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TRANSFORMER CONDITION ASSESSMENT EXPERIENCES USING AUTOMATED ON-LINE DISSOLVED GAS ANALYSIS

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SUMMARY

Automated on-line monitoring of individual dissolved gases is now a reality. Although it has been a long time coming, 24 x 7 Green-Yellow-Red condition assessment's time has come, logically starting at power plants where "non-redundant" GSU transformers are vital in delivering the power plant's product. Critical system-tie autotransformers and phase-angle-regulators are close behind. The 50 years experience with laboratory dissolved gas analysis (DGA) tends to be considered a baseline, however the dynamic behavior of dissolved gases requires continuity & trending unlikely to be captured through periodic manual sampling. Automated on-line DGA brings opportunities for new experiences, learning, & knowledge vital to take full advantage of the information the gases can provide to understand what is happening inside a transformer. Examples are presented showing dynamic loading and other effects. Special attention is given to on-line DGA data from an operating GSU transformer that failed 3 weeks after the application of recent & recently-proposed diagnostic methods would have provided three confirming indicators of a serious problem, whereas existing industry DGA guidelines would not.

KEYWORDS

Power transformer – Dissolved gas analysis – On-line DGA – Cellulose degradation – AC voltage breakdown – Failure prediction – Condition assessment - Reliability

1. 500 kV Single-Phase FOA Autotransformer (Sealed Conservator)

"Hot-metal" gases have accumulated since last de-gassing. Ethylene, methane, along with traces of acetylene, appear to increase during loading above 50% of nameplate and diminish as loading drops off (S*table & Green)* as shown on the "3 Months" chart in figure 1. (*LoadGuide*® charts data from a current transformer; magnitude varies for individual installations depending upon the transformer's CT ratio plus loading.) The "hot-metal" gassing is believed to be associated with circulating currents in the core support structure. In this example, top-oil passes through the analyzer and returns at the bottom of the transformer.

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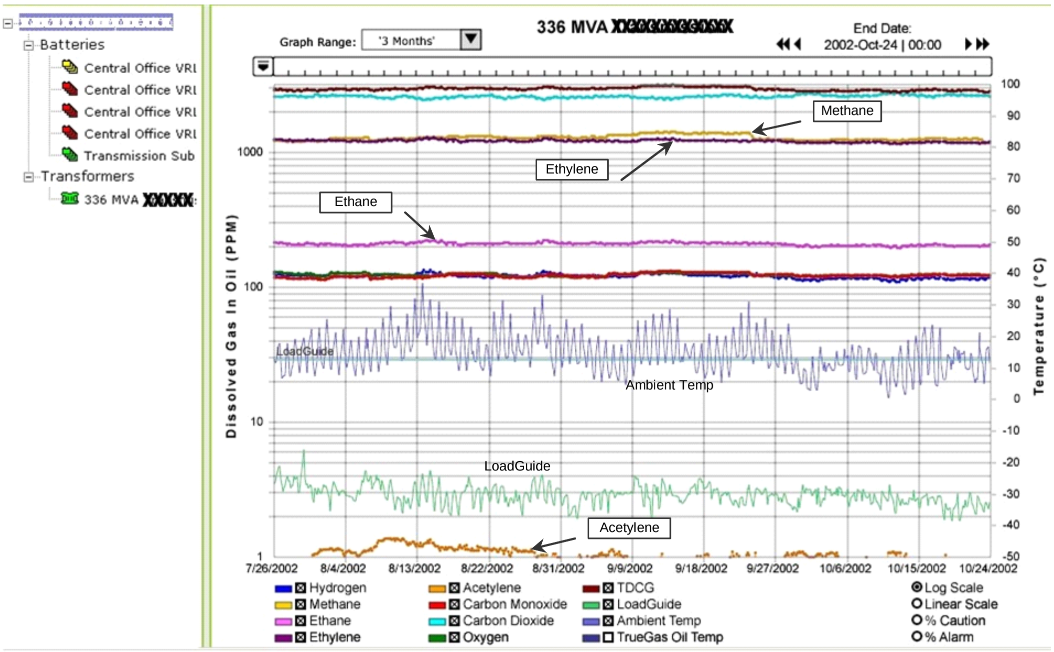

Figure 1: 500 kV Autotransformer individual gas ppm on log scale 3-month chart (selectable)

Higher resolution of the individual gases can be seen from the *% Caution* (or *% Alarm*) "1 Week" chart shown in figure 2. Caution for acetylene is set at 2 ppm (Alarm at 5 ppm), so ppm shown varies from 0.4 to 1.4 ppm. Caution & Alarm limits can be set at ppm increments, such as 25/50 ppm ethylene above an accumulated level such as 1300 ppm shown here, to react to new events. *Events generate "ppm increases", not "% increases".*

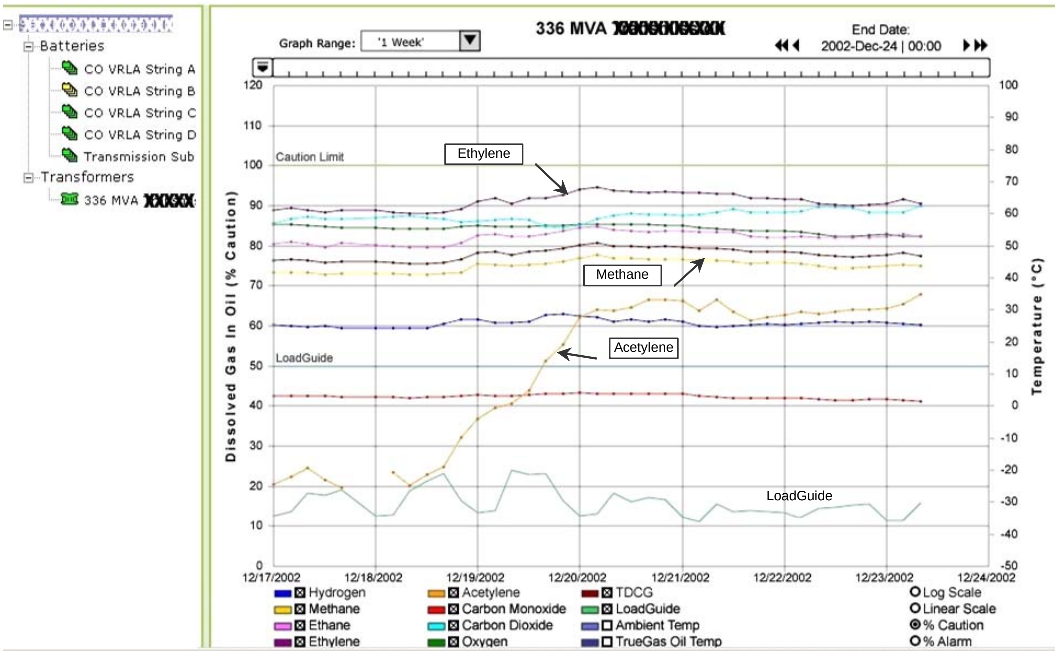

Figure 2: 500 kV Autotransformer gases shown as % of Caution limits (individually selectable)

It appears small ppm increases in ethylene, methane, ethane & hydrogen drop back as gases distribute throughout the oil volume. However with time, gases including acetylene seem to disappear. Where do they go? Are some absorbed into the paper insulation as some people believe? Close watching after degassing could provide some clues. Acetylene peaked August 9th at 1.4 ppm (hydrogen, methane & ethane also peaked) and then gradually diminished to 0.4 ppm in November/December.

Ethylene peaked at 1298 ppm August 14th and dropped back to about 1160 ppm 4 months later (as shown in the tabulated data in figure 3).

Sample Time	H2	CH4	C2H6	C2H4	C2H2	CO	CO2	O2	T(amb)	T(tgo)	TDCG
2002-Aug-14 20:00	130	1305	224	1288	1.3	120	2515	122	22	40	3068
2002-Aug-14 16:00	136	1297	221	1280	1.3	120	2454	122	32	49	3055
2002-Aug-14 12:00	130	1303	219	1260	1.3	119	2494	122	29	46	3033
2002-Aug-14 08:00	129	1308	224	1286	1.3	120	2521	123	23	39	3069
2002-Aug-14 04:00	130	1304	226	1298	1.3	119	2504	122	17	40	3078
2002-Aug-14 00:00	130	1304	224	1289	1.3	119	2470	123	21	42	3068
2002-Aug-09 20:00	126	1259	217	1241	1.4	116	2523	123	23	40	2961
2002-Aug-09 16:00	126	1255	215	1236	1.4	118	2529	123	30	45	2951
2002-Aug-09 12:00	125	1256	213	1226	1.4	118	2533	124	24	39	2939
2002-Aug-09 08:00	123	1265	215	1238	1.4	118	2565	124	17	33	2961
2002-Aug-09 04:00	125	1271	215	1244	1.4	119	2535	125	11	35	2975
2002-Aug-09 00:00	126	1266	215	1240	1.4	118	2533	125	15	39	2967

Sample Time	H2	CH4	C2H6	C2H4	C2H2	CO	CO2	O2	T(amb)	T(tgo)	TDCG
2002-Dec-06 20:00	112	1127	209	1175	0.4	125	2578	121	-0.8	27	2748
2002-Dec-06 16:00	113	1125	206	1165	0.4	125	2590	121	5.2	30	2735
2002-Dec-06 12:00	112	1119	205	1154	0.4	125	2598	121	6.8	29	2716
2002-Dec-06 08:00	111	1125	206	1161	0.5	125	2611	121	-1.4	25	2728
2002-Dec-06 04:00	112	1128	210	1174	0.4	125	2587	122	-2.2	24	2749
2002-Dec-06 00:00	113	1130	210	1180	0.5	126	2566	122	-2.4	26	2759
2002-Dec-05 20:00	114	1131	210	1175	0.4	126	2562	122	-0.6	29	2757
2002-Dec-05 16:00	113	1120	206	1155	0.5	126	2557	122	4.2	30	2721
2002-Dec-05 12:00	112	1117	205	1153	0.4	125	2562	121	7.6	30	2714
2002-Dec-05 08:00	112	1116	203	1148	0.5	125	2572	121	2.8	29	2706
2002-Dec-05 04:00	112	1115	205	1152	0.4	125	2589	121	2.8	28	2709
2002-Dec-05 00:00	112	1108	204	1149	0.5	124	2591	121	1.9	27	2698

Figure 3: 500 kV Autotransformer gas and temperature data at 4-hour intervals

2. 230 kV Three-Phase FOW GSU Transformer (sealed conservator)

Accumulated "hot-metal gases. Ethylene, methane & ethane, along with traces of acetylene, increased rapidly until mid-October as shown on "1 Month" chart in figure 4. *Oil Temp* displayed in this chart is sensed as oil from the transformer passes through the analyzer, in this case from a valve at the transformer base returning to another valve near the base.

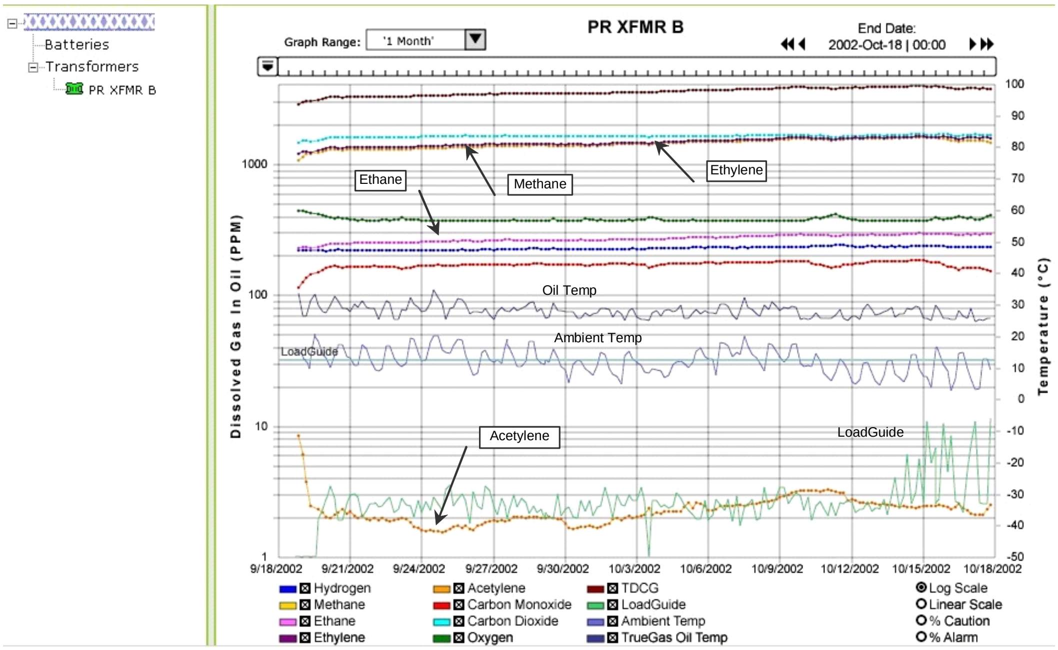

Figure 4: 230 kV GSU Transformer individual gas ppm on log scale 1-month chart (selectable)

The transformer is loaded from 2 generators connected to 2 LV windings. Only one was loaded until mid-October. Daily loading varies very widely. Gassing appears somewhat more severe when a single LV winding is loaded as can be seen more clearly from TDCG on the *Linear* chart in figure 5.

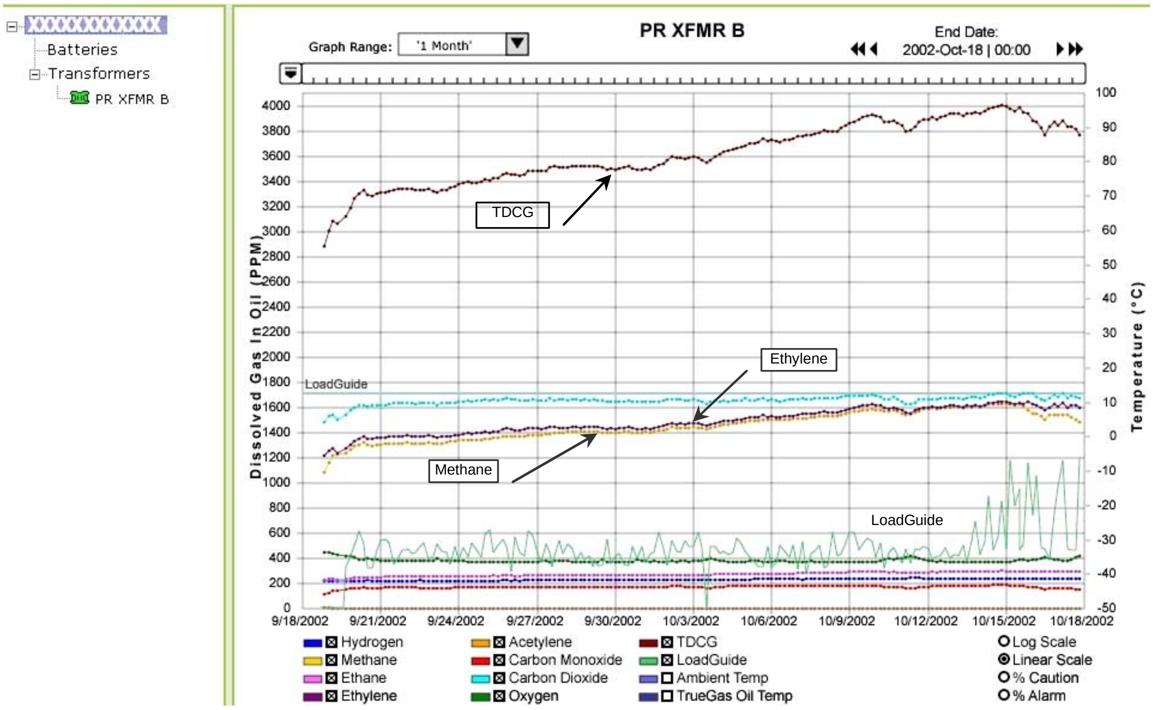

Figure 5: 230 kV GSU Transformer individual gas ppm on linear scale 1-month chart (selectable)

Sample Time	H2	CH4	C2H6	C2H4	C2H2	CO	CO2	O2	T(amb)	T(tgo)	TDCG
2002-Oct-09 20:00	236	1592	295	1624	3.3	182	1702	372	11	26	3932
2002-Oct-09 16:00	236	1582	293	1620	3.2	183	1694	372	18	29	3917
2002-Oct-09 12:00	237	1578	293	1619	3.1	183	1690	372	18	30	3913
2002-Oct-09 08:00	236	1568	292	1610	3	183	1692	372	14	29	3892
2002-Oct-09 04:00	237	1567	291	1594	3	183	1694	372	12	30	3875
2002-Oct-09 00:00	236	1559	291	1588	2.9	183	1693	372	14	28	3859

Figure 6: 230 kV GSU Transformer gas and temperature data at 4-hour intervals

As can be seen from the chart in figure 6, ethylene & methane increased 36 & 33 ppm respectively in 20 hours October 9th while only one LV winding was loaded (*Unstable & Red)* at that time. The "hot-metal" gassing appears similar to the first example (same manufacturer), and may be caused by circulating current in the core clamping structure. Gassing started dropping with loading on both LV windings, (*Stable & Green)* as shown in figure 5.

The "1-week" snapshot in figure 7 shows this transformer generating C2H4 at less than 1/10th this rate in December when both LV windings are loaded.

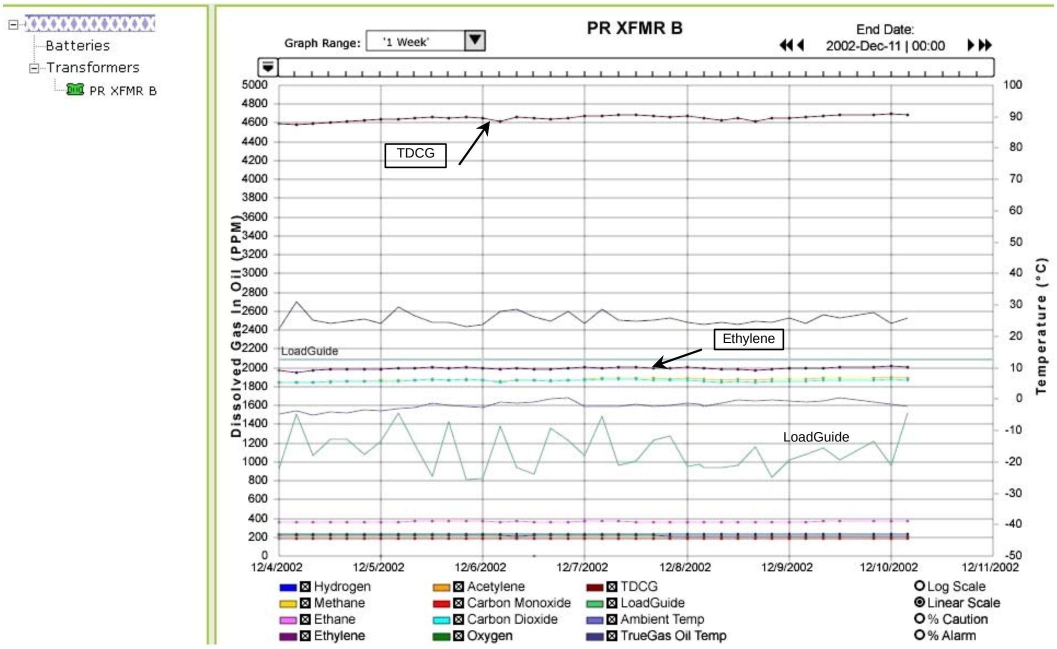

Figure 7: 230 kV GSU Transformer individual gas ppm on linear scale 1-week chart (selectable)

3. GSU Transformer (details unavailable)

The GSU Transformer in figure 8 failed 25 days after on-line gas analysis was commissioned. The analyzer operated properly and within spec; LoadGuide was not connected; "Caution/Alarm" limits and monitoring were set by the user.

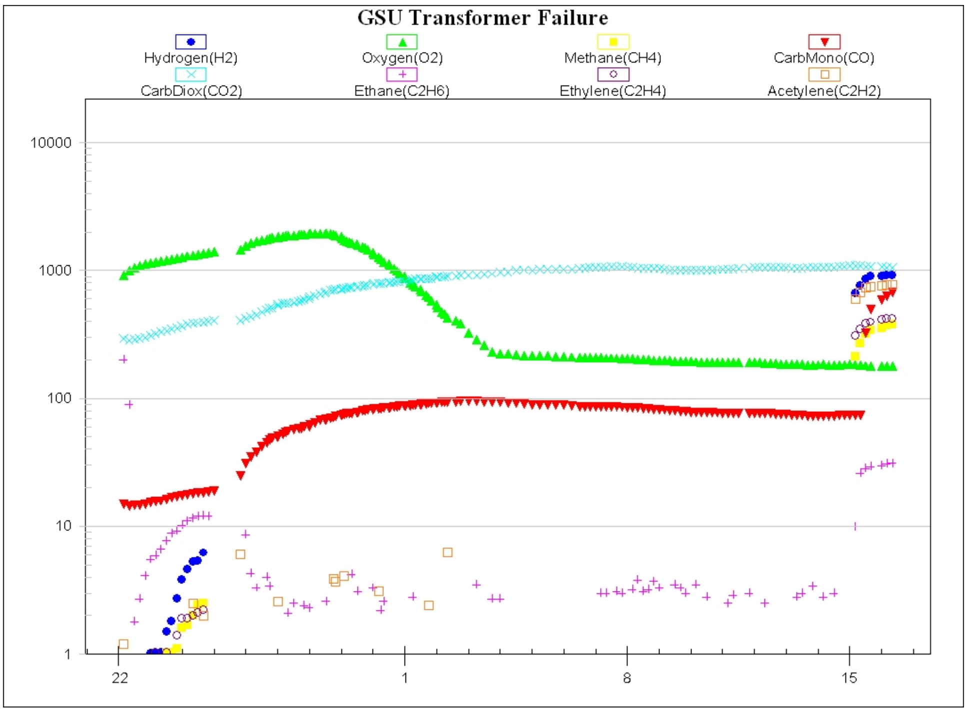

Figure 8: GSU Transformer Failure individual gas ppm on log scale 1-month chart (selectable)

The following observations can be made from the gas analyzer data charted in figure 8:

- A trace of acetylene (1.2 PPM) in the first set of measurements followed by increasing ethane (1.8 to 5.5 PPM) during first 20 hours suggest a problem probably started prior to analyzer commissioning.
- Traces of hydrogen, methane & ethylene (each less than 10 PPM) follow in Days 2 & 3.
- Unexplained power-down of the analyzer caused a 20 hour gap in measurements Day 4.
- After re-powering, data immediately show rapidly rising carbon monoxide (25 to 96 PPM) & carbon dioxide (407 to 915 PPM), followed by decreasing oxygen (1940 to 325 PPM) plus intermittent traces of acetylene & ethane (no other gases) through Day 11.
- Data show only carbon monoxide, carbon dioxide, oxygen & traces of ethane (sometimes intermittent) until Day 24 when a major fault occurred causing hydrogen, acetylene, & ethylene to jump to high levels, followed by carbon monoxide.
- Transformer failed mid-Day 25 (32 hours later).

It is interesting to note gas analyses indicated by various methods including recent experimental data regarding gassing behavior and carbon dioxide to carbon monoxide ratios.

Duval Triangle Method for analyzing transformer gases. (See References [1, 2]. and points plotted on figure 9 below.)

- Traces of acetylene, ethylene & methane Days 2 & 3 indicate 300 to 700 °C **thermal faults** interspersed with **high-energy discharges**.
- High gas levels Day 24 (32 hours before transformer failure) indicate **high-energy discharges** (consistent with Days 2 & 3).
- Rapidly rising carbon monoxide & carbon dioxide along with decreasing oxygen, confirm the fault involved the **degradation of cellulose**.

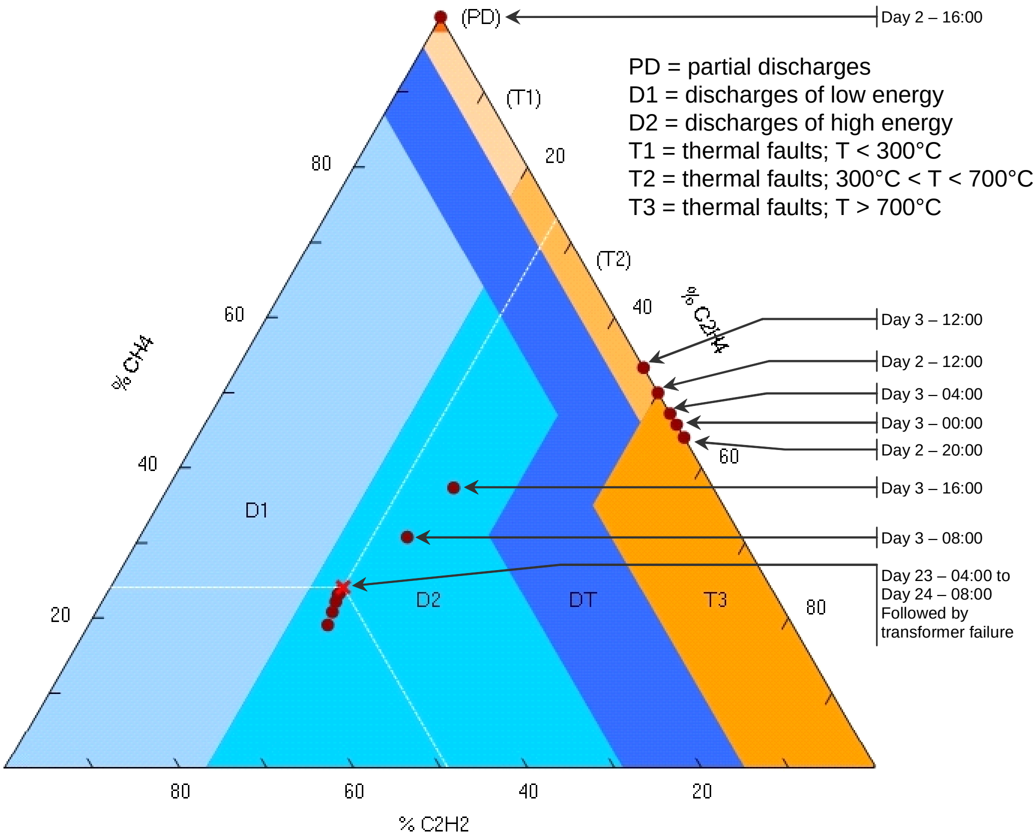

Figure 9: GSU Transformer Failure fault gases analyzed using Duval Triangle method

Carbon Dioxide/Carbon Monoxide Ratios:

Days 1, 2, 3 **-** CO2/CO = 20 to 21:

- Indicates **overheated cellulose**
  per Reference [3],
- Indicates **70 °C**
  per Reference [4]
  (normal for a GSU transformer).

Day 1 through Day 3 using accumulated gas increments– CO2/CO = 28:

- Indicates **overheated cellulose**
  per Reference [3],
- Indicates **50-60 °C**
  per Reference [4]
  (normal for GSU transformer).

Kan & Miyamoto [4] report laboratory experimental data showing that CO2/CO ratios are stable at constant high temperatures (above 80 C where absorption of CO2 & CO into cellulose does not occur) and suggest incremental CO2/CO ratios can be applied to indicate cellulose thermal decomposition temperatures. Using this approach:

- <u>Day 5</u> using two-hour gas increments after re-powering – CO2/CO = 1.95 **- 240 C**. (Insulation life is a matter of hours at this temperature.)
- <u>Day 5</u> using next 4-hour gas increments – CO2/CO = 2.15 – **192 C.**
- <u>Day 5</u> using next 4-hour gas increments – CO2/CO = 2.3 – **161 C.**
- <u>Days 10-11</u> using 48-hour gas increments – CO2/CO = 10 – **110 C.**

4. OBSERVATIONS

The problem may have started with winding deformation (perhaps due to a through-fault), or broken or loose connection, causing intermittent AC voltage-breakdowns, strand-to-strand or turn-to-turn shorts, severe degradation of paper insulation and ultimately, sustained AC voltage-breakdown leading to complete failure of the transformer.

Hydrogen produced by the AC voltage-breakdowns probably rose rapidly through the oil in the form of bubbles and escaped. Borsi [5] reports laboratory experimental data indicating that during AC voltage-breakdowns in mineral oil <u>dissolved</u> gases were too small to measure – *"The reason for the small amount of dissolved gases is the existence of large gas bubbles which rise very fast, thus leaving not enough time to dissolve."* (This is consistent with my personal experiences starting back in the old days. Whenever a transformer "wumped" on the test floor, the first thing you did was to scurry up a very tall ladder, look in the manhole, and look for where a bubble, or a stream of bubbles, came up. Bubbles always got larger & larger, never smaller. In addition to the location, we always looked for a wisp of smoke, always bad news - *very early head-space analysis*. [6])

Dynamic behavior of acetylene, ethylene & methane including trace amounts, rapidly rising carbon monoxide & carbon dioxide along with decreasing oxygen, and dynamic cellulose-decomposition temperatures indicated by incremental CO2/CO ratios provided three independent confirming indicators that a serious problem was happening in a transformer. However, 4-hour DGA & 24 x 7 monitoring was necessary to take advantage of the dynamic behavior of the gases in diagnosing the problem at an early stage.

5. CONCLUSIONS

- On-line monitoring of all 8 gases can provide insight regarding loading and other conditions associated with the generation of gases in oil-filled transformers.
- Gassing behavior of individual transformers tends to be unique due to specific operating conditions as well as internal characteristics. On-line monitoring can provide a history that identifies a transformer's "personality" including capability under unusual conditions.
- Trending of individual gases on-line makes it possible to see gas-generation events as they happen, despite high levels of accumulated gases, not possible through laboratory DGA (due to variables in sampling, testing and specific transformer conditions at time of sampling).
- On-line monitoring of oxygen can reveal air-leaks that provide a warning of potentially hazardous entrance of water (whereas oxygen content per DGA often contains a variable amount of air).
- 24 x 7 on-line monitoring of all 8 gases makes Green-Yellow-Red condition assessment feasible for managing transformer asset populations large & small while developing new knowledge and understanding from the dynamic behavior of gases. This presents the opportunity to move transformer DGA interpretation from "an art" to "engineering" – *The New Ballgame*.

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