# A Review of Faults Detectable by Gas-in-Oil Analysis in Transformers

**Key Words:** Transformer, fault, dissolved gas analysis

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*Load tap changers, low-temperature hot spots, and partial discharges require particular attention.*

IEC Publication 60599 [1] provides a coded list of faults detectable by dissolved gas analysis (DGA): PD = partial discharges, D1 = discharges of low energy, D2 = discharges of high energy, T1 = thermal faults of temperature < 300 °C, T2 = thermal faults of temperature 300 °C < T < 700 °C, T3 = thermal faults of temperature > 700 °C.

The IEC TC10 databases of DGA results corresponding to faults identified by visual inspection of faulty transformers in service have been presented in a previous paper [2]. The present paper reviews these DGA results in a more user-friendly graphical form. It also reviews the DGA results of laboratory models attempting to simulate these faults, as published in the scientific literature or technical reports.

The specific case of on-load tap changers (OLTC) is reviewed much more extensively, and separately, since DGA interpretation in this case must take into account the large background of residual gases resulting from the normal current-breaking operation of the OLTC. Particular attention is also given to DGA results related to PDs and low- temperature thermal faults.

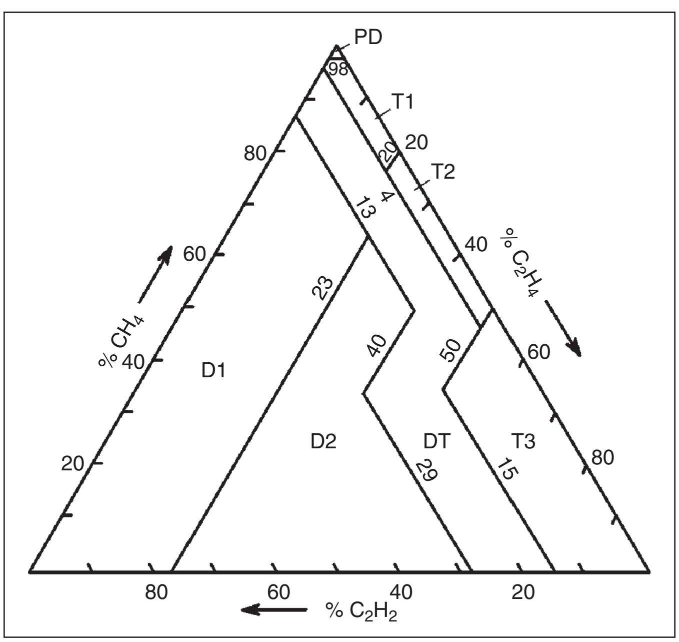



*Fig. 1. Coordinates and fault zones of the Triangle.*

The Triangle graphical method of representation [1] is used to visualize the different cases and facilitate their comparison. The coordinates and limits of the discharge and thermal fault zones of the Triangle are indicated in Fig. 1, and are not repeated in Figs. 2-13 for clarity. Zone DT in Fig. 1 corresponds to mixtures of thermal and electrical faults.

Readers interested in visualizing their own DGA results using the Triangle representation should preferably use triangular coordinate drawing paper, such as the one provided by Keffel & Esser Co (# 46 4493), for better precision.

The Triangle coordinates corresponding to DGA results in ppm can be calculated as follows: % C2H2 = 100 x /(x+y+z); %C2H4 = 100y /(x+y+z); %CH4 = 100z /(x+y+z), with x = (C2H2); y = (C2H4); z = (CH4), in ppm.

## Thermal Faults (T1, T2, T3)

### *Thermal Faults in Transformers in Service*

Thirty-five cases of thermal faults (hot spots) in faulty transformers in service, identified by visual inspection of the equipment, are indicated in Figs. 2 and 3. The corresponding values in ppm have already been published on page 37 of [2].

Figure 2 contains 16 cases of hot spots in paper/oil insulation. Seven cases where carbonized paper was found upon inspection (T > 300 °C), and five cases where only brownish paper was found (T < 300 °C), are indicated separately. Pa-

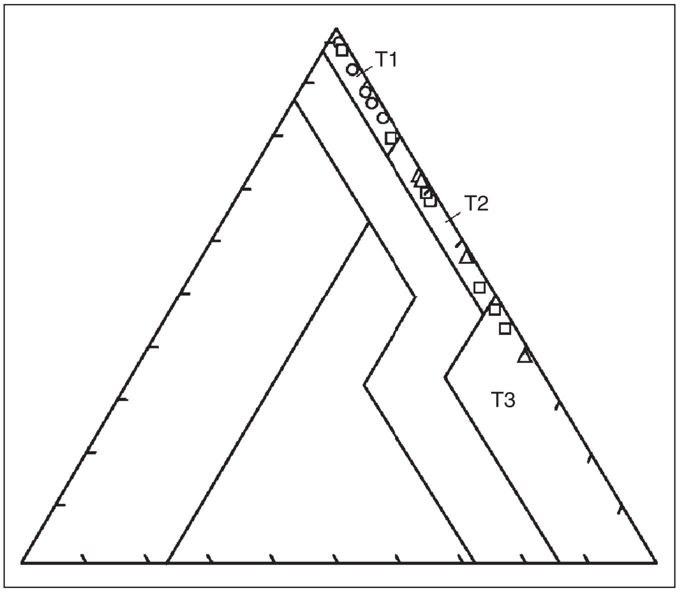



*Fig. 2. Thermal faults in the paper/oil insulation of transformers in service, identified during inspection by visual marks of: □: carbonized paper (T > 300 °C); ○: brownish paper (T < 300 °C); △: not mentioned.*

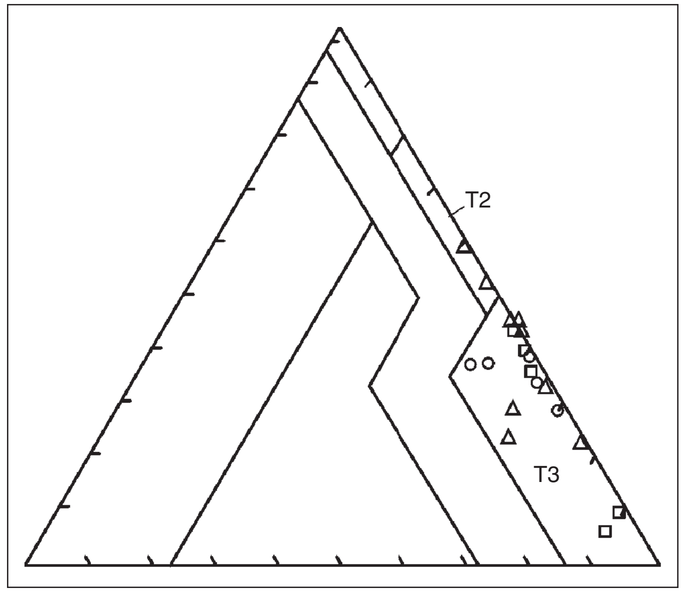



*Fig. 3. Thermal faults in the oil only of transformers in service, identified during inspection by visual marks of: ○: laminations burnt, eroded, or broken; □: circulating currents in bolts, tank, or clamps; △: bad contacts in welds, windings, terminals.*

per involvement in these cases often results in a $CO_2$/CO ratio < 3, but not always, therefore this ratio should be used with caution when trying to predict whether or not paper is involved in a fault.

Figure 3 contains 19 cases of hot spots in oil only (with no paper involved). These were located in the laminations, or were the results of circulating currents in bolts, tank, or clamps, or the results of bad contacts in welds, windings, or terminals, as indicated.

Figures 2 and 3 suggest that DGA results appearing in the T3 zone correspond in general to a thermal fault in oil, and those in the T2/T1 zones to a thermal fault in paper. Carbonized paper tends to appear in or close to the T2 zone.

## *Thermal Faults in Laboratory Models*

Twenty-two cases of hot spots simulated in the laboratory are indicated in Figs. 4 and 5. The corresponding DGA results in ppm can be found in Tables I and II, and their references in Table IV. Figure 4 contains 12 cases of hot spots in paper or in paper/oil insulation. Figure 5 contains 10 cases of hot spots in oil only.

Hot spots in paper or paper/oil insulation at all temperatures are located in the T1 and T2 zones. Hot spots in oil at temperatures > 500 °C are located in the T3 zone.

Hot spots in oil at temperatures < 300 °C require some discussion. Most "normal" oils do not produce significant or measurable amounts of gases at these temperatures (except the carbon oxides). However, some types of oils ("stray gassing oils") have been shown in recent studies [3]-[4] (especially among the new oils appearing on the market) to produce gases (mainly $H_2$ and $CH_4$) at the beginning of their life. These gases are formed the first time the stray gassing oil is heated at these temperatures, up to a concentration plateau (typically, 5 to 250 ppm), which depends on the type of

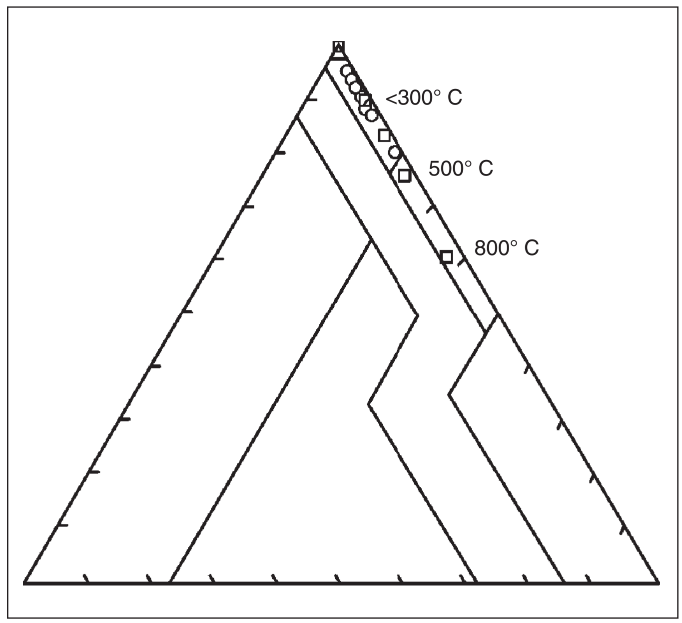



*Fig. 4. Thermal faults simulated in the laboratory; ○: in paper/oil insulation; □: in paper only.*

oil. Then, if the oil is heated a second time at these temperatures, no more gassing is observed. This behavior has been related to the oil refining technique used, and investigations are underway at CIGRE to identify the stray gassing oils presently in use and their gas concentration plateaus.

Hot spots in stray gassing oils at temperatures < 300 °C are indicated in Fig. 5. They are located in the T1 and T2 zones. If stray gassing oils are used during factory heat-run tests or in the early life of transformers, it may thus be difficult to tell whether DGA results appearing in the T2/T1 zone indicate a hot spot in paper or stray gassing of the oil. After

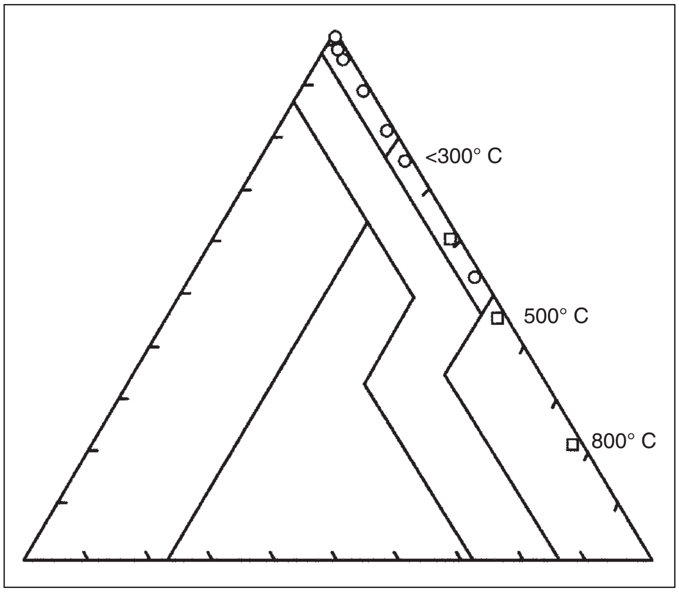



*Fig. 5. Thermal faults simulated in the laboratory, in oil only, of temperatures: □: > 300 °C; ○: < 250 °C.*

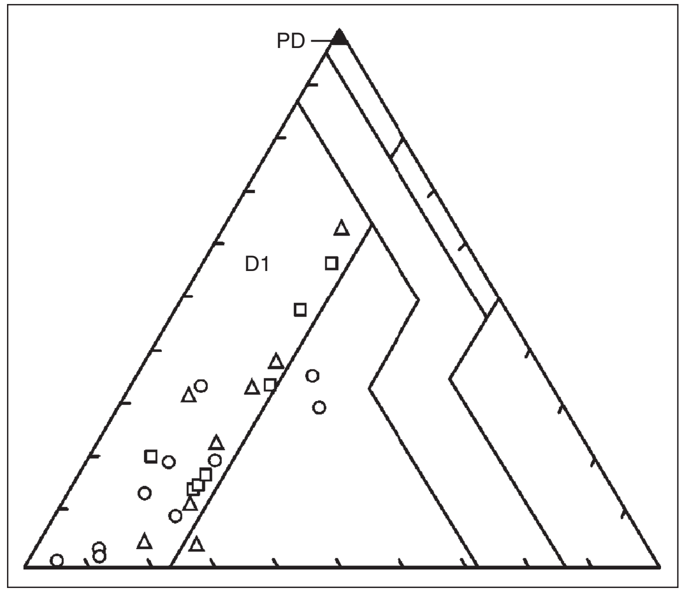



*Fig. 6. Discharges of low energy (D1) and partial discharges of the corona-type (PD) in transformers in service identified during inspection by visual marks of: □: tracking; △: sparking; ○: small arcing (OLTC-type) ; ▲: corona-type PDs.*

some months in service, however, or after heat treatment of the oil, stray gassing will stop, and DGA results in the T1 and T2 zones will indicate a hot spot in paper only.

## Low-Energy Discharges (D1)

Twenty-five cases of discharges of low energy (D1) in faulty transformers in service—as identified during inspection by visual marks of tracking, small arcing, sparking, carbonized pinholes in paper, or carbon particles in oil—are indicated in Fig. 6. The corresponding values in ppm can be found on page 35 of [2].

Twelve cases of discharges or PDs of the D1 type simulated in laboratory models are indicated in Fig. 7. The corresponding values in ppm can be found in Table III (cases 6-17), and their references in Table IV. Various configurations have been used in these laboratory models: needle-to-sphere, point-to-plane, oil/paper wedge, sparking or small arcs, in oil and/or in paper-oil insulation.

Small breakdowns in oil produce relatively more $C_2H_2$ (cases 14-16 of Fig. 7). Also, increasing pC amplitudes of the discharges appear to pull the gas composition towards the D1/D2 zone boundary (cases 8-12). A lightning impulse discharge (case 17) appears as a discharge D2 in terms of DGA formation.

In transformers in service, D1 discharges of low energy such as tracking, small arcs, and uninterrupted sparking discharges are usually easily detectable by DGA, because gas formation is large enough.

**Table I. Hot Spots in Paper and Paper/Oil Insulation Simulated in the Laboratory.**

| Case # | Paper | Paper/Oil | Temp., ºC | H2 | CH4 | C2H4 | C2H2 | C2H6 | CO | CO2 | Unit | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | X | | 800 | 22,400 | 22,400 | 13,440 | 1570 | 2690 | 112,000 | 56,000 | $\mu$l / g | 2 |
| 2 | X | | 500 | 670 | 224 | 67 | 2 | 45 | 11,200 | 15,680 | $\mu$l / g | 2 |
| 3 | X | | 300 | 224 | 4.5 | - | - | 2 | 2 | 560 | $\mu$l / g | 2 |
| 4 | X | | 150 | 900 | 9,180 | 900 | 22 | - | 1344 | 8950 | $\mu$l / g | 2 |
| 5 | X | | 100 | - | 224 | 45 | - | - | - | 670 | $\mu$l / g | 2 |
| | | | | | | | | | | | | |
| 6 | | X | 300 | 470 | 4637 | 448 | - | 1300 | 25,312 | 51,000 | $\mu$l / l | 5 |
| 7 | | X | 300 | 65 | 20 | 5 | - | 10 | | | % | 6 |
| 8 | | X | 300 | 53 | 39 | 4.5 | - | 3 | | | % | 6 |
| 9 | | X | 225 | 219 | 44 | 3 | - | 3 | 3000 | 13,000 | ppm | 3 |
| 10 | | X | 200 | 37 | 47 | 5.5 | - | 10 | | | % | 6 |
| 11 | | X | 150 | 34 | 30 | 2.5 | - | 34 | | | % | 6 |
| 12 | | X | 140 | 14 | 62 | 3 | - | 16 | 68 | 7500 | ppm | 3 |

| Table II. Hot Spots in Oil Simulated in the Laboratory. | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Case # | Temp., ºC | H2 | CH4 | C2H4 | C2H2 | C2H6 | CO | CO2 | Unit | Ref. |
| 1 | 800 | 65 | 34 | 112 | - | 16 | | | μl/g | 2 |
| 2 | 500 | 0.7 | 1.5 | 1.8 | - | 0.3 | | | μl/g | 2 |
| 3 | 300 | - | 0.2 | 0.13 | - | 0.1 | | | μl/g | 2 |
| | | | | | | | | | | |
| 4 | 235 | 48 | 40 | 0.5 | - | 11 | | | % | 6 |
| 5 | 225 | 130 | 140 | 120 | - | 24 | 2 | 400 | ppm | 3 |
| 6 | 175 | 86 | 8 | 2.5 | - | 2.5 | | | % | 6 |
| 7 | 168 | 6 | 3 | 0.7 | | 0.8 | | | ml | 4 |
| 8 | 160 | 50 | 3 | - | - | 1 | 14 | 581 | ppm | 7 |
| 9 | 140 | 55 | 22 | 2.6 | - | 0.5 | 358 | 961 | ppm | 10 |
| 10 | 120 | 78 | 66 | 2.6 | - | 62 | 283 | 1772 | ppm | 10 |

PDs of the D1 type, however, may not be detected by DGA unless the PD activity is intense and/or occurring over a long period of time. For example, during high-voltage factory tests on transformers, performed over a relatively short period of time, low-to-medium levels of PD activity are often detected by acoustic or other electrical techniques, but detectable amounts of gases related to these PDs are seldom found by DGA, and visual damage is seldom found by inspection of the transformer.

The reason is most likely that PDs produce only a small amount of gases and damage: PDs of 100 mJ of energy will produce only 5 µl of gas [5], or about 0.1 ppm in the oil of a transformer, which is the DGA analytical detection limit during factory tests. A discharge energy of 1 to10 mJ is estimated as the minimum required to produce damage or carbonization of paper insulation [6]. An energy of 10 mJ corresponds to several charge pulses of 100,000 to 1,000,000 pC [5], considered as PDs of high or very high amplitude. Similar levels of pC amplitude have been reported in [7] as necessary to produce visible damage to the paper insulation.

This might explain why, during factory or field tests, detectable amounts of gases and damage to the paper insulation are found only in relation to PDs of higher amplitudes [8]. In service, detectable amounts of gases and damage might possibly be produced by a larger number of PDs of smaller amplitude occurring over a longer period of time.

Monitoring by acoustic and electrical techniques is thus more efficient for detecting low-to-medium PDs in the incipient stage, before they become damaging to the paper insulation [8] and produce detectable gases. At this stage, however, their location may be difficult to find because of the absence of visual marks of damage.

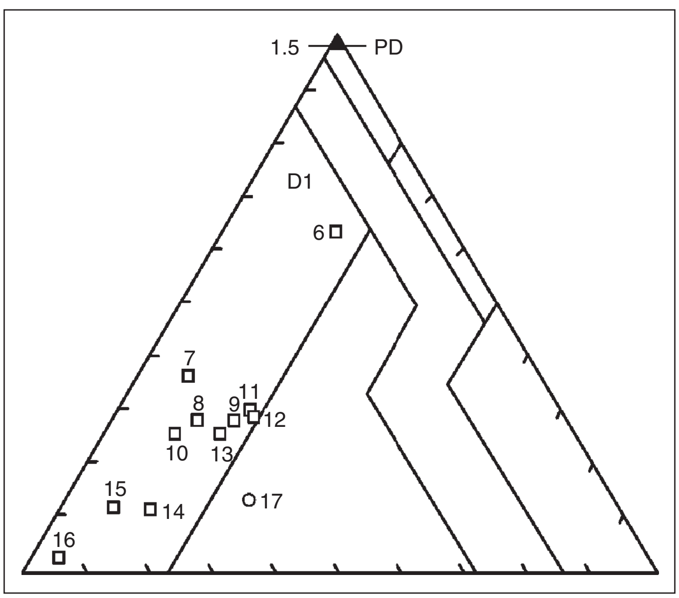



*Fig. 7. Electrical/partial discharges simulated in the laboratory: □: sparking/arcing (6-16); ○: PDs of the lightning impulse-type (17); ▲: PDs of the corona-type (1-5).*

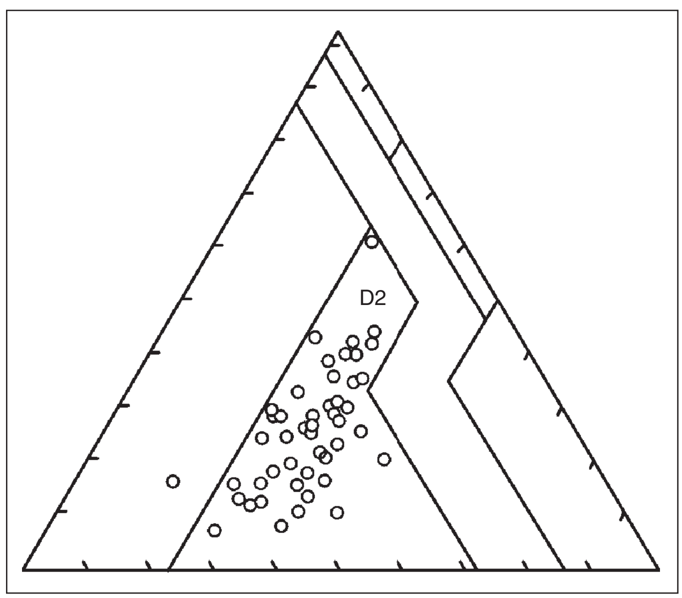



*Fig. 8. Discharges of high-energy (D2) in transformers in service identified by inspection.*

DGA is more useful for determining the onset of the next stage, when PDs just start damaging the paper insulation and may be detected by DGA and visual inspection. PDs may also be harmful if they produce free bubbles in oil, but at this stage enough gas is produced to be easily detectable by DGA.

## PDs of the Corona Type

In terms of chemical degradation and DGA results, PDs of the corona-type occurring in the gas phase of voids or gas bubbles are very different from the PDs of the sparking type (D1) occurring in the oil phase.

Nine cases of corona-type PDs in faulty transformers in service, as identified during inspection by the formation of x-wax deposits, are indicated in Fig. 6. The corresponding values in ppm can be found on page 34 of [2]. They all fall in the small PD zone of Fig. 6.

Five cases of corona-type PDs simulated in laboratory models are indicated in Fig. 7. The corresponding values in ppm can be found in Table III (cases 1-5) and their references in Table IV. They all fall in the small PD zone of Fig. 7.

PDs of the corona type are of very low amplitude (10 to 30 pC) and in the µJ range [6]. They are usually easily detectable by DGA, however, because they are produced over very long periods of time and within large volumes of paper insulation. They often generate large amounts of hydrogen. They are also often associated with x-wax formation (an un-

**Table III. Electrical/PDs Simulated in the Laboratory.**

| Case # | Description | H2 | CH4 | C2H4 | C2H2 | C2H6 | CO | CO2 | Unit | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Corona in oil | 16,000 | 3600 | 14 | - | 670 | 180 | 790 | ppm | 3 |
| 2 | Corona in ASTM D2300 | 6600 | 1000 | 2 | 19 | 38 | 14 | 400 | ppm | 3 |
| 3 | Corona in gas bubbles | 88 | 9 | 0.03 | - | - | | | % | 6 |
| 4 | 30 pC in gas occlusions in paper | 2240 | 168 | - | - | 25 | 20 | 90 | l | 2 |
| 5 | 30 pC in moist paper | 1950 | 123 | 2 | 2 | 38 | 29 | 56 | ml | 1 |
| | | | | | | | | | | |
| 6 | 30 pC in moist paper | 2240 | 157 | 45 | 45 | 90 | 45 | 67 | l | 2 |
| 7 | Pds in badly impregnated paper | 73 | 8 | 2 | 12 | 4 | | | % | 6 |
| 8 | Needle-to-plane Pds > 100 pC | 5000 | 4000 | 2000 | 8000 | 2000 | | | ppm | 9 |
| 9 | Needle-to-plane Pds > 1000 pC | 24.3 | 15.7 | 11.2 | 29.8 | 6.4 | | | ppm | 9 |
| 10 | 5,000 pC in paper/oil wedge | 2240 | 360 | 169 | 828 | 25 | 45 | 2240 | l | 2 |
| 11 | 10,000 pC in oil | 4480 | 560 | 403 | 896 | 380 | 67 | 403 | µl | 1 |
| 12 | 500,000 pC in paper/oil wedge | 2240 | 560 | 450 | 940 | 380 | 45 | 672 | l | 2 |
| 13 | Arcing in oil | 200 | 230 | 170 | 480 | 2 | 6 | 160 | ppm | 3 |
| 14 | Point-to-plane discharge in oil | 60 | 5 | 6 | 29 | 1 | | | % | 6 |
| 15 | Needle-to-sphere discharge in oil | 890 | 110 | 84 | 700 | 3 | - | 430 | ppm | 3 |
| 16 | Rod-to-rod discharge | 41 | 112 | 254 | 4536 | - | - | 98 | ppm | 8 |
| 17 | Needle-to-plane lightning impulse | 16,000 | 4000 | 8500 | 16,000 | 500 | | | ppm | 9 |

**Table IV. References for Laboratory Results.**

| Ref. | Year | Authors | Journal/Report |
|---|---|---|---|
| 1 | 1970 | Thibault et al. | Rev.Gen.Elec., 80 (1) 46 |
| 2 | 1972 | Galand et al. | Rev.Gen.Elec.,81 (11) 727 |
| 3 | 1974 | Pugh | Doble Conf. 10-1205 |
| 4 | 1976 | Lampe et al. | CIGRE Paper 12-05 |
| 5 | 1982 | Carballeira et al. | CIGRE TF-15-01 |
| 6 | 1987 | Samat | CIGRE TF-15-01 |
| 7 | 1997 | Oommen | IEC-TC 10-WG13 |
| 8 | 1999 | Farber | EPRI Sub.Equip.Diag.Conf. |
| 9 | 2000 | Borsi | Electra, 188, 27 |
| 10 | 2001 | Sokolov | CIGRE TF-15/12-01-11 |

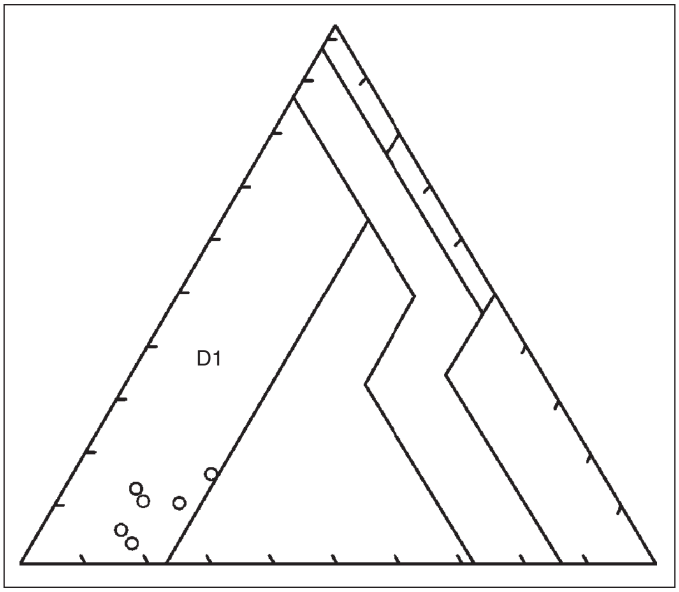



*Fig. 9. Normal operation of tap changers in service OLTC).*

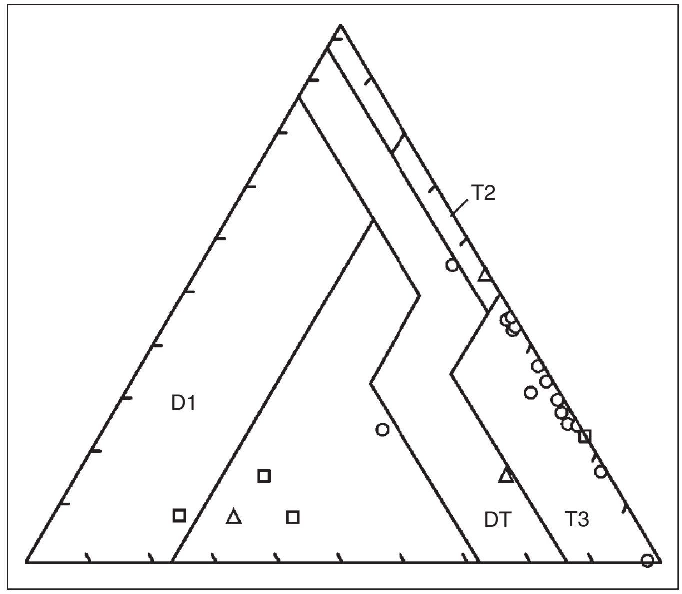



*Fig. 10. Thermal faults in OLTCs in service identified during inspection by visual marks of: ○: severe coking, □: light coking; △: "Heating."*

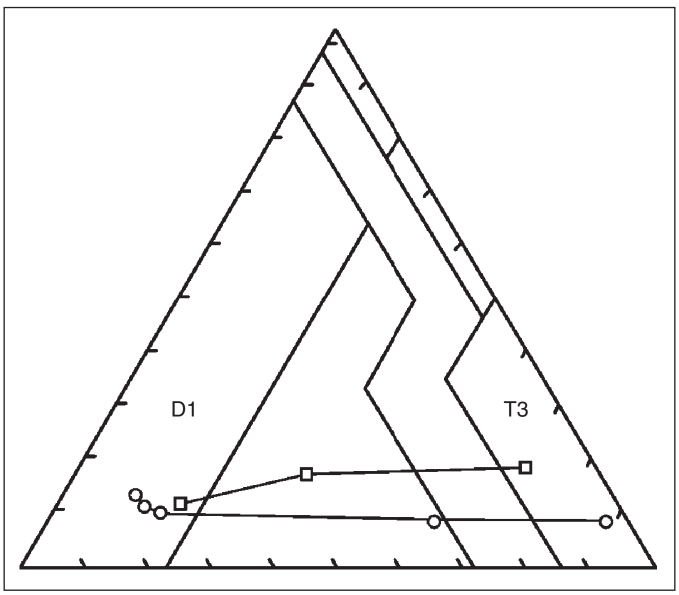



*Fig. 11. OLTCs subjected to a large number of operations without changing the oil: ○: 500, 3600, 49,000, 202,000, and 269,000 operations; □: 2750, 8730, and 47,830 operations (from left to right of Triangle).*

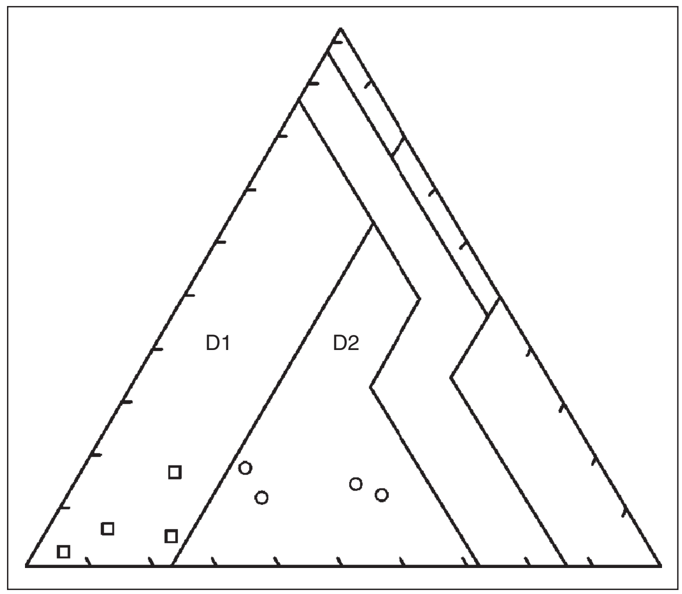



*Fig. 12. Arcing in OLTCs in service identified during inspection by visual marks of: □: arcing; ○: serious arcing.*

saturated hydrocarbon polymer), which increases the tan δ of the oil and may lead to thermal runaways in instrument transformers and bushings.

## High-Energy Discharges (D2)

Forty-seven cases of high-energy discharges (D2) in faulty transformers in service are indicated in Fig. 8. The corresponding values in ppm can be found on page 36 of [2].

High-density current or power follow-through could be identified by the presence of molten copper or extensive damage to the windings or other elements of the transformers (tank, laminations, etc.). Such cases cannot usually be simulated in a general-purpose laboratory but only in a high-power laboratory.

## On-Load Tap Changers (OLTC)

Forty-three cases of faults in OLTCs, identified by visual inspection of the equipment, are indicated in Figs. 9-12. The corresponding DGA analyses in ppm are indicated in Table V, and their references in Table VI.

Six cases identified as "normal operation" are indicated in Fig. 9. The "normal" current-breaking operation of OLTCs corresponds to a discharge of low energy (D1). The main gas formed is $C_2H_2$, at a typical rate of 1 to 4 ppm per

| Table V. Faults in Tap Changers (OLTCs) Identified by Inspection in Service. | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Case # | Description | H2 | CH4 | C2H4 | C2H2 | C2H6 | CO | CO2 | Ref. |
| N1 | 500 normal operations | 6870 | 1028 | 900 | 5500 | 79 | 29 | 388 | 2 |
| N2 | 3600 normal operations | 12,125 | 5386 | 6400 | 35,420 | 400 | 37 | 403 | 2 |
| N3 | 2750 normal operations | 17,248 | 2912 | 4703 | 18,144 | 963 | 672 | 4042 | 2 |
| N4 | Normal operation | 43 | 8 | 11 | 61 | 2 | 191 | 482 | 4 |
| N5 | Normal operation | 18,705 | 3610 | 7136 | 45,947 | 557 | 374 | 2606 | 7 |
| N6 | Normal operation | 580 | 617 | 2691 | 15,045 | 146 | 16 | 618 | 11 |
| | | | | | | | | | |
| T1 | Pyrolitic carbon growth between selector contacts | 1100 | 1600 | 2010 | 26 | 221 | - | 1430 | 1 |
| T2 | Severe coking and damage of reversing switch | 3130 | 3255 | 5668 | 4191 | 580 | 732 | 3176 | 5 |
| T3 | Tap shaft failure, coking | 458 | - | 1486 | 33 | 116 | 323 | 1295 | 5 |
| T4 | Serious coking | 2217 | 53,434 | 235,024 | 1633 | 55,535 | 1198 | 8534 | 5 |
| T5 | Serious coking | 1210 | 7260 | 17,800 | 453 | 4130 | 411 | 1430 | 5 |
| T6 | Severe coking | 658 | 3167 | 9278 | 381 | 1160 | 309 | 787 | 6 |
| T7 | Severe coking | 217 | 749 | 1754 | 33 | 171 | 210 | 602 | 6 |
| T8 | Severe coking | 244 | 1160 | 2354 | 189 | 688 | 460 | 4905 | 6 |
| T9 | Severe coking | 1312 | 39,981 | 120,319 | 774 | 35,146 | 307 | 2152 | 7 |
| T10 | Contacts damaged, carbon particles | 1481 | 18,191 | 31,233 | 230 | 7215 | - | - | 7 |
| T11 | Severe thermal damage to diverter switch | 19,700 | 117,000 | 142,000 | 3490 | 44,600 | 1110 | 8270 | 7 |
| T12 | Heavy coking on reversing switch | 591 | 6088 | 11,433 | 193 | 2626 | 294 | 934 | 8 |
| T13 | Reversing switch badly coked | 69 | 450 | 329 | 41 | 137 | 164 | 837 | 8 |
| T14 | Contacts heavily coked | 1025 | 3498 | 4360 | 1 | 2024 | - | - | 9 |
| T15 | Arcing tips burnt away | 30,682 | 13,268 | 51,608 | 12,327 | 6779 | 773 | 5231 | 9 |
| T16 | Light coking and damage of reversing contacts | 1094 | 7535 | 23,548 | 426 | 3803 | 230 | 2212 | 5 |
| T17 | Light coking | 2193 | 956 | 1714 | 125 | 307 | 1804 | | 5 |
| T18 | Light coking | 13,918 | 6439 | 10,970 | 20,812 | 1221 | 1165 | 8400 | 5 |
| T19 | Moveable contacts started to coke | 859 | 843 | 3574 | 5155 | 843 | 180 | 3454 | 8 |
| T20 | Excessive heating in nozzles, stationary contacts | 2251 | 2159 | 6055 | 18,490 | 887 | 1951 | 4758 | 8 |
| T21 | Signs of heating on contacts | 150 | 990 | 838 | - | 643 | - | - | 9 |
| | | | | | | | | | |
| A1 | 2750 operations | 17,248 | 2912 | 4703 | 18,144 | 963 | 672 | 4042 | 2 |
| A2 | 8730 operations | 32,444 | 7830 | 15,766 | 20,895 | 4796 | 262 | 2954 | 2 |
| A3 | 47,830 operations | 30,354 | 15,258 | 37,352 | 10,259 | 26,032 | 210 | 10,500 | 2 |
| | | | | | | | | | |
| B1 | 500 operations | 6870 | 1028 | 900 | 5500 | 79 | 29 | 388 | 2 |
| B2 | 3600 operations | 12,125 | 5386 | 6400 | 35,420 | 400 | 37 | 403 | 2 |
| B3 | 49,000 operations | 14,320 | 10,740 | 35,839 | 53,670 | 3944 | 405 | 4893 | 2 |
| B4 | 202,300 operations | 18,100 | 16,100 | 126,600 | 60,800 | 19,900 | 150 | - | 2 |
| B5 | 269,000 operations | 9030 | 20,300 | 200,000 | 10,500 | 29,700 | 64 | 490 | 2 |
| | | | | | | | | | |
| D1 | Arcing on selector switch ring | 1084 | 188 | 166 | 769 | 8 | 38 | 199 | 3 |
| D2 | Serious arc damage | 9083 | 3279 | 9606 | 8527 | 1136 | 381 | 4769 | 5 |
| D3 | 50% of arcing tips burnt away | 14,999 | 6803 | 21,417 | 28,381 | 3212 | 549 | 3354 | 8 |
| D4 | Arcing contact burnt off | 1317 | 608 | 2278 | 8739 | 841 | 312 | 4576 | 8 |
| D5 | Arcing between springs of contacts | 47 | 12 | 17 | 144 | 31 | 62 | 381 | 8 |
| D6 | Arc in selector switch | 210 | 43 | 102 | 187 | 12 | 167 | 1070 | 10 |
| D7 | Selector breaking current in selector tank | 35 | 6 | 26 | 482 | 3 | 200 | 2240 | 10 |
| D8 | Arcing on contacts | 391 | 164 | 293 | 736 | 14 | 29 | 72 | 11 |

| Table VI. References for Cases of Faults in OLTCs. | | | |
|---|---|---|---|
| Ref. | Year | Authors | Journal/Report |
| 1 | 1975 | Rogers | Doble Conf. 10-205 |
| 2 | 1988 | Carballeira et al. | CIGRE WG 15-01 |
| 3 | 1991 | Caldwell | CIGRE TF 15-01-01 |
| 4 | 1993 | Youngblood et al. | Doble Conf. 6-4.1 |
| 5 | 1994 | Youngblood | Doble Conf. 6-14.1 |
| 6 | 1995 | Deskins et al. | Doble Conf. 8-16.1 |
| 7 | 1996 | Haupert et al. | EPRI- LTC Conf. |
| 8 | 2001 | H2b Anal. Services | Web site |
| 9 | 2001 | Haupert et al. | * |
| 10 | 2001 | Duval / Pablo | IEEE EI-Mag.17 (2) 31 |
| 11 | 2001 | Foata / Faucher | Hydro-Quebec report |

* Title of paper: "The Use of Diagnostic Testing of Insulating Oil for Fault Detection in Electrical Equipment."

| Table VII. Additional Cases of Faults Identified by Inspection of Equipment in Service. | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Case # | Inspection | H2 | CH4 | C2H4 | C2H2 | C2H6 | CO | CO2 | Ref. |
| | | | | | | | | | |
| D1 | Capacitive discharges on loose bolts | 400 | 40 | 60 | 200 | 6 | 200 | 1000 | 1 |
| D2 | Arcing in oil and wet paper | 2320 | 616 | 800 | 822 | 72 | 9 | 72 | 2 |
| D3 | Trace of overflashing between coils | 245 | 30 | 35 | 245 | 5 | | | 7 |
| | | | | | | | | | |
| T1 | Circulating current in aluminum shields | 200 | 700 | 500 | - | 200 | 300 | 2000 | 1 |
| T2 | Flux overheating | 101 | 184 | 243 | 10 | 32 | 61 | 298 | 3 |
| T3 | Loose bolts, no visible damage | - | 57 | 4 | - | 40 | 72 | 203 | 3 |
| T4 | Hot spot in oil pump | 81 | 70 | 68 | - | 25 | 57 | 243 | 3 |
| T5 | Overheating of leads | 30 | 200 | 308 | 8 | 114 | 219 | 1040 | 4 |
| T6 | Overheating of leads | 465 | 3100 | 3360 | 1 | 1221 | 1530 | 8060 | 4 |
| T7 | Overheating of bottom core cross bar | 50 | 100 | 305 | 9 | 51 | 404 | 3560 | 4 |
| T8 | Overheated core packets | 3650 | 6730 | 9630 | 191 | 1570 | 674 | 7230 | 4 |
| T9 | Overheating of lead crossover | 1040 | 2100 | 2720 | 10 | 579 | 220 | 366 | 4 |
| T10 | Hot spot in a conductor | 305 | 538 | 101 | - | 157 | 1900 | 4210 | 5 |
| T11 | Overheating of cable to windings * | 12 | 17.6 | 4.5 | - | 4.6 | 554 | 1710 | 6 |
| T12 | Overheating of paper insulation * | 93 | 194 | 27 | - | 52 | 2330 | 6350 | 6 |
| T13 | Circulating currents in laminations* | 107 | 143 | 222 | 2 | 35 | 193 | 1330 | 6 |
| T14 | Burnt oil pump | 220 | 1660 | 1140 | - | 1880 | 410 | 2430 | 7 |
| T15 | Severe overheating of lead connection | 78 | 259 | 640 | - | 117 | 219 | 1827 | 7 |
| | | | | | | | | | |
| O1 | Coking of OLTC | 310 | 410 | 472 | 10 | 89 | 180 | 490 | 4 |
| O2 | Coked OLTC contacts | 75 | 700 | 799 | 1 | 623 | 480 | 8690 | 4 |

* During heat-run tests at 1.5 PU.

| Table VIII. References for Cases of Table VII. | | | |
|---|---|---|---|
| Ref. | Year | Authors | Journal/Report |
| 1 | 1970 | Fallou et al. | CIGRE Paper 15-07 |
| 2 | 1971 | Dind et al. | Doble Conf. 6-1101 |
| 3 | 1981 | Oommen et al. | IEEE PES Paper # 81 SM 352-4 |
| 4 | 1981 | Baker et al. | Doble Conf.10A-01 |
| 5 | 1982 | Thibault et al. | CIGRE Paper 12-01 |
| 6 | 1993 | Aubin | Hydro Quebec private communication |
| 7 | 2001 | Sokolov | CIGRE TF 15/12-01-11 |

current-breaking operation of the OLTC, depending on the type of OLTC.

Any faulty behavior of the OLTCs will alter their "normal" gas composition, especially the relative percentage of $C_2H_4$, and is detectable by DGA if the background of gases does not interfere too much.

Fifteen such cases where severe coking was identified by inspection of the faulty equipment are indicated in Fig. 10. The chain of events leading to coking usually starts with worn-out contacts of increasing resistance, higher currents flowing through these contacts, and increasing their temperature, carbonization of oil, and carbon deposition on the contacts increasing further their resistance. Most of these cases are in zones T3/T2, meaning that there are more gases formed by the hot spot than by the normal operation of the OLTC.

Six cases where light coking or overheating of the contacts were reported by inspection are also identified in Fig. 10. Their unexpected presence in the D2 zone may be explained by the formation of similar amounts of gases by the hot spot and by the normal operation of the OLTC, resulting in a gas composition intermediate between faults T3/T2 and D1. In such cases, zone D2 should not be considered as a zone of high-energy arcing but rather as a zone of mixture of faults (DT).

Figure 11 indicates eight cases where very large numbers of operations had been made without changing the oil, in two different types of OLTCs. Current-breaking operations increase the amount of carbon particles in oil, which deposit on the contacts, increasing their resistance and resulting in a more and more severe hot spot.

Eight cases where arcing was identified by inspection of faulty OLTCs are indicated in Fig. 12. Those appearing to the left of normal operation, deeper into the D1 zone, are related to abnormal arcs of the D1 type in the equipment. When monitoring by DGA, faults occurring in this region can be clearly attributed to abnormal D1s.

Those appearing to the right of normal operation are related to more severe arcing or short circuits of the D2 type. When monitoring OLTCs by DGA, faults occurring in this region may be attributed either to D2 or to slight coking. One way to make the distinction is to look at the number of current-breaking operations since the last oil change: if it is low, the fault is more likely to be a fault D2 than slight coking. To make sure, change the oil, clean the contacts, run a few current-breaking operations, then another DGA.

## Additional Cases

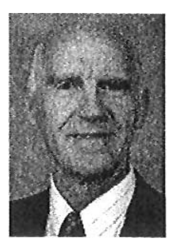
For the benefit of readers, 20 additional cases of inspected faults found in the literature are indicated in Table VII, and their references in Table VIII. These cases have not been included in Figs. 2, 3, 7, 9, and 11, but they confirm the conclusions drawn previously. The two cases of burnt oil pumps reported (cases T4 and T11 of Table VII) are located in the T2 zone.

## Conclusions

One hundred and seventy-nine cases of faults in transformers in service, identified by visual inspection, have been examined, as well as 19 cases of faults simulated in the laboratory.

From these cases, six main types of faults detectable by DGA can be established (PD, D1, D2, T1, T2, T3). Among these, faults T3 in service tend to be related to hot spots in oil and faults T1 and T2 to hot spots in paper, unless stray gassing oils are used. PDs potentially harmful to the equipment are detected by DGA but may otherwise remain undetected.

Finally, the relatively new application of DGA to load tap changers has been examined, with indications on how to reliably detect hot spots and abnormal arcing in this equipment.



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