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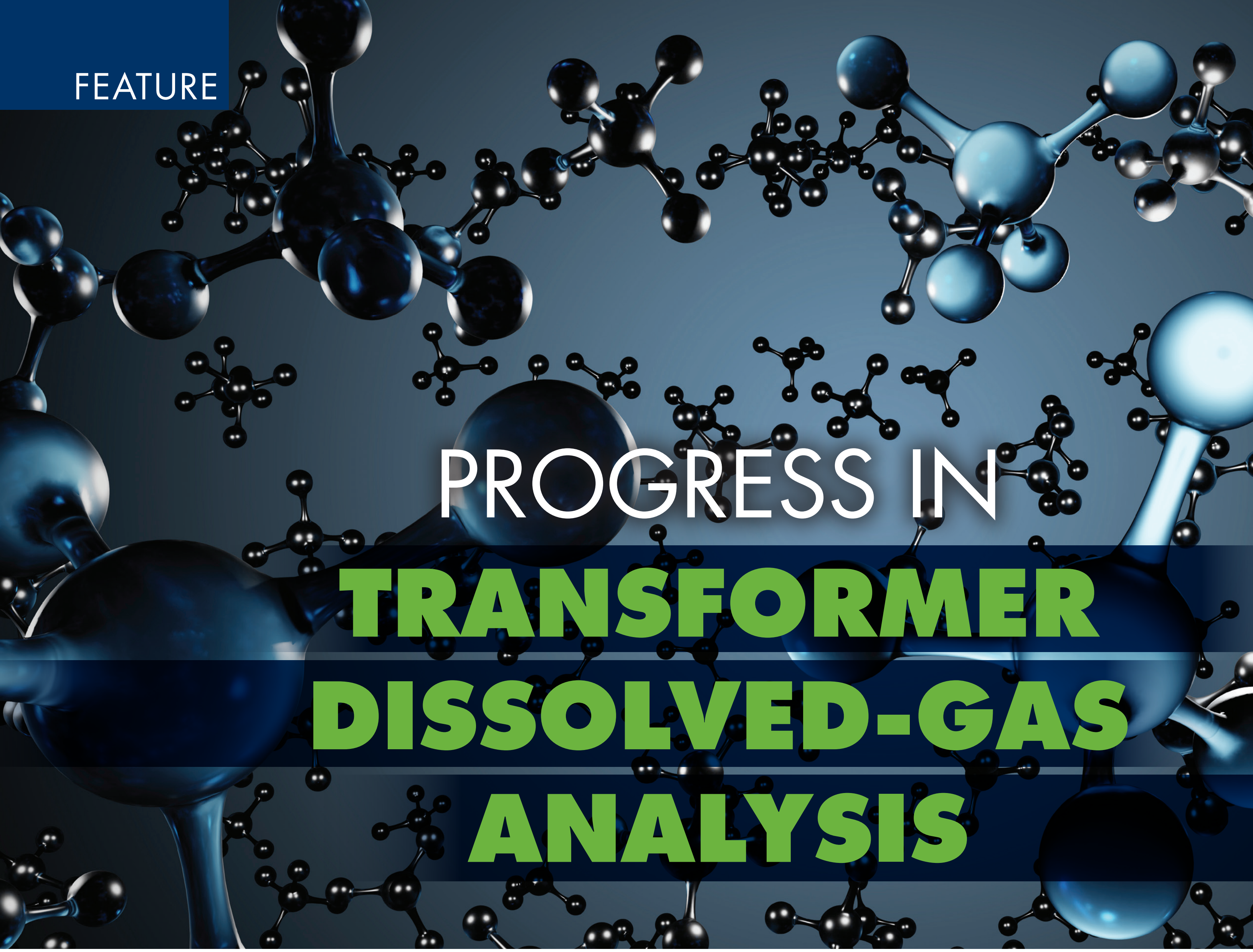
FEATURE



PROGRESS IN TRANSFORMER DISSOLVED-GAS ANALYSIS

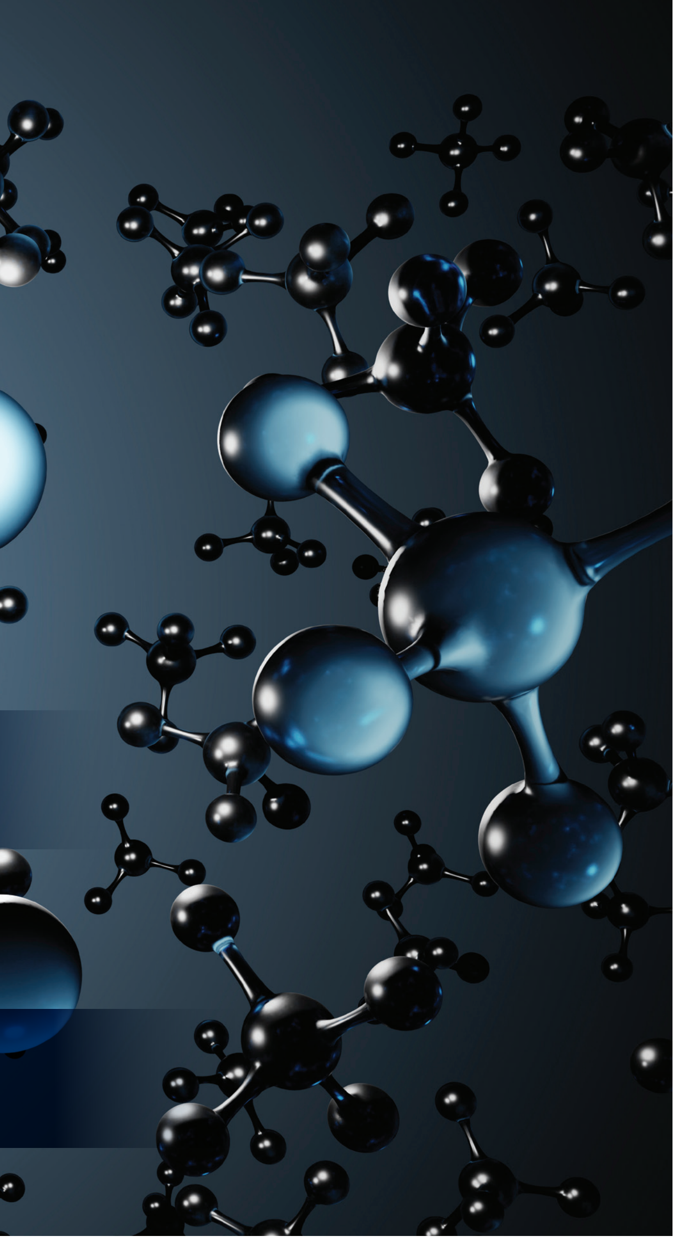
BY JAMES J. DUKARM, *Delta-X Research Inc.*

Dissolved-gas analysis started out many years ago as a quick and simple test: Someone in the substation would briefly open a valve and sniff the transformer's head-space gas. The pungent odor of a trace of acetylene would signify a potentially serious problem.

By the late 1960s, it was possible to use a gas chromatograph as a much more sensitive nose for sniffing transformer oil. Pioneers such as R. R. Rogers and E. Doernenburg realized that the fault gases in oil came from breakdown of the solid and liquid insulation and intuitively understood the Fundamental Principle of Transformer DGA (sidebar). They collected DGA data and came up with ideas for (a) detecting problems, (b) assessing their severity, and (c) identifying the general nature of the problem.

The Fundamental Principle of Transformer DGA

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



To detect problems, gas concentration and rate of increase limits were developed based on the reasonable assumption that an unusually high fault gas concentration or rate of change should be a sign of trouble. To assess severity, additional limits and considerations of rates of increase were employed to get a grade-school report card result of OK, so-so, or bad, expressed in North America as numeric condition code scores from 1 (OK) to 4 (terrible). The limits-based approach to DGA interpretation has been refined over the years, and the IEEE C57.104 and IEC 60599 gas guides are considered the authoritative sources on how to apply it. Those guides include the gas ratio methods for fault type identification developed by Doernenburg, Rogers, Duval, and others. A good summary of limits-based DGA interpretation was published by Hamrick in *NETA World*.

Building on five decades of industry experience and data collection, plus the wide availability of computers, a re-examination of transformer DGA from the point of view of physical chemistry and advanced statistics is breathing new life into the subject. This article describes important advances. An example shows how they can improve fault detection and provide new risk assessment information.

RECENT INNOVATIONS IN DGA

Since about 2014, several innovations have increased the usefulness and effectiveness of DGA interpretation.

- **Accounting for gas loss.** Gas loss — whether by design or by accident such as leakage through a bushing gasket or air exposure of a DGA sample — can be a serious problem for DGA interpretation, especially when based on gas concentration and rate of change limits. It is helpful to work with cumulative data to avoid overlooking serious problems.
- **Fault energy indexes for trend detection and severity assessment.** It is known that some fault gases are more significant than others. For example, ethylene and acetylene are associated with extremely high temperature faults. The physical basis for the differing significance of fault gases is their heats of formation from solid or liquid insulation. Those heats of formation, weighted by the respective gas concentrations in oil, can be used to calculate normalized energy intensity (NEI) for fault energy indexes to use for trending, fault detection, and severity assessment.
- **Focus on gassing events.** Concentrating on time intervals in which a fault energy index is trending upwards (boxed intervals

in Figure 4 and Figure 5) is a natural and very useful way to look at fault gas production.

- **Gassing status score based on the Fundamental Principle of DGA.** The fundamental principle of DGA provides a natural basis for ranking transformers according to their apparent need for extra attention. The transformer has either been gassing recently or not, and where there is gassing, it is either more or less severe (gassing status sidebar).

Gassing Status

1. No significant fault gas production ever
2. Some fault gas production, but not recently
3. Recent moderate fault gas production
4. Recent extreme fault gas production

- **Gas increments over gassing events for fault type identification.** The Duval triangle (Figure 6) is a very good method for fault type identification. When trying to identify the cause of fault gas production during a gassing event, don't use gas concentrations, which include possibly irrelevant pre-event gas. Instead, use gas increments calculated between the earliest and latest oil samples in that time interval.
- **Percent change in the CO/CO_2 ratio for locating paper degradation.** The carbon oxide gas ratio can be used to estimate the approximate location of a fault affecting paper insulation. It also sometimes gives early warning of a developing problem. A strong increase (by 200% or more) suggests a hot spot affecting winding insulation. A smaller increase suggests that paper insulation outside the windings, such as on bushing or LTC leads, may be affected. A decrease may indicate CO_2 production due to general low-range overheating of paper insulation.
- **Reliability statistics relating DGA results to transformer failure.** Instead of assessing severity in terms of limits exceeded, use a statistical model of the fault energy index distribution in transformers about to fail to estimate prior risk exposure and risk of near-term failure.

RELIABILITY STATISTICS IN DGA

The statistical model referred to in the previous paragraph shows the distribution of fault energy index values in gassing transformers that are about to fail. The models (one for each fault energy index) were derived from a large DGA database with additional information about transformer failures. The information provided by the model of the failure-related values of the hydrocarbon gas fault energy index (NEI-HC) is summarized by the failure rate graph shown in Figure 1. The four vertical dotted lines represent (left to right) the 90th, 95th, 98th, and 99th percentiles of cumulative hydrocarbon gas fault energy index (NEI-HC) in a large DGA database. The peak failure rate occurs at about the 82nd percentile, well below

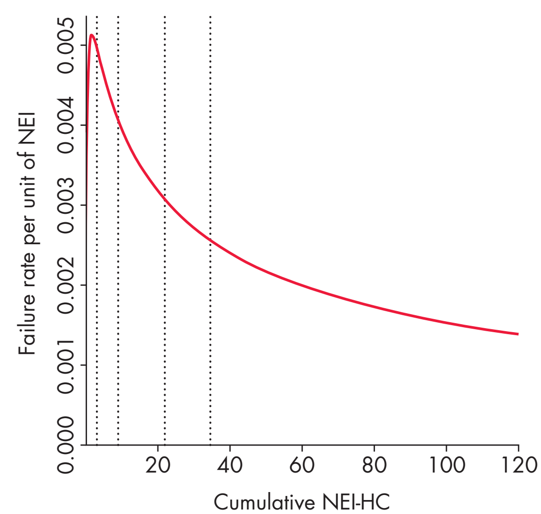


Figure 1: *The curve shows transformer failure rate (fraction of surviving population) as a function of the cumulative hydrocarbon gas fault energy index (NEI-HC). Vertical dotted lines represent the 90th, 95th, 98th, and 99th percentiles of cumulative NEI-HC in a large DGA database.*

the 90th percentile, suggesting that waiting for something to exceed the 90th percentile before investigating may not be a good idea!

If a transformer with very little fault gas begins to produce hydrocarbon fault gas, it should raise immediate concern since the associated failure risk is increasing very steeply. As NEI-HC increases further, the failure rate decreases, indicating that — contrary to how higher DGA limits are often interpreted — continued gassing does not necessarily imply worsening reliability. This means that either:

a. Whatever is causing the gassing is not very harmful to the transformer and may continue indefinitely; or

b. The transformer is gassing because it is damaged or defective, and the next through fault may kill it; or

c. Something between the extremes of (a) and (b) is going on.

CASE STUDY

The new DGA approach using reliability statistics was evaluated on 7200 transformers in 2016 by a large US electric utility. It performed so well, identifying many previously undetected serious problems, that the utility immediately adopted it as a key part of its transformer condition assessment system.

To see how the innovations mentioned above improve DGA for oil-filled transformers, consider the example of a 250 MVA 230 kV nitrogen-blanketed transformer manufactured in the early 1980s. The transformer's fault gas levels were unexceptional, except for a persistently high CO_2 concentration averaging about 4200 ppm. One day in 2011, the transformer experienced turn-to-turn arcing and was removed from service. A post-mortem surprisingly revealed very extensive charring of winding insulation paper and pressboard spacers, suggesting that the windings had been overheating for a long time.

The problem had gone unnoticed for years because periodic gas expulsion by the head space nitrogen pressure regulation system had prevented upward trends in heat gases (methane, ethane, and ethylene) from developing. Except for the consistently high CO_2 levels, no gas concentration or rate of change limits were ever exceeded until the day the transformer failed.

Figure 2 shows that the transformer's hydrogen and hydrocarbon gas concentrations were consistently low to moderate with a lot of bumps. Methane and ethane increased in 2008–2009, but no limits were exceeded. Those upward trends were reversed in 2009–2010.

Figure 3 shows that oxygen and CO_2 levels were consistent with some ups and downs. The average CO_2 concentration was about 4200 ppm. CO concentration was variable and always lower than 60 ppm. Nitrogen

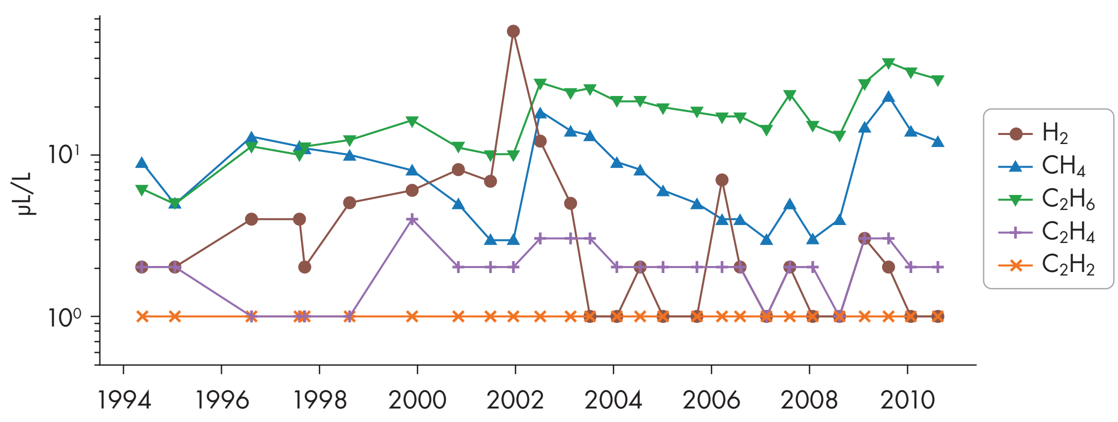


Figure 2: *Hydrogen and Hydrocarbon Gas Concentrations*

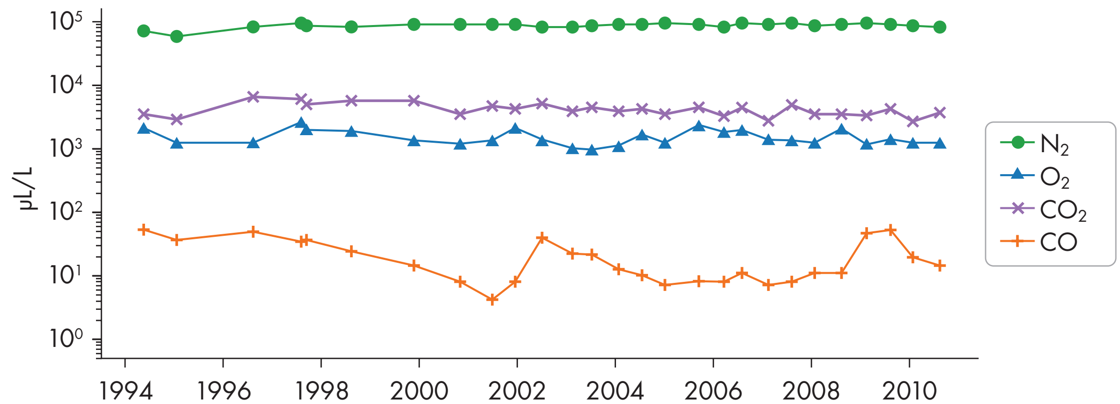


Figure 3: *Atmospheric and Carbon Oxide Gas Concentrations*

was consistently very high, as expected in a nitrogen-blanketed transformer.

As Figure 2 and Figure 3 illustrate, it can be difficult to understand what is happening by trending and assessing multiple fault gases. On the other hand, fault energy indexes — one for the oil and one for the paper insulation — show when significant fault gas is produced and provide a sound basis for assessing severity. Compare Figure 4 and Figure 5 with Figure 2 and Figure 3.

Figure 4 and Figure 5 show how long-term fault gas production is revealed by:

a. Using cumulative data to compensate partially for gas loss

b. Trending fault energy indexes

The raw (non-cumulative) values of the fault energy indexes are shown as gray plus (+) signs, while the cumulative values are plotted as a solid line. Boxed intervals on the accumulated

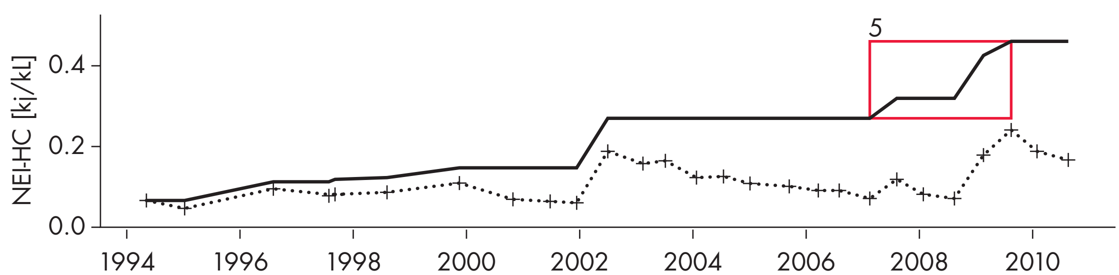


Figure 4: *The heavy black line represents the hydrocarbon gas fault energy index (NEI-HC) calculated from cumulative gas concentrations. The dotted line with plus symbols represents NEI-HC calculated from raw gas concentrations.*

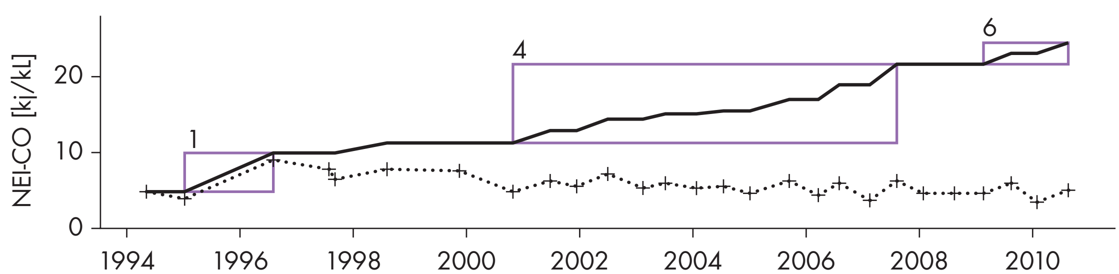


Figure 5: *The heavy black line represents the carbon oxide gas fault energy index (NEI-CO) calculated from cumulative gas concentrations. The dotted line with plus symbols represents NEI-CO calculated from raw gas concentrations.*

fault energy index graphs represent gassing events or time intervals when there appears to be active fault gas production. Clearly, the upward trends in both cumulative hydrocarbon gas NEI and cumulative carbon oxide gas NEI would be difficult to notice by looking at the spaghetti graphs in Figure 2 and Figure 3 or the raw numbers from the lab reports. Because there is evidently moderate ongoing carbon oxide gas production as of the latest sample, the gassing status of this transformer would be 3.

For each of the gassing events indicated in Figures 4 and 5, increments of methane, ethylene, and acetylene during the event are used to plot a point on the Duval triangle (Figure 6), with the most recent result plotted as a red plus sign. The apparent fault type is consistently T1 — a thermal problem at less than 300° Celsius.

What about the CO/CO_2 ratio? In a transformer without gas loss, extensive charring of winding insulation would be expected to cause a large increase (by more than 200%) of the CO/CO_2 ratio due to rapid production

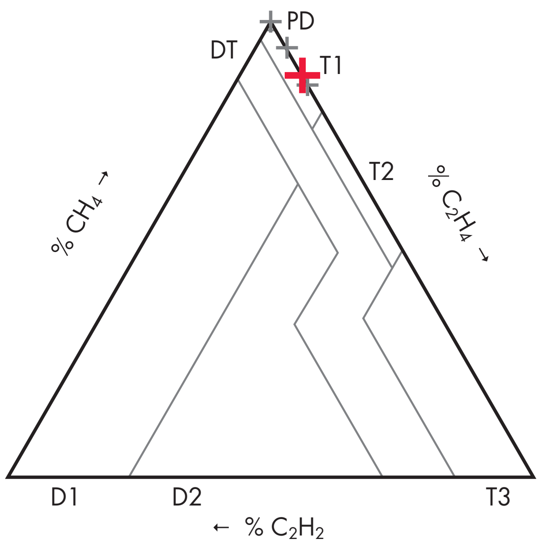


Figure 6: *Duval Triangle. Each plotted cross is based on the increments (amounts of increase) of methane, ethylene, and acetylene during a gassing event. The red plus sign represents the most recent gassing event. A persistent T1 thermal fault (below 300° Celsius) is indicated.*

of CO. The subject transformer's reported CO concentration was consistently very low, however, and the CO/CO_2 ratio based on cumulative gas concentrations remained near 0.008 with very little variation. That could be explained by loss of CO as fast as it was produced; due to the low solubility of CO in oil, most of the CO in the oil migrated to the head space, where it was expelled by frequent pressure regulation gas release. The lack of any warning of winding insulation deterioration by the CO/CO_2 ratio in this case is an example of the potentially serious impairment due to gas loss of DGA's sensitivity to faults, even when the gas loss is partially compensated for by the use of cumulative data.

The overall conclusion of this analysis using recent improvements in DGA is that, in spite of very significant gas loss due to headspace pressure regulation, this transformer's abnormal fault gas production could have been detected several years before failure, raising the transformer's gassing status to 3 and providing an opportunity for investigation and possible mitigation of the thermal problem or at least planning for eventual replacement of the transformer. The application of DGA limits without consideration of gas loss failed to detect that the transformer had a problem.

The quantitative statistical results as of August 2010 (seven months before failure) show a 1.1% probability of failure with NEI-CO below 24.2, meaning that about 11 transformers out of a thousand would have failed at a lower level of cumulative NEI-CO. The hazard factor or estimated time-based failure rate as of that time was 0.18% per year, calculated by multiplying the NEI-CO model's failure rate (0.1% per NEI unit) times the most recent rate of increase of NEI-CO (1.8/year). These statistics indicate that the observed fault gas production to date, underestimated by an unknown amount due to gas loss, represents a modest amount of risk exposure, with that risk continualy increasing. Whether those results alone would have enabled the utility to avoid failure of the transformer is questionable; however, with fair warning that the dice were being rolled, it would have been possible to prepare for eventual replacement, and the eventual failure would not have been surprising.

CONCLUSION

This analysis does not and cannot take into account the unknown amount of gas that was lost and never measured, so the severity and risk level are understated to an unknown degree. The new approach, however, could have led to early discovery that the transformer was gassing and that — as suggested by very low hydrogen and CO levels — gas loss could be masking the problem. Perhaps the pressure regulation system could have been locked down at that time to stop gas expulsion long enough to obtain a more accurate assessment of fault gas production, CO/CO_2 trend, and the associated hazard factor.

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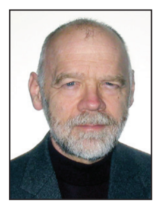

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