
2023	$1200	$100
2024	$1200	$000
2025	$1200	$000
2026	$1200	$100
2027	$1200	$000

Once these factors are incorporated, an economic evaluation must be made. The comparison of different O-DGA monitors is meaningless unless the costs are brought to the same common economic basis - calculating the net present value and payback period. Each O-DGA monitor will have different indirect costs. If the question were to evaluate two different O-DGA technologies, the indirect costs need to be factored in the payback period calculation. Two such payback period calculations are evaluated - O-DGA with regular maintenance requirements and O-DGA monitor with minor maintenance requirements. All costs indicated in this article should be converted into local costs, which vary from country to country.

A) O-DGA with regular maintenance requirements

Regular maintenance requirements would include:

- Visual inspection every 12 months. Approximately $2000 per visit (local visit).
- Carrier gas and calibration gas replacement every 24 months. Approximately $2400 per replacement.

- Oil piping system maintenance every 2 years. Approximately $500 combined with a visual inspection.
- Minor refurbishment every 3 years (electronic parts, control circuitry, software upgrade, communications). Approximately $3000 per refurbishment.
- Major refurbishment upon expiry of 10 years (not included in this case, as 10 years is beyond expected transformer replacement age).

B) O-DGA with minor maintenance requirements

Minor maintenance requirements would include:

- Minor refurbishment every 3 years (electronic parts, control circuitry, software upgrade, communications) Approximately $3000 per refurbishment.
- Major refurbishment at the end of 10 years (not included in this case as 10 years is beyond the expected transformer replacement age).

V. ECONOMIC CALCULATIONS

For a commercial manager, when comparing different options and decide which one to invest in, there are generally three options available: the internal rate of return (IRR), payback period, and net present value (NPV). Three parameters are:

- NPV is the value of all future cash flows (positive and negative) over the entire life of an investment discounted to the present. Assumed discount rate = 4 %.
- IRR is the discount rate that makes the NPV = 0. This equates to the expected compound annual rate of return that will be earned on the O-DGA monitor.
- The payback period is the time taken to recover the cost of an investment in an O-DGA monitor. For this service aged transformer, the payback period should be less than 5-7 years, after which the transformer may be replaced.

For a commercial manager, when comparing different options and decide which one to invest in, there are generally three options available: IRR, payback period, and NPV

A) Payback for O-DGA with minor maintenance requirements

Table 10 lists the payback calculations for an O-DGA with minor maintenance requirements. The results are as follows:

- the purchase price = $60,000.00,
- IRR = 38.38 %,
- NPV = $87,808.00,
- the payback period is less than 3 years.

B) Payback for O-DGA with regular maintenance requirements

Table 11 lists the payback calculations for O-DGA with regular maintenance requirements. The results are as follows:

- purchase price = $55,000.00,
- IRR = 28.195 %,
- NPV = $64,256.00,
- payback period is less than 3 years.

While the payback period is less than 5-7 years in both cases, the IRR and NPV are higher for an O-DGA with minor maintenance requirements. This implies that an O-DGA with minor maintenance requirements is a better choice in terms of yielding a higher rate of return.

VI. CONCLUSIONS

If a transformer is suspected of a high potential of failure, the investment in

For this service aged transformer, the payback period should be less than 5-7 years, after which the transformer may be replaced

Table 10. Payback calculations for an O-DGA with minor maintenance requirements

Year	Failure rate	Life extension	DGA reduction	Net income	Cost of DGA	Other costs	Cash flow	Present value	Cumulative CF
0 (2020)	$0	$0	0	$0	-$60,000	$0	-$ 60,000.00	$60,000.00	$60,000.00
1 (2021)	$1,443.75	$20,000	$1,162.50	$22,606.25	$0	$0	$22,606.20	$21,736.78	$38,263.22
2 (2022)	$1,443.75	$20,800	$1,162.50	$23,406.25	$0	$0	$23,406.25	$21,640.39	$16,622.83
3 (2023)	$1,443.75	$21,632	$1,162.50	$24,238.25	$0	-$3,000	$21,238.25	$18,880.73	-$2,257.90
4 (2024)	$1,443.75	$22,497	$1,162.50	$25,103.25	$0	$0	$25,103.25	$21,458.36	-$23,716.26
5 (2025)	$1,530.38	$23,397	$1,162.50	$26,089.88	$0	$0	$26,089.88	$21,443.98	-$45,160.24
6 (2026)	$1,934.62	$24,333	$1,162.50	$27,430.18	$0	-$3,000	$24,430.18	$19,307.53	-$64,467.77
7 (2027)	$2,237.81	$25,306	$1,162.50	$28,706.69	$0	$0	$28,706.69	$21,814.73	-$86,282.49

Table 11. Payback calculations for O-DGA with regular maintenance requirements

Year	Failure rate	Life extension	DGA reduction	Net income	Cost of DGA	Other costs	Cash flow	Present value	Cumulative CF
0 (2020)	$0	$0	$0	$0	-$55,000.00	-$5,000.00	-$60,000.00	$60,000.00	$60,000.00
1 (2021)	$1,443.75	$20,000	$1,162.50	$ 22,606.25	$0	-$2000.00	$ 20,606.20	$19,813.70	$40,186.30
2 (2022)	$1,443.75	$20,800	$1,162.50	$ 23,406.25	$0	-$4900.00	$ 18,506.25	$17,110.07	$23,076.23
3 (2023)	$1,443.75	$21,632	$1,162.50	$ 24,238.25	$0	-$5,000	$ 19,238.25	$17,102.73	-$5,973.50
4 (2024)	$1,443.75	$22,497	$1,162.50	$ 25,103.25	$0	-$4,900.00	$ 20,203.25	$17,269.82	-$11,296.33
5 (2025)	$1,530.38	$23,397	$1,162.50	$ 26,089.88	$0	-$2000.00	$ 24,089.88	$19,800.13	-$31,096.45
6 (2026)	$1,934.62	$24,333	$1,162.50	$ 27,430.18	$0	-$7,900.00	$ 19,530.18	$15,434.98	-$46,531.44
7 (2027)	$2,237.81	$25,306	$1,162.50	$ 28,706.69	$0	-$2,000.00	$ 26,706.69	$20,294.89	-$66,826.33

an O-DGA monitor is justified because the indirect costs are, in practice, higher than the price of an online DGA monitor. Similarly, the cost of lost production or cost of lost customers should always be quantified apart from the benefits quantified in this article. The IEEE c57.143 guide provides a comprehensive cost benefit analysis method and should always be utilized by the commercial team when deciding on O-DGA purchases.

For this transformer and based on the submitted data, the furans levels indicate significant paper aging. The CO_2 and CO trending should be established by investing in an O-DGA monitor. Among the choice for various O-DGA monitors, a comparison was made between two choices - a lower-priced O-DGA monitor with regular maintenance requirements versus a higher-priced O-DGA monitor with minor maintenance requirements. Economic calculations show investing in a higher-priced O-DGA monitor with minor maintenance requirements yields better returns. A sensitivity analysis for different discount rates and different transformer life extension period should also be considered.

Bibliography

[1] M. Duval, *Dissolved gas analysis: It can save your transformer*, IEEE Electrical Insulation Magazine, Vol. 5, No. 6, 1989

[2] IEC 60599:2015, *Mineral oil-filled electrical equipment in service*, Guidance on the interpretation of dissolved and free gases analysis

[3] IEEE C57.104:2019, *IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers*

[4] CIGRE 771: 2019, *Advances in DGA interpretation*, Working group D1/A2

[5] ASTM D3612-02:2017, *Standard test method for analysis of gases dissolved in electrical insulating oil by gas chromatography*

[6] IEC 60567:2011, *Oil-filled electrical equipment - Sampling of gases and analysis of free and dissolved gases* - Guidance

[7] IEEE Std. C57.143-2012 - *IEEE guide for application for monitoring equipment to liquid-immersed transformers and components*

[8] I. Hohlein, A. J. Kachler, *Aging of cellulose at transformer service temperatures - Part 2.: Influence of moisture and temperature on degree of polymerization and formation of furanic compounds in free breathing systems*, IEEE Electrical Insulation Magazine, Vol. 21, pp. 20–24, 2005

[9] L. Cheim et al., *Furan analysis for liquid power transformers*, IEEE Electrical Insulation Magazine, Vol. 28, pp. 8–21, 2012.

[10] CIGRE ELECTRA, 88:1983, *An international survey on failures in large power transformers*, pp. 21-48, Working group 12-05.

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