

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

Key Words: Transformer, fault, dissolved gas analysis

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

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

also given to DGA results related to PDs and low-temperature thermal faults.

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 = 100 y / (x+y+z); % CH₄ = 100 z / (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-

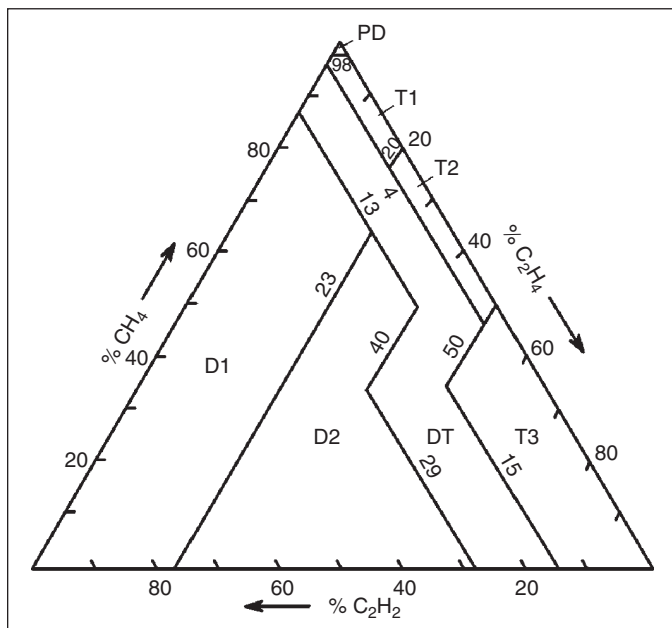


Fig. 1. Coordinates and fault zones of the Triangle.

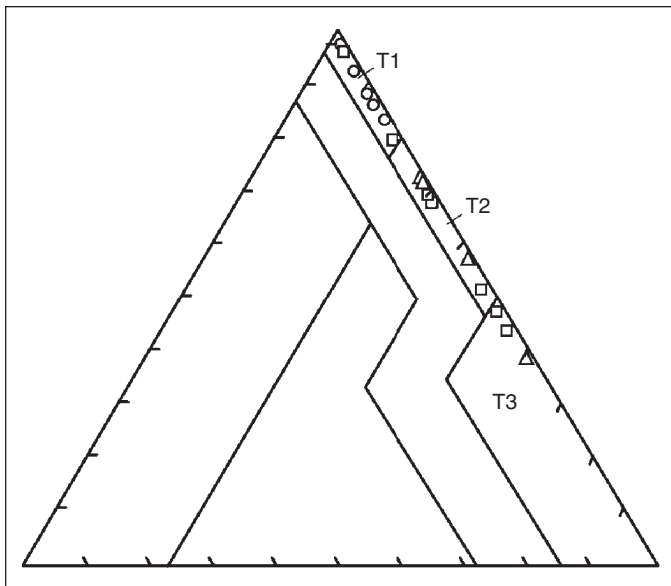


Fig. 2. Thermal faults in the paper/oil insulation of transformers in service, identified during inspection by visual marks of: □: carbonized paper ($T > 300^{\circ}\text{C}$); ○: brownish paper ($T < 300^{\circ}\text{C}$); △: not mentioned.

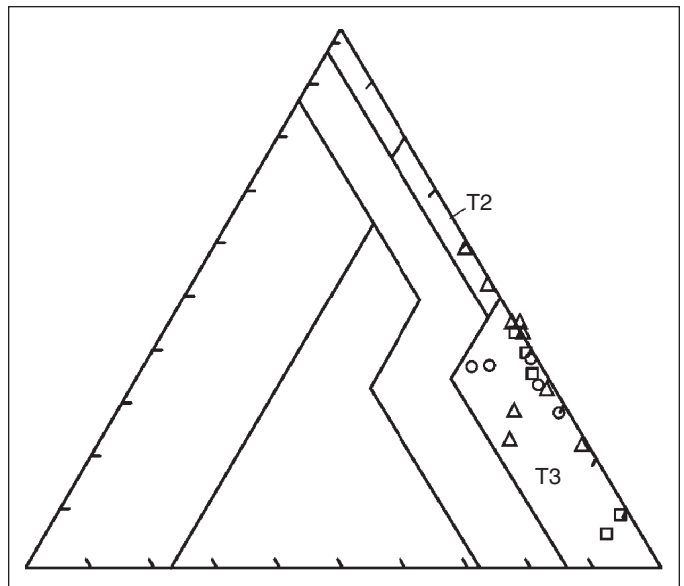


Fig. 3. Thermal faults in the oil only of transformers in service, identified during inspection by visual marks of: ○: laminations burnt, eroded, or broken; □: circulating currents in bolts, tank, or clamps; △: bad contacts in welds, windings, terminals.

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 $> 500^{\circ}\text{C}$ are located in the T3 zone.

Hot spots in oil at temperatures $< 300^{\circ}\text{C}$ 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

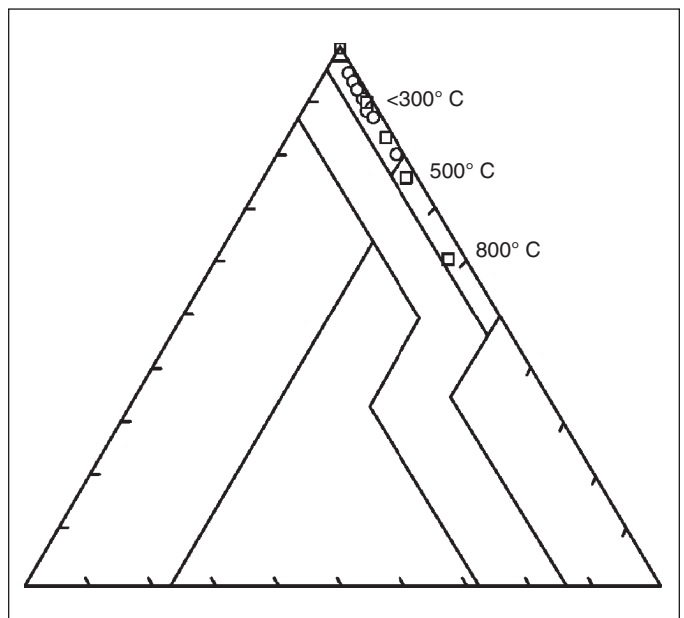


Fig. 4. Thermal faults simulated in the laboratory; ○: in paper/oil insulation; □: in paper only.

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 $< 300^{\circ}\text{C}$ 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

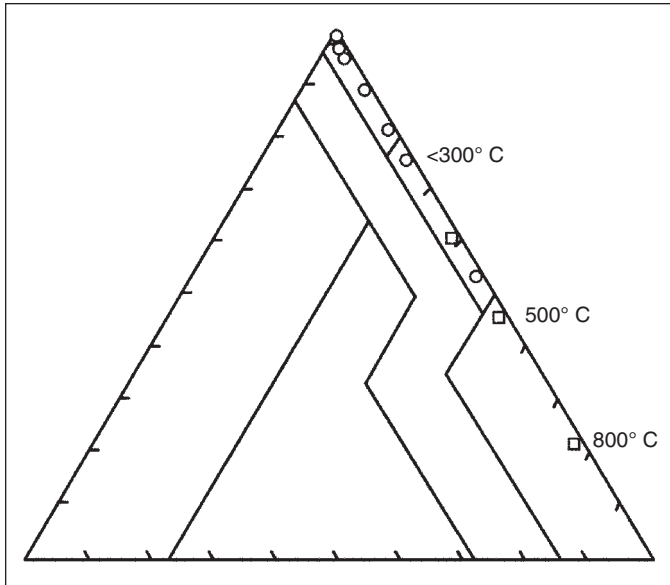


Fig. 5. Thermal faults simulated in the laboratory, in oil only, of temperatures: □: > 300 °C; ○: < 250 °C.

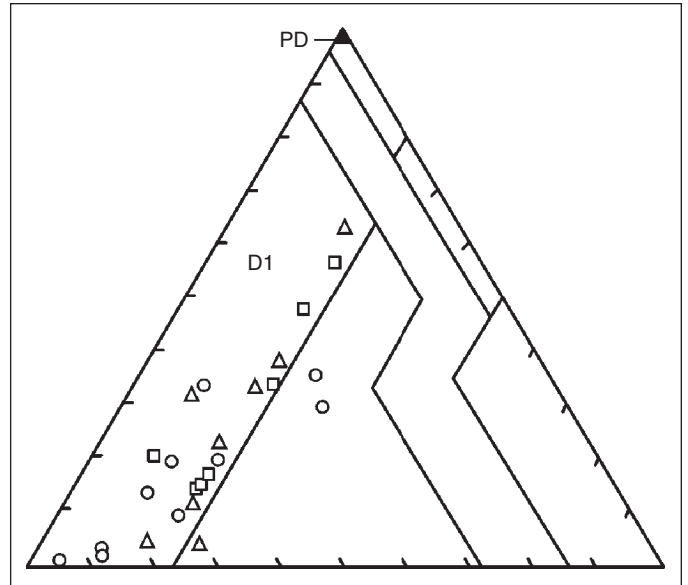


Fig. 6. Discharges of low energy (D1) and partial discharges of the corona-type (PD) in transformers in service identified during inspection by visual marks of: □: tracking; △: sparking; ○: small arcing (OLTC-type); ▲: corona-type PDs.

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 C₂H₂ (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., °C	H2	CH4	C2H4	C2H2	C2H6	CO	CO2	Unit	Ref.
1	X		800	22,400	22,400	13,440	1570	2690	112,000	56,000	μl/g	2
2	X		500	670	224	67	2	45	11,200	15,680	μl/g	2
3	X		300	224	4.5	-	-	2	2	560	μl/g	2
4	X		150	900	9,180	900	22	-	1344	8950	μl/g	2
5	X		100	-	224	45	-	-	-	670	μl/g	2
6		X	300	470	4637	448	-	1300	25,312	51,000	μl/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., °C	H2	CH4	C2H4	C2H2	C2H6	CO	CO2	Unit	Ref.
1	800	65	34	112	-	16			μV/g	2
2	500	0.7	1.5	1.8	-	0.3			μV/g	2
3	300	-	0.2	0.13	-	0.1			μV/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 to 10 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.

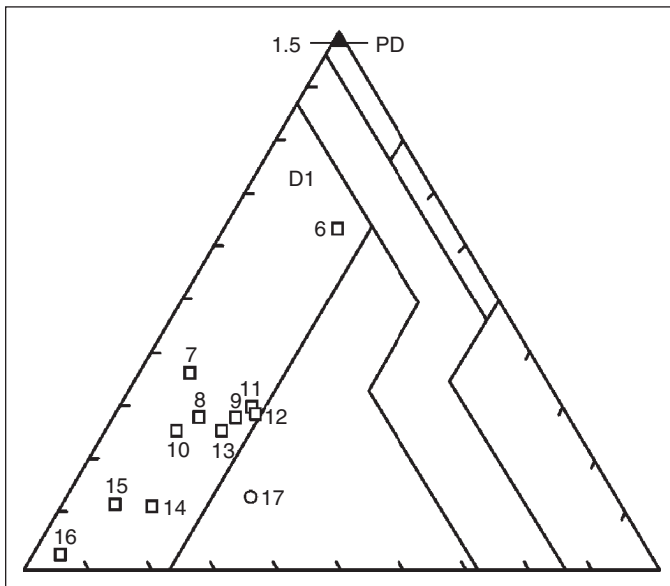


Fig. 7. Electrical/partial discharges simulated in the laboratory: □: sparking/arcing (6-16); ○: PDs of the lightning impulse-type (17); ▲: PDs of the corona-type (1-5).

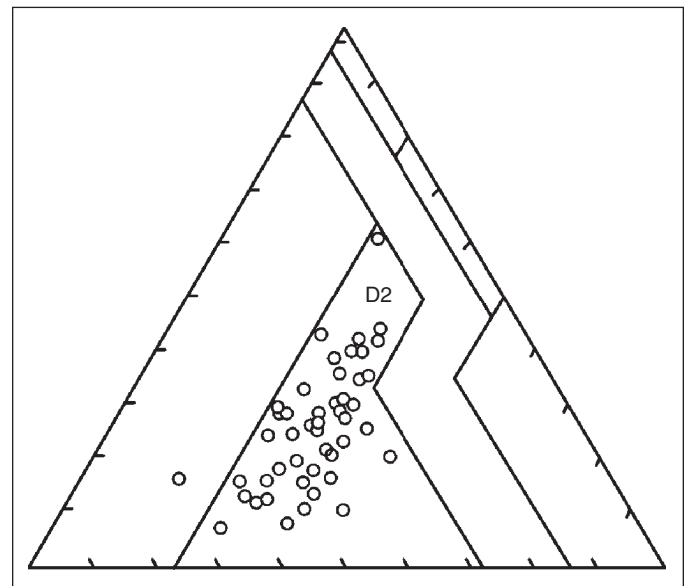


Fig. 8. Discharges of high-energy (D2) in transformers in service identified by inspection.

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

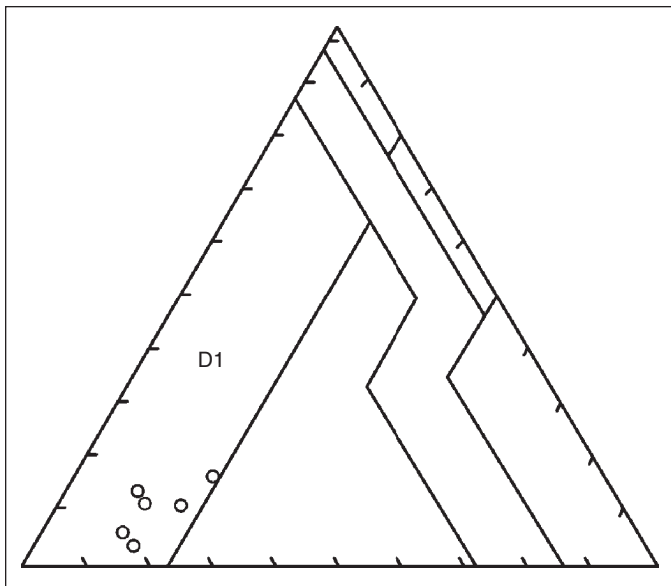


Fig. 9. Normal operation of tap changers in service OLTC).

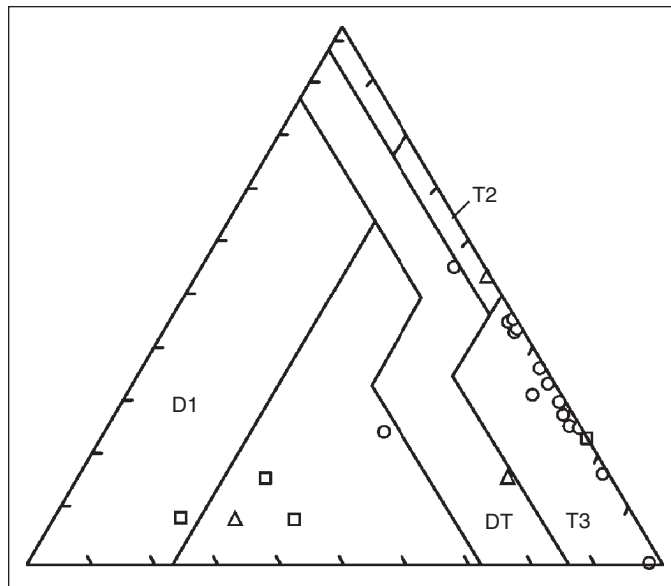


Fig. 10. Thermal faults in OLTCs in service identified during inspection by visual marks of: ○: severe coking, □: light coking; △: "Heating."

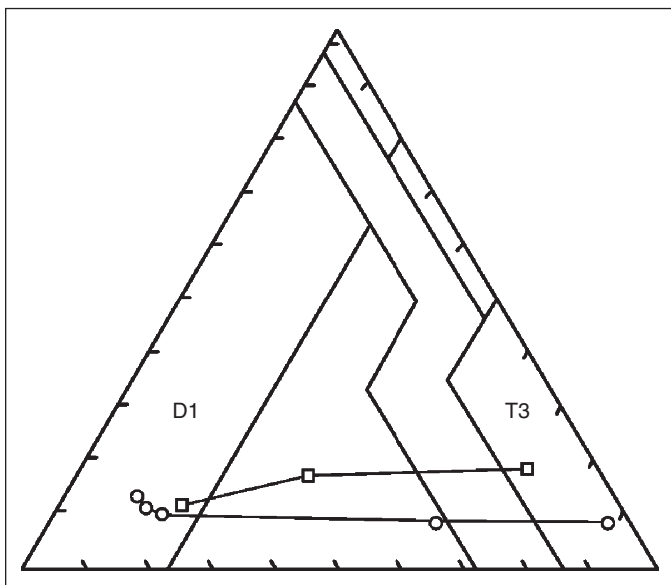


Fig. 11. OLTCs subjected to a large number of operations without changing the oil: ○: 500, 3600, 49,000, 202,000, and 269,000 operations; □: 2750, 8730, and 47,830 operations (from left to right of Triangle).

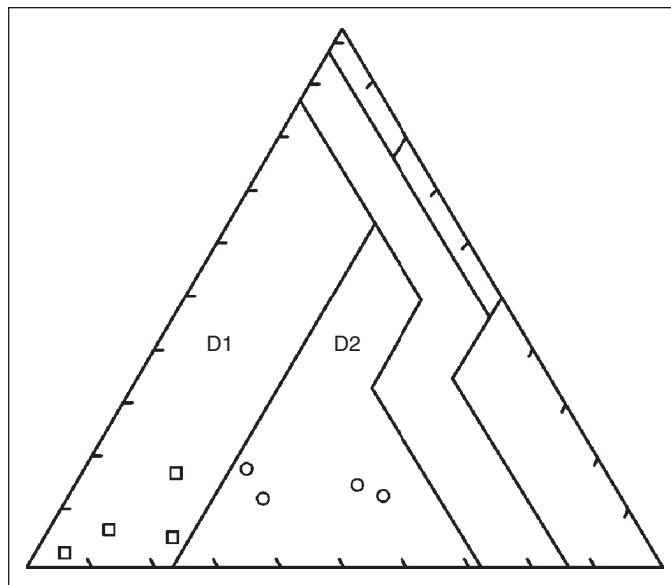


Fig. 12. Arcing in OLTCs in service identified during inspection by visual marks of: □: arcing; ○: serious arcing.

saturated hydrocarbon polymer), which increases the $\tan \delta$ 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 sim-

ulated 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	Pyrolytic 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	Hauptert et al.	EPRI- LTC Conf.
8	2001	H2b Anal. Services	Web site
9	2001	Hauptert 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 cur-

rent-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 gasing 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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