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Reliability-based DGA Quick Start Guide for TOA Users

Delta-X RESEARCH

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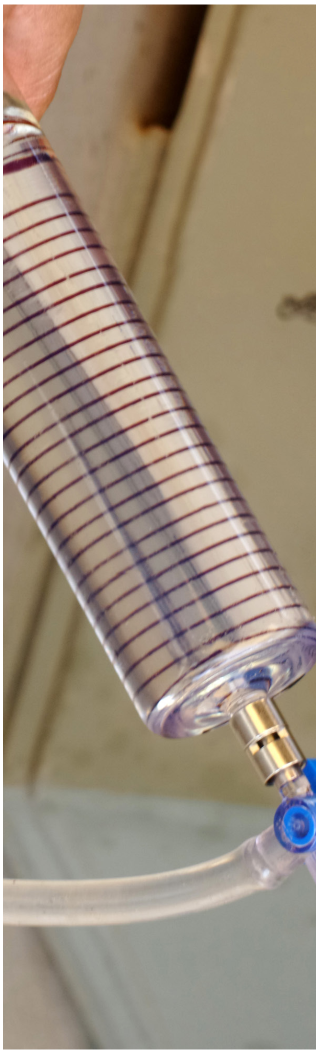
Chapter 1

Introduction

This Reliability-based DGA Quick Start Guide is documentation to help TOA™ users understand and use new software features relating to reliability-based dissolved-gas analysis (R-DGA) for oil-filled power transformers. Reliability-based DGA is a new method of dissolved-gas analysis interpretation, developed by Delta-X Research. It is based on the trending of fault energy indices, with assessment of fault gas production in terms of failure probability and failure rate.



Fundamental Principle of Transformer DGA

A transformer is designed not to damage its internal insulation in the course of normal operation. If insulation deterioration byproducts dissolved in the oil are increasing (beyond what is expected due to normal aging), something is wrong.

Both R-DGA and conventional DGA are methods of interpreting the same dissolved-gas data, and both are based on the Fundamental Principle of Transformer DGA displayed above. Conventional DGA, as described in the IEEE C57.104 [1] and IEC 60599 [2] guides, uses numerical limits to judge whether gas concentrations, increments, and rates of change are abnormal, and if so, how abnormal. R-DGA does not need limits; instead, it uses a statistical model of "how the gases look when the transformer is about to fail" to estimate how risky the transformer's past gassing activity was and how risky continued gassing might be.

TOA provides both R-DGA and conventional DGA operating side by side. In the software's home page, there is a link to a results comparison report showing where the two DGA methods have assessed some transformers similarly and others differently.

In the next section some basic technical concepts are discussed. The section after that provides a detailed example of how to use R-DGA in TOA, based on the case history of a large transformer that failed unexpectedly. Finally, there is a section in which some frequently asked questions about R-DGA are answered.

Chapter 2

Technical details

Reliability-based DGA builds on advancements that have been made in the last several years supporting an approach to transformer DGA that is conceptually simple, closely aligned with the Fundamental Principle of Transformer DGA, and rooted in chemistry, physics, and reliability engineering statistics.

- Base the gassing status score (1-4) on Fundamental Principle of Transformer DGA.
- Use fault energy indices to simplify trending and fault detection.
- Detect and account for gas loss from the transformer or the oil sample.
- Identify and assess gassing events (time intervals during which fault gas generation is occurring).
- Base fault type identification on gas increments during gassing events.
- Interpret the percent change in the CO/CO2 ratio during carbon oxide gassing events.
- Use reliability statistics to relate DGA results to transformer failure.

2.1 Gassing status

A transformer's gassing status is a number between 1 and 4 defined as follows.

Conventional DGA	Code	Reliability-based DGA
Operating satisfactorily	1	No gassing ever
Greater than normal combustible gas level. Any individual gas exceeding specified levels warrants additional investigation.	2	No recent fault gas production
High level of decomposition. Any individual gas exceeding specified levels warrants additional investigation.	3	Recent fault gas production
Excessive decomposition. Continued operation could result in transformer failure.	4	Current extreme fault gas production (high Hazard Factor)

The difference between moderate and extreme fault gas production is further explained in **subsection 2.6.**

2.2 Fault energy indices

The hydrocarbon gas normalized energy intensity (NEI-HC), as the sum of heats of formation of the four low molecular weight hydrocarbon gases, weighted by fault gas concentrations, was introduced as NEI in [3] and shown to be useful for DGA trending and for assessment of fault severity. NEI-HC is defined as follows:

$$\text{NEI-HC} = \frac{77.7(CH_4) + 93.5(C_2H_6) + 104.1(C_2H_4) + 278.3(C_2H_2)}{22400} \qquad (1)$$

The parenthesized gas names denote dissolved-gas concentrations (μL/L) in mineral oil, measured in the same sample and expressed at standard temperature and pressure conditions of zero degrees C and one atmosphere as specified in ASTM D3612 [4].

The numeric coefficients of the gas concentrations in the formulas are the respective standard heats of formation (kJ/mol), from n-octane (C_8H_{18}), a model for a typical mineral oil molecule for the hydrocarbon gases. The units for NEI-HC and all other forms of NEI are kJ/kL.

When there is suspicion of ethane stray gassing (significant ethane production not related to a fault), ethane is omitted from the formula above to obtain NEI-T, the "Duval triangle gas NEI."

The carbon oxide gas normalized energy intensity (NEI-CO) is defined as NEI for the carbon oxide gases CO and CO_2, with standard heats of formation from cellulose.

$$\text{NEI-CO} = \frac{101.4(CO) + 30.2(CO_2)}{22400} \qquad (2)$$

NEI-CO is used for the detection and assessment of faults affecting the solid (cellulosic) insulation.

2.3 Detecting and accounting for gas loss

Unfortunately, gas loss is not a rare occurrence in DGA. When there is loss of fault gas, active fault gas production can go undetected or be underestimated. Once formed in the transformer, fault gas can escape via a leaky bushing gasket or a torn conservator diaphragm. It can escape during sampling if the oil sample is exposed to air or if the sampling syringe is leaky. Gas loss from a leaking transformer often affects several consecutive samples, whereas gas loss during sampling typically affects a single sample.

Symptoms of gas loss due to leakage or air exposure include:

- O_2/N_2 ratio greater than 0.2
- Low concentrations of hydrogen and carbon monoxide

Nitrogen-blanketed transformers can lose fault gas in a different way. When gas accumulation or high temperature raises the gas pressure in the head space, a pressure relief valve allows some of the head space gas to escape. If the temperature drops later, nitrogen is added to the head space to keep the gas pressure in the right range. The effect of occasional gas expulsion and subsequent dilution of the head space gas with nitrogen is to reduce the fault gas content of the oil, since some gas goes from the oil into the head space each time to re-establish equilibrium. If a nitrogen-blanketed transformer has a pattern of fault gas concentrations in the oil simultaneously rising and then simultaneously falling, with hydrogen and CO being strongly affected, there may be active fault gas production partially masked by gas expulsion.

Another reason for gas loss is degassing, which usually shows up in a transformer's DGA history as a simultaneous deep drop in all gases. Over several weeks following the degassing, some of the dissolved gas trapped in the windings diffuses out into the bulk oil to re-establish an equilibrium.

To mitigate the effects of gas loss on fault detection and assessment, TOA bases its R-DGA interpretation on a statistical estimate of gas production obtained by smoothing the gas data to reduce the "noise" inherent in sampling and laboratory analysis, then ignoring large decreases. In the NEI event graphs (Figure 6), the gray crosses represent "raw" data, while the black line represents cumulative data.

2.4 Gassing events

A gassing event in a time series graph is a time interval during which the variable is increasing. For example, in Figure 6 the numbered boxes indicate gassing events in which NEI-CO and NEI-HC increased. Other gassing events that may be noted by TOA are CO/CO_2 events, associated with increases in that gas ratio, and acetylene events, when the acetylene concentration is increasing.

The apparent fault type during a gassing event is determined by calculating how much methane, ethylene, and acetylene increased during the event and plotting those amounts in the Duval triangle. Those gas increments represent new fault gas produced by whatever is causing the event.

NEI-HC, NEI-T, and NEI-CO gassing events have statistical properties called severity and hazard factor that are explained in subsection 2.6 below.

2.5 CO/CO_2 ratio

The percent increase of the CO/CO_2 ratio during a gassing event, especially during an NEI-CO event, can provide an indication of the location of a fault affecting paper insulation. An increase in the CO/CO_2 ratio by 33% to 100% suggests local deterioration of paper insulation outside of the windings, such as on a hot bushing or NLTC lead. A very large increase – 185% or more – may indicate deterioration of paper insulation inside the windings or in some confined space. The meaning of an increase between those two ranges is ambiguous. A decrease in the ratio indicates that CO2 is being produced faster than CO, which commonly is a sign that paper insulation is being stressed by general overheating.

Remarkably, the interpretation of percent increases in the CO/CO_2 ratio is valid even when gas loss is involved, i.e. even when one or both of the carbon oxide gas concentrations is decreasing. That is explained by the fact that CO is more volatile and much less soluble in oil than CO_2. Any gas loss must affect CO much worse than CO_2, so it follows that the CO/CO_2 ratio can increase only if there is active production of CO.

2.6 Statistical model

Reliability-based DGA relies upon a pre-defined statistical model, derived from a large DGA database augmented with failure data, showing how the level of each fault energy index is distributed in transformers that are not far from failure [5]. From the model, various quantities can be obtained for assessment of fault gas production. R-DGA is especially concerned with these statistical quantities related to a gassing event where a fault energy index increases from an initial value a to a final or most recent value *b*:

Severity: The severity of the event is the prevalence (expressed as a percentage) of transformers, actively gassing with NEI in that range, that fail. Cumulative severity is the severity of a gassing event starting from zero and increasing to b.

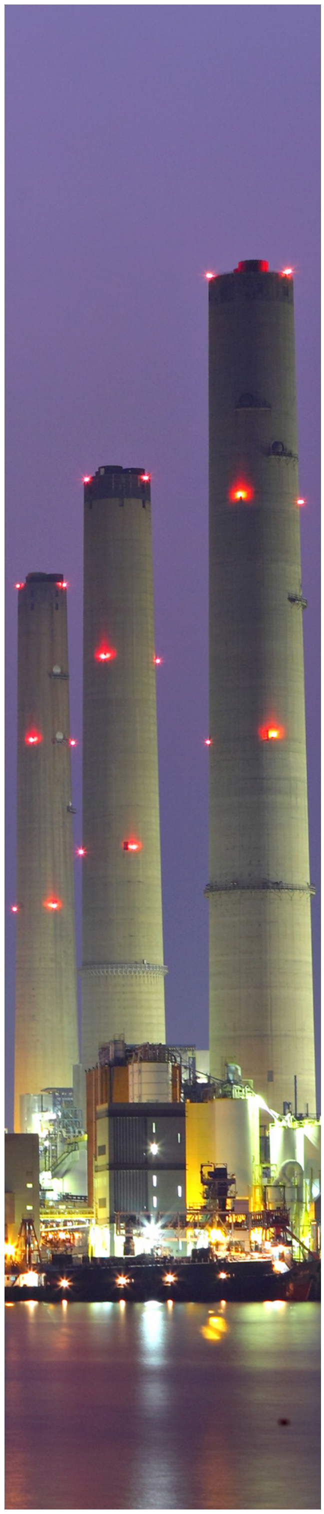
Hazard factor (HF): The hazard factor at the upper end b of the event is the failure rate (percent failures per additional NEI unit of gassing) for NEI = b, times the NEI rate of increase (NEI units per year) at that point. HF can be understood as an estimate – in percentage points per year – of how fast the severity is increasing as of the latest sample in the event.

In TOA, to qualify as “extreme” a gassing event must have high enough severity to not be just a “blip,” and its hazard factor has to exceed the 90th percentile value of HF in a large number of gassing events observed in our research database.

Chapter 3

Example

The following detailed example shows how to look at and understand Reliability-based DGA results in TOA. Here R-DGA reveals a serious transformer problem that was overlooked by conventional DGA. The transformer is a 230 kV, 250 MVA nitrogen-blanketed unit manufactured in 1982.



3.1 Equipment list - R-DGA status

First Row: 1 | Rows to Show: 20 | Records: 1 | Sort: Assessment | Columns: R-DGA status

|<< | < | > | >>|

	Equip Num	S/N	Apprtype	Substation	Desig	Last DGA sample	DGA	Gassing	HF %	Sev %	FT	Event	RCOR %
**	EXAMPLE-TL12	EXAMPLE-TL12	TRN	EXAMPLE	TL12	2010-08-18	1/1	3	0.13	0.70	T1	CO	

Figure 1: TOA Online Equipment List with example transformer shown.

The TOA Equipment List has a “Columns” selection, “R-DGA status,” that adds some additional information to that displayed in the “DGA status” and “Review new data” views of the equipment list.

This item in the equipment list has a gassing status of 3 (recent fault gas production), even though the conventional DGA result is 1/1, i.e. 1 (unexceptional) previously and still 1 as of the latest sample – no conventional DGA limits have been exceeded.

The recent gassing is in the form of an upward trend in NEI-CO, the carbon oxide gas fault energy index. The severity (Sev%) is 0.70%, meaning that 7 out of 1000 transformers (on average) would fail during similar gassing. The hazard factor (HF%) of 0.13 percentage points per year means that continued gassing will add about 1.3 per thousand transformers to the severity per year. The apparent fault type is T1, overheating below 300 degrees Celsius. Does this seem like it should be ignored? Perhaps not. To open the R-DGA report, you could click the “3” under “Gassing.”

3.2 R-DGA report - diagnostic overview

Read the “Reliability-based DGA diagnosis” text below (Figure 2) to get the bottom-line conclusion of the report. In this example, it is short and undramatic. Apparently, some paper insulation is being cooked.

Reliability-based DGA Diagnosis

Recent fault gas production (gassing status 3). Recent carbon oxide gas production suggests thermal stressing of paper insulation.

Figure 2: Diagnostic remarks in R-DGA report

The R-DGA summary just below the diagnostic text in the report provides a compact overview of the results, the most important of which we have already seen in the equipment list. See Figure 3.

Reliability-based DGA Summary

DGA last date	2010-08-18	Event Summary	nei_co+
DGA samples	27	Cumulative sev liquid %	0.00
Gassing events	6	Cumulative sev paper %	1.11
Event fault type	N/A	Gassing status	3
Hazard factor %	0.18		

Figure 3: Summary of results in R-DGA report.

We have DGA data for this transformer starting in May 1994. From then until August 2010, the DGA results seem pretty unexceptional by conventional standards, not budging above IEEE status code 1. As Figure 4 shows, the CO_2 concentration bounced around a bit, averaging about 4000 μL/L, while CO remained low but also varied. There were three occasions when hydrogen, methane, or ethane had a large increment, although no limits were exceeded. Figure 5 shows that hydrogen and the hydrocarbon gases stayed low but varied quite a bit.

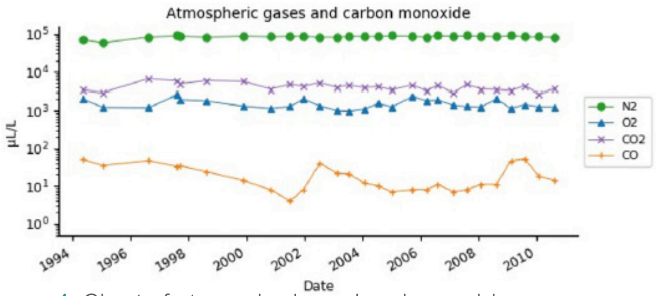


Figure 4: Chart of atmospheric and carbon oxide gases.

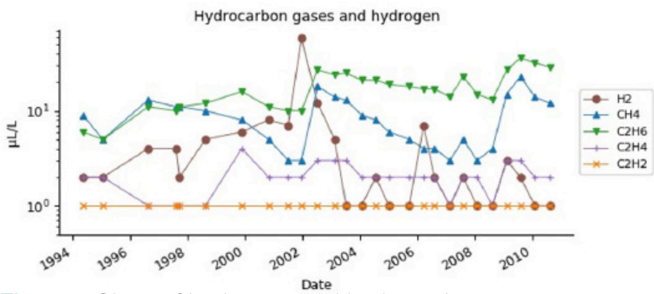


Figure 5 Chart of hydrogen and hydrocarbon gases.

The gassing event charts for NEI-HC and NEI-CO (see Figure 6) are usually the most important and informative part of the R-DGA report, and in this example they illustrate the usefulness of using cumulative fault energy indexes for DGA trending. The gray crosses represent the NEI values calculated from raw data, while the black line is the result of smoothing and accumulation. For both NEI-HC and NEI-CO, the cumulative graphs reveal that gas loss has been concealing long-term upward trends, i.e., fault gas production.

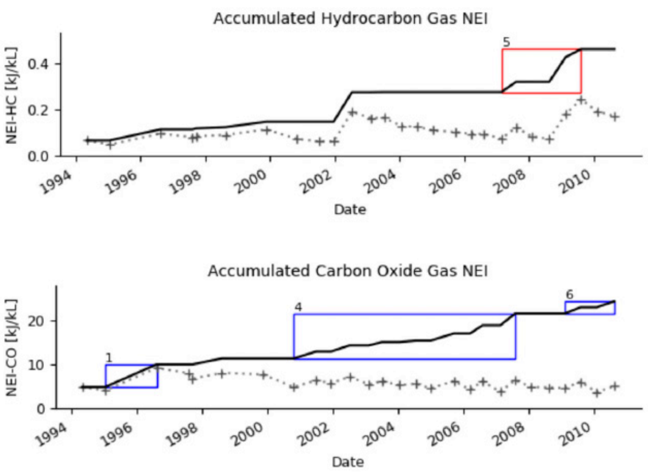


Figure 6: Fault energy index charts with gassing events indicated by colored boxes.

According to the dissolved-gas data shown in the report, the O2/N2 ratio is consistently well below 0.1, suggesting that there is no gas leak or sampling problem. The transformer is nitrogen-blanketed, so evidently gas loss in this case is due to pressure relief head space gas expulsion.

In both NEI gassing event graphs, colored boxes mark gassing events – episodes where an upward trend results in a significant increase in NEI-CO or NEI-HC. In general, some gassing events may coincide with overloading, and in other cases the onset of a gassing event may coincide with a traumatic incident such as a through fault. In this example no information is available to identify possible external reasons for fault gas production.

Figure 7 is the events table from the report. Numbers in the ID column of the table correspond to the numbers above the gassing event boxes on the graphs. Event types CO and HC correspond to boxes in the NEI-CO and the NEI-HC graphs, respectively. Event type R corresponds to event boxes in the graph of the CO/CO2 ratio, not shown because for this example those events are not very interesting.

ID	Event	Event start	Start value	Inc	Days	Samples	FT	RCOR %	Sev %	HF %
1	CO	1995-01-16	4.795	5.142	576	2	S		0.11	0.11
2	R	2001-07-02	0.005	0.002	374	3	O	45		
3	R	2003-07-10	0.006	0.002	545	4		35		
4	CO	2000-10-27	11.286	10.200	2474	14	O		0.68	0.11
5	HC	2007-02-21	0.275	0.186	897	6	O		0.08	0.03
6	CO	2009-02-11	21.487	2.757	553	4			0.26	0.18

Figure 7: Table describing gassing events.

Event fault types are indicated in column FT. Fault type S is said to represent stray gassing, but in our experience it more often seems to indicate T1. Fault type O designates a thermal fault that can be regarded as a mild T1 – temperatures below 250 degrees C instead of 300 degrees C. The S and O fault types belong to a supplementary Duval triangle for low-energy thermal faults (not shown). In the classic Duval triangle (Figure 8), each cross represents a gassing event, with the red one being the most recent, event 6. The indicated fault type for all the events is T1.

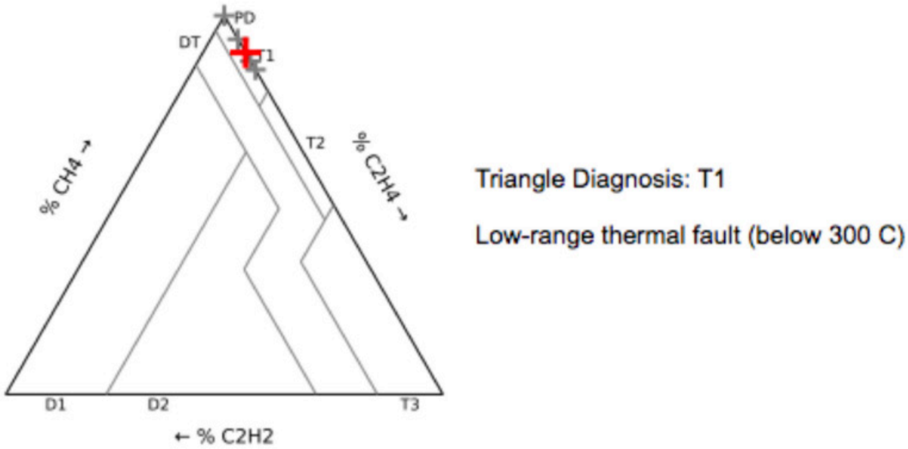


Figure 8: Duval triangle with one point plotted for each event having a fault type.

The probability density graphs (Figure 9) near the top of the R-DGA report can now be explained. The curves are the probability density curves for the distributions of NEI-HC and NEI-CO just before transformer failure. Annotations to the curves compare the example transformer's gassing to the statistical model. The gray area indicated under each curve represents cumulative severity of the transformer's gassing, and the red arrow pointing to the right represents the hazard factor.

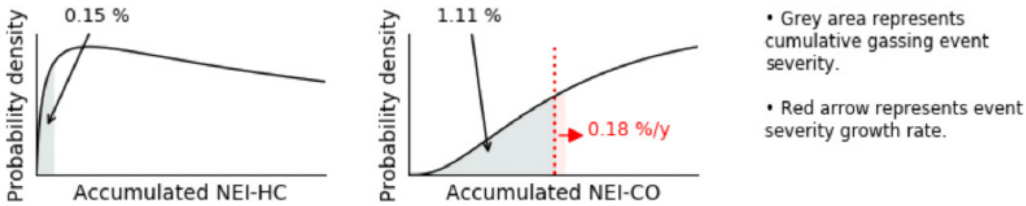
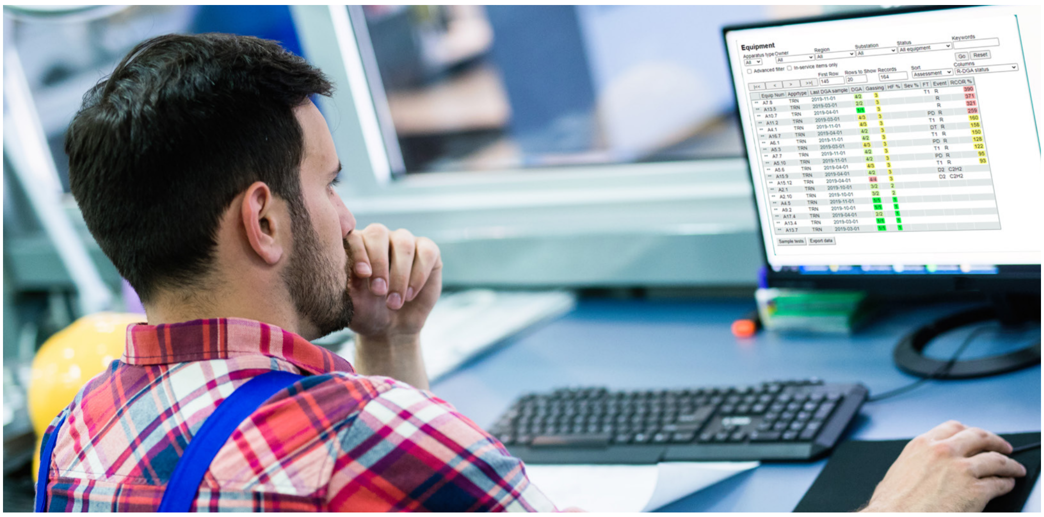


Figure 9: Probability density graphs comparing the example transformer's gassing to the statistical model.

The NEI-CO cumulative severity of 1.11% means that (according to the model) on average 11.1 out of 1000 transformers would fail before reaching the NEI-CO level of the example transformer. The NEI-CO hazard factor of 0.18 percentage points per year indicates that about 1.8 additional ones out of 1000 transformers gassing similarly to the example transformer would fail per year. While such numbers do not suggest an emergency, they do indicate the existence of a problem that poses an increasing risk of failure and therefore should not be ignored. While this large transformer continues to cook its insulation paper, the dice are being rolled.

This transformer failed seven months after the last sample shown here with turn-to-turn arcing. The post-mortem inspection revealed extensive charring of winding insulation paper and clamping plate pressboard.



Chapter 4

Questions

4.1 What should be done for “under the radar” cases?

In cases such as the example presented in Section 3, where Reliability-based DGA classifies a transformer as abnormal because of recent fault gas production that has low severity and HF, especially if conventional DGA does not identify the transformer as abnormal, what is the appropriate follow-up? Neither Delta-X Research nor its software TOA provides direct advice on transformer operation and maintenance, but in answer to this question we can point out some reasonable generalities.

- Each case must be evaluated on the basis of all available relevant information, not just DGA.
- Any active fault gas production is, by the Fundamental Principle of Transformer DGA, abnormal and undesirable and, according to our statistical analysis, risky. Understanding the origin and cause of the gassing (say, by electrical testing and IR scanning) may help to quantify the risk beyond what R-DGA is able to do.
- If the indicated problem (such as chronic T1 heating) cannot in some way be mitigated or eliminated as a concern, increased DGA sampling frequency or online monitoring (with either a hydrogen or a multi-gas monitor) could help to manage the risk of the problem worsening.

4.2 Does the R-DGA statistical model have to be recalculated for my transformers?

No. Derivation of the model requires a very large database of transformer DGA and failure data. The current R-DGA statistical model is based on DGA histories and failure data from significant transformer populations provided by some of our customers. It is not subdivided with regard to transformer size, age, loading, or other properties, so it represents “power transformers in general”. This model performed extremely well when it was used to assess DGA data for transformers of a major electric utility that did not contribute to the initial research data set. When we have collected sufficient additional data, we will investigate whether separate statistical models are useful for specific transformer types and sizes.

4.3 Does R-DGA replace the Duval triangle?

No. R-DGA is not a method for fault type identification. It is all about:

- Determining whether the transformer is or has been producing fault gas; and
- If so, providing a numerical estimate of the associated risk.

In TOA, both conventional DGA and R-DGA use the Duval triangle, if there is evidence of fault gas production, to determine what kind of fault seems to be producing the gas.

4.4 Does R-DGA work for transformers with alternative insulating liquids? LTCs?

For now we are providing R-DGA only for transformers filled with mineral oil. Because the “classic” Duval triangle based on methane, ethylene, and acetylene required only minor alterations for application to transformers using ester and silicone insulating liquids, it appears that those gases play approximately the same role for esters and silicone as for mineral oil, in which case R-DGA based on NEI-T (methane, ethylene, and acetylene) should work pretty well for those alternative liquids. To apply R-DGA fully to each of the alternative liquids, however, a large amount of DGA and failure data must be collected, and then more research will be needed.

It is known that gassing behavior can differ greatly between LTC models and even between populations of the same model due to differences in operating frequency, loading, and maintenance practices. These and other complications make it very impractical to apply the statistical method of R-DGA to LTCs, although some other elements of R-DGA, such as the use of energy indexes, may turn out to be useful.

References

[1] "IEEE guide for the interpretation of gases generated in oil-immersed transformers," IEEE Std C57.104-2008 (Revision of IEEE Std C57.104-1991), pp. 1–36, Feb 2009.

[2] Mineral oil-filled electrical equipment in service – Guidance on the interpretation of dis- solved and free gases analysis, 3rd ed. International Electrotechnical Commission, Sep 2015, no. IEC 60599-2015-09.

[3] F. Jakob and J. J. Dukarm, "Thermodynamic estimation of transformer fault severity," IEEE Transactions on Power Delivery, vol. 30, no. 4, pp. 1941–1948, Aug 2015.

[4] ASTM, Standard Test Method for Analysis of Gases Dissolved in Electrical Insulating Oil by Gas Chromatography. ASTM International, 2017, no. ASTM D3612-02(2017).

[5] J. J. Dukarm and M. Duval, "Transformer reliability and dissolved-gas analysis," in 2016 CIGRE Canada Conference, no. CIGRE-807, Vancouver BC, Oct 2016.

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