UNAPREĐENI TROUGAO I POREĐENJE SA DRUGIM METODAMA ANALIZE GASOVA RASTVORENIH U ULJU

IMPROVED TRIANGLE AND COMPARISON WITH OTHER DISSOLVED GAS ANALYSIS METHODS

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KRATAK SADRŽAJ:

Mnogo godina se koriste različite metode za analizu gasova rastvorenih u ulju (u daljem tekstu: AGRU): Dernenburg, Rodžersovi odnosi, MSS (Meler, Šlizing i Zoldner), Duvalovi trouglovi, Duvalovi pentagoni, Univerzalni trougao, Ključni gas, Logaritamski nomograf, IEC odnosi, IEEE, Metod analize obrasca gasa, Japan ETRA dijagnostički dijagram,... U suštini se sve metode bave jednostrukim ili čistim kvarovima. Neke od metoda mogu da daju tumačenje višestrukih ili mešovitih kvarova. Široko rasprostranjeno mišljenje među poznavaocima i stručnjacima je da je postotak višestrukih kvarova mali što je netačno.
Tokom godina neke metode su imale značajne izmene. Među njima je i Duvalov trougao koji je imao značajne promene u granicama između svih područja sa pojavom područja višestrukih kvarova električnih pražnjenja i pregrevanja (DT) u postojećem Duvalovom trouglu 1. Nova metoda je Unapređeni trougao koji unapređuje postojeći Duvalov trougao 1. Jedna od razlika je da se na stranici Duvalovog trougla 1 sa metanom kod Unapređenog trougla nalaze i metan i etan. Metan i etan su gasovi bliskog temperaturnog opsega, a izostanak etana koji se stvara u značajnoj količini samo kod termičkih kvarova nižih temperatura može da dovede do pogrešnog tumačenja AGRU. Druga razlika su značajno izmenjene granice područja kvarova sa pojavom novih područja D+T1, D+T2 i D+T3.
Autor je prikupio veći broj AGRU za koje se može sa sigurnošću utvrditi postojanje jednostrukih kvarova ili višestrukih kvarova. To su slučajevi gde je obavljen podroban pregled nakon kvara sa fotografijama ili su vršene učestale AGRU ili se vrši stalno praćenje AGRU ili su vršena različita ispitivanja koja potvrđuju kvar, nekad i više navedenih stavki zajedno. Poređena su tumačenja AGRU nekoliko različitih metoda podrobno po vrsti kvara i zajedno za sve kvarove. Poređenje je vršeno po tome da li se kvar prepoznaje ili ne, a ukoliko prepoznaje da li je tumačenje ispravno ili ne. Metode koje se porede su: Unapređeni trougao, Duvalov trougao 1, Dernenburg, Rodžersovi odnosi, IEC odnosi i MSS.

KLJUČNE REČI: Unapređeni trougao, Duvalov trougao 1, analiza gasova rastvorenih u ulju, kvar

SUMMARY

For many years different methods for interpretation of results of dissolved gas analysis (in following text: DGA) were in use: Doernenburg, Rogers ratios, MSS (Mueller, Schliesing and Soldner), Duval Triangles, Universal triangle, Key Gas, Logarithmic nomograph, IEC ratios, IEEE, Gas pattern analysis method, Japan ETRA diagnostic diagram,... Basically all methods deals with single or pure faults. Some of methods have certain area of mulitple or mixed faults. Widely adopted hypothesis among academics and experts is that percentage of multiple faults among all faults is small which is incorrect.
During years some of the methods have significant changes. Among them is Duval triangle which had significant borders modification between all areas with appearance of new area of multiple faults of electrical discharges and overheating DT in present Duval triangle 1. New method is Improved triangle which improves Duval triangle 1. First difference is that on side of Duval triangle 1 with Methane Improved triangle has Mthane and Ethane. Methane and Ethane are gases of similar thermal range and absence of Ethane, which is gas which appears at low temperatures range, could lead to wrong DGA interpretations. Second difference is significant modifications of borders between fault areas with appearance of new areas D+T1, D+T2 and D+T3.
Author has collected a large number of DGA for which is possible to determine with certainty the existence of single faults or multiple faults. These are the cases where a detailed visual inspection was carried out after fault

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or failure with a photos or frequent DGAs or DGA monitoring or different tests were carried out confirming the fault, sometimes several of mentioned items together. The interpretations of DGAs of several different methods are compared in detail by type of failure. Comparison is made by whether or not fault is recognized, and if fault is recognized whether the interpretation is correct or not. The methods that are compared are: Improved Triangle, Duval Triangle 1, Doernenburg, Rogers ratios, IEC Ratios and MSS.

KEY WORDS: Improved triangle, Duval triangle 1, dissolved gas analysis, fault

INTRODUCTION

For many years different methods for interpretation of results of dissolved gas analysis (in following text: DGA) were in use: Doernenburg, Rogers ratios, MSS (Mueller, Schliesing and Soldner), Duval Triangles, Universal triangle, Key Gas, Logarithmic nomograph, IEC ratios, IEEE, Gas pattern analysis method, Japan ETRA diagnostic diagram,... Basically all methods deals with single or pure faults. Some of methods have certain area of mulitple or mixed faults. Widely adopted hypothesis among academics and experts is that percentage of multiple faults among all faults is small. Main reason is fact that majority of existed methods recognize mostly single faults, i.e. majority of DGA interpretations are single faults even if significant number have multiple faults.

During years some of the methods have significant changes. Among them is Duval triangle which had significant borders modification between all areas with appearance of new area of multiple faults of electrical discharges and overheating DT in present Duval triangle 1. New method is Improved triangle which improves Duval triangle 1. First difference is that on side of Duval triangle 1 with Methane Improved triangle has Methane and Ethane. Methane and Ethane are gases of similar thermal range and absence of Ethane, which appears in significant quantities only at low temperatures range, could lead to wrong DGA interpretations. Second difference is significant modifications of borders between fault areas with appearance of new areas D+T1, D+T2 and D+T3.

Author has collected a large number of DGA for which is possible to determine with certainty the existence of single faults or multiple faults. These are the cases where a detailed visual inspection was carried out after fault or failure with a photos or frequent DGAs or DGA monitoring or different tests were carried out confirming the fault, sometimes several of mentioned items together. The interpretations of DGAs of several different methods are compared in detail by type of fault. Comparison is made by whether or not fault is recognized, and if fault is recognized whether the interpretation is correct or not. The methods that are compared are: Improved Triangle, Duval Triangle 1, Doernenburg, Rogers ratios, IEC Ratios and MSS. Benefits of Improved triangle for engineers who deals with DGA are more accurate fault determination and easier determination of multiple faults.

IMPROVED TRIANGLE

Improved triangle was created on the basis of Duval Triangle 1, which is most commonly used in the interpretation of DGA results. The old Duval Triangle [1] from 1989 is shown in Figure 1. Due to new cognitions there were significant changes in the boundaries of the old Duval Triangle for mineral insulating oils. The boundaries and ranges of thermal fault temperatures have changed significantly, and a new area of multiple or mixed electrical and thermal faults has emerged.

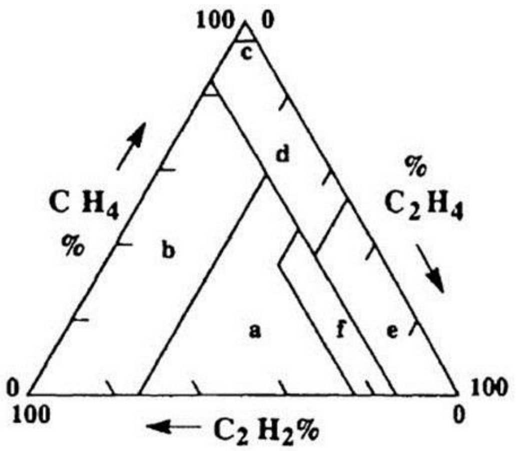

Figure 1 – Old Duval Triangle from 1989

Description of old Duval Triangle areas:
a) High-energy arcing
b) Low-energy arcing
c) Corona discharges
d) Hot spots, T<200 ^oC
e) Hot spots, 200<T<400 ^oC
f) Hot spots, T>400 ^oC

A lot of fault cases with DGA results, visual inspection and laboratory experiments gave cognitions that significant number of DGA cases are of DT faults. According to considered DGA database small percentage of DGA results with DT faults confirmed by visual inspection or by DGA monitoring enter DT area of modern Duval Triangle 1.
Modern Duval Triangle 1 [2] is shown in Figure 2.

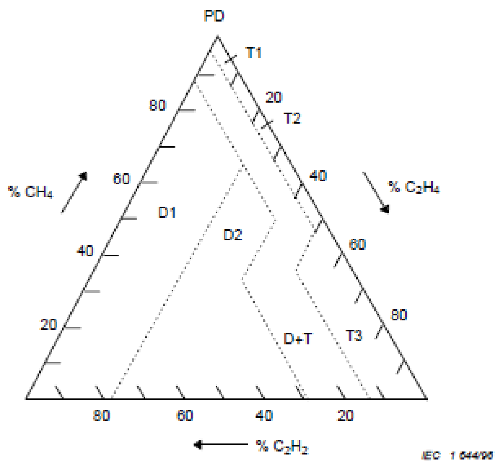

Figure 2 – Present Duval Triangle 1

Description of modern Duval triangle areas:
D2) High energy discharges
D1) Low energy discharges
DT) Mixtures of electrical and thermal faults
PD) Partial discharges
T1) Thermal faults T<300 ^oC
T2) Thermal faults 300<T<700 ^oC
T3) Thermal faults T>700 ^oC
Long-term consideration of various cases of faults from personal experience and other sources have provided new cognitions which led to the Improved Triangle [3] shown in Figure 3.

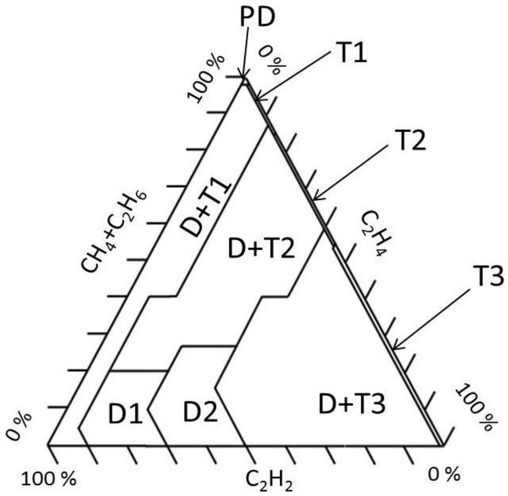

Figure 3 – Improved Triangle

Description of Improved Triangle areas are:
D2) High energy discharges
D1) Low energy discharges
D+T1) Mixtures of electrical and thermal fault T1
D+T2) Mixtures of electrical and thermal fault T2
D+T3) Mixtures of electrical and thermal fault T3
PD) Partial discharges
T1) Thermal faults T<300 ^oC
T2) Thermal faults 300<T<700 ^oC
T3) Thermal faults T>700 ^oC
Further considerations of the Improved Triangle indicate the need to partially change the borders shown here in order to further improve the borders and improve the interpretation of DGA results. Part of the necessary changes has been considered and the remainder is to be processed.

Basics which lead to new borders in Improved Triangle are:
- Pure D1 and D2 types of faults are clustered in relatively small areas. A lot of cases with frequent sampling or monitoring confirm absence of any type of fault before electrical discharging type of fault.
- Mixed thermal and electrical discharge faults are frequent. A lot of cases with frequent sampling or monitoring and visual inspection confirm thermal fault before fault with sparking or arc.
- Thermal faults must be placed at the triangle side or very close to it.
- Sources of Acetylene generation are sparking and arcing types of discharge.
- Absence of Ethane could lead to incorrect interpretation. Ethane can be placed on the triangle side along with methane because they have similar temperature ranges on which they are generated.

Further considerations and examples will indicate the reasons and the need to change and thus improve modern Duval Triangle 1. The most common cause of overheating are bad contact surfaces. Other could be blocked ducts, circulating currents, bad designing (low cross-sections of leads, core), stray flux, bad cooling, overloading, absence of ventilation or pumping and other types of errors. Focus will be on bad contact areas which source could be lose bolts, low contact pressure at De-Energized Tap Changer (DETC) contacts or selector contacts of On-Load Tap Changer (OLTC), bad welded or soldered joints. There is empirical evidence that long-term formation of contact surface layer starts with surface oxidation and the formation of organic polymers which reduce the conductivity [4-7]. The decomposition of transformer insulation oil leads to the deposition of carbon between the contacts [4]. This formation of pyrolytic carbon is called coking [8]. Experiments show that the surface film grows thicker as the contacts age, and that the growth rate of this layer is strongly dependent on the surface temperature of the contacts [9, 10].
The contact resistance can also fall during the long-term aging, as the surface film breaks down due to discharges or contact wiping. Small discharges can restore a better current path by disrupting the surface film, but the contact resistance can increase by several orders of magnitude before the contact improves again. These discharges become worse as degradation proceeds, and the oil dissociates due to these discharges and the high contact temperatures. These effects together constitute advanced long-term aging [4]. Different contacts faults

interpreted by present Duval Triangle 1 mainly as T3 reveal fact that in a lot of cases Ethylene quantities exceed 1000 ppm but without Acetylene appearance. Estimated temperatures according to gas ratios are higher than 700 ^{o}C but without Acetylene. Where is Acetylene? There was no Acetylene because there was no low or high energy discharges. Acetylene evaporation from oil is slow [11]. In some cases it is possible that small discharges of sparking type occur forming low quantity of Acetylene and then disappear as Acetylene disappear from oil during time.
In Figure 4 [3] all DGA results are showed, including those without visual inspection or frequent DGA or monitoring or different tests, i.e. including those which fault was not proven. Figure 5 shows the DGA results for the fault cases that have been proven. Figure 6 shows Duval triangle 2 for diverter switch compartments of OLTC for mineral insulating oil.

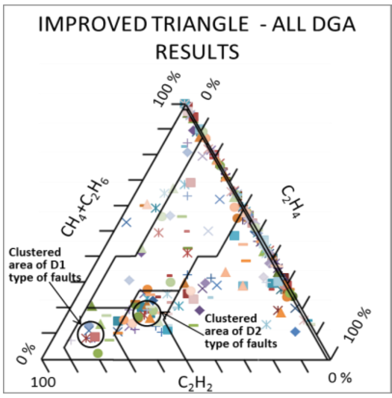

Figure 4 – All DGA results

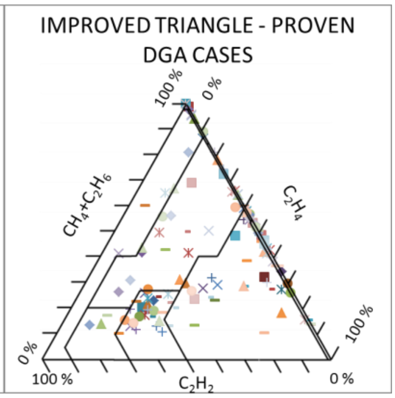

Figure 5 – Proven DGA cases

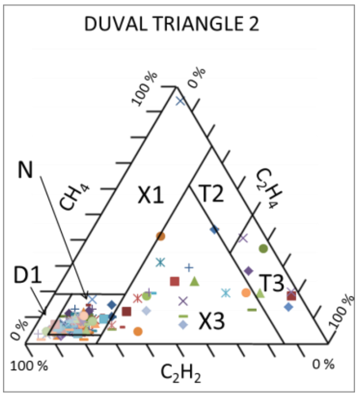

Figure 6 – Duval Triangle 2

Ther are more proven cases in Figure 5 than in Figure 4. The distribution of points of proven and unproven cases is very similar. It is known that low energy discharges occur in the normal operation of the diverter switch compartment of OLTC and that these results are clustered on a relatively small area of Duval's triangle 2 in the area N and in the area D1. Description of X1 area in Duval Triangle 2 is an abnormal electrical discharge or the development of a thermal fault. This consideration confirms the need for decreasing the relatively large area D1 in Duval Triangle 1 and to be as in the Improved Triangle. Possible causes of defective borders in Duval Triangle 1 are the use of old DGA results without detailed visual inspection and/or without monitoring, as well as the use of laboratory DGA results where low energy discharging can be easily occur during partial discharge testing and thermal tests T2 and T3. Often, due to the large damage caused by electrical discharges, the overheating site can not be spotted or, due to severe overheating in a small area, it can not easily be seen damage from low electrical discharges or other type of fault.

COMPARISON OF THE IMPROVED TRIANGLE AND OTHER METHODS

For the comparison of the Improved Triangle and other methods, author's DGA results and other DGA results were used. Comparison of the following methods was performed: Improved Triangle, Duval Triangle 1, Doernenburg [12], Rogers ratios [12], IEC ratios [2] and MSS (Mueller, Schliesing and Soldner) [13]. A comparison had to include certain assumptions:
- Because Doernenburg method recognizes only a thermal faults without classifying the temperature range and because different methods have different temperature ranges any interpretation that gives any kind of thermal fault is accepted as a correct interpretation in a unified comparison. For most of the faults which most of the methods recognize as T1, usually there is no visual prove, but they are still included in the analysis. That's 10 out of a total of 40 faults of types T1, T2 and T3.
- In the Doernenburg and Rogers methods for checking methods possibilities gases limitations of 2xL1 and L1 at the beginning of the algorithm are neglected. In case these limits are used, the percentage of recognition of faults is less than 50%. The data from [13] is taken for limit concentration of Acetylene, which is more favorable for both methods.
- For mixed faults such as electrical discharges and thermal faults DT or D+T whether methods recognize or not recognize such faults, i.e. they have not got such interpretation, D type of interpretation is accepted as correct interpretation because electrical discharge D is more dangerous than thermal fault T.
- Propylene (C_3H_6) was not used in the MSS method because this gas is not often tested except in several countries. There is no significant error in the recognition of the fault and the interpretation of DGA.
A total of 150 faults were processed. Table 1 shows faults by type and number.

TABLE 1 – FAULTS BY TYPE AND NUMBER

Fault type	T (T1+T2+T3)	D (D1+D2)	D+T (D+T1)+(D+T2)+(D+T3)	PD	PD+T
Fault number	40 (10+18+12)	34 (3+31)	55 (4+17+34)	13	8

The numerical ratio of faults shown in Table 1 does not correspond to the one in practice. The relative majority of faults in practice are thermal faults especially faults of type T3. The least numerous thermal faults are of T1 type. Next numerous are D+T types of fault, of which the most frequent are D+T3, and of these the most frequent are D2+T3. Of the pure D faults, there is far more of D2 type than D1 type. In addition to the faults listed in Table 1, there are also D+T+PD faults and mixed D+PD. Multiple or mixed faults may be located in the same place, but may also be located in different locations. Therefore, after the failure, it is necessary to carry out a detailed check of all data, if it is possible carry out all possible tests and, if possible, a detailed inspection of the interior of the equipment during the dismantling of the equipment elements.
The first comparison was made for the percentage of recognition of faults. Table 2 shows the results of the methods comparison to recognize the fault. Recognition of a fault means that the method gives an interpretation, but this interpretation does not have to be correct.

TABLE 2 – METHODS COMPARISON ACCORDING TO FAULT RECOGNITION

Method	Total faults	Fault not recognized – no interpretation	Fault recognized	Percentage of recognition
Improved triangle	150	0	150	100.00
Duval Triangle 1	150	0	150	100.00
IEC 60599	150	28	122	81.33
MSS	150	33	117	78.00
Doernenburg	150	80	70	46.67
Doernenburg[1]	150	35	115	76.67
Rogers	150	88	64	42.67
Rogers[1]	150	47	103	68.67

[1] After the condition for gas limits of 2xL1 or L1 has been eliminated.

Table 2 shows that, with regard to recognition of fault, more reliable are new methods Improved Triangle and Duval Triangle 1. Methods IEC 60599 and MSS have approximately the same percentage of recognition of faults. Doernenburg and Rogers method in the case that gas limits 2xL1 or L1 are in use has an exceptionally low percentage of fault recognition.
Some other mutual relation of number of faults by type would yield different results compared to those in Table 2, probably with an increased percentage of recognition of faults for all methods except the Improved Triangle and Duval Triangle 1 which are set to always give an interpretation.
In Table 3 the methods are compared according to correct interpretations by type of faults.

TABLE 3 – METHODS COMPARISON ACCORDING TO CORRECT INTERPRETATIONS [2,3]

Fault type	T (T1+T2+T3)	D (D1+D2)	D+T (D+T1)+(D+T2)+(D+T3)	PD	PD+T	Correct interpret.[2,3]	% correct interpret.[2,3]
Total fault type	40	34	55	13	8	153	100.00
Improved Triangle	40	34	55[2]	13	4[3]	146[2,3]	97.33
Duval Triangle 1	40	34	25[2]	13	4[3]	116[2,3]	77.33
IEC 60599	38	31	8[2]	6	2[3]	85[2,3]	55.56
MSS	37	31	14[2]	7	2[3]	91[2,3]	59.48
Doernenburg	24	15	3[2]	0	0[3]	42[2,3]	27.45
Doernenburg[1]	37	34	9[2]	7	2[3]	89[2,3]	58.17
Rogers	20	14	6[2]	0	0[3]	40[2,3]	26.14
Rogers[1]	28	27	12[2]	6	2[3]	75[2,3]	49.02

[1] After the condition for gas limits of 2xL1 or L1 has been eliminated.
[2] In the case of non-recognition of the fault of type DT or D+T, D is accepted as the correct interpretation.
[3] In the case of non-recognition of the fault of type PD+T, PD is accepted as the correct interpretation.

From Table 3 it can be seen that all methods including Doernenburg[1] and Rogers[1] have a high percentage of correct interpretations for T and D faults. Improved Triangle and Duval Triangle 1 provide the correct interpretation for PD faults while the other methods are approximately half-way. Only Improved Triangle provides correct interpretation for DT or D+T faults. Duval Triangle 1 recognizes 25 out of 55 faults of type DT or D+T, which is 45.45% only because D2 and D1 are accepted as DT or D+T, and if D2 and D1 were not accepted, the correct interpretation would be in only 6 cases. In this case Duval Triangle 1 would give only 64.67% correct interpretations for the considered sample. In several cases, there are D+PD+T and D+PD faults that are not shown in Table 3 so all methods for such faults have an error so percentage of correct interpretations for all methods must be reduced by several percentages. Some other mutual relation of number of faults by type which corresponds to that from practice would get better percentages of correct interpretations for all methods.

Below are some examples of D+T faults that confirm the error made by Duval Triangle 1 setting D+T faults in areas D or T. Several other DGA cases of D+T types are also shown in [3].

In Table 4 and Figures 7 and 8 fault case D+T3 is shown, confirmed by the frequent DGA and visual inspection. In the triangle of Figure 8 the area borders with full lines are for the Improved Triangle, and the dashed lines for Duval Triangle 1 where CH_4 is used on the triangle side denoted CH_4+C_2H_6. The square shaped point is for the Improved Triangle and the rhomb shaped point is for the Duval Triangle 1. The same will be in the following cases.

TABLE 4 – FREQUENT DGA

Date	H_2 (ppm)	CH_4 (ppm)	C_2H_2 (ppm)	C_2H_4 (ppm)	C_2H_6 (ppm)	CO (ppm)	CO_2 (ppm)
20160620	364	459	181	1543	360	305	1905
20151123	108	324	22	1260	344	410	2267
20150222	80	295	6	1303	445	232	2182
20130910	6	64	5	314	67	300	2693
20120705	5	42	1	273	67	391	3177
20110704	9	60	2	308	75	340	2863
20100324	11	107	1	474	97	315	3086
20090413	18	249	2	872	159	332	3521

Figure 7 – Appearance of movable contacts

DGA from 2009 showed the dominant thermal fault T3 and the measurement showed resistance problem at the contacts of the DETC. Contacts were wiped by moving which led to a reduction in the amount of gases until 2013 when again the amount of gases showed growing. The last DGA of 20160620 was made after the Buchholz trip which together with the significant damage of one moving contact due to electric arc and the larger and minor damages of other contacts due to sparking in Fig. 7 clearly shows D fault. The previous DGAs with the amounts of acetylene of 2 ppm or more indicate that even before there were small sparking and obviously there was a dominant thermal fault T3. So D+T3 (D2+T3). Duval Triangle 1 gives incorrect interpretation setting a point in the T3 area, Doernenburg, IEC 60599 and MSS give a T type fault, and Rogers has no interpretation.

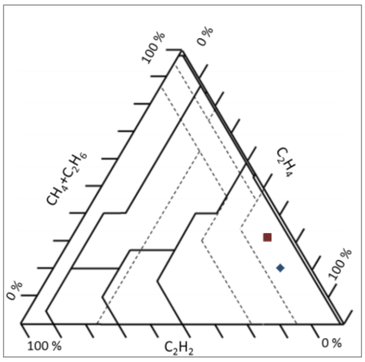

Figure 8 – Last DGA form 20160620

Figure 7 shows pairs of movable contacts, some of which are more and some are less damaged. The plate of the movable contacts is made of brass, while the pair of copper contacts is attached to the brass plate and further on the DETC lath. The melting point of the copper is 1084 ^{o}C and the brass is 900-940 ^{o}C. Movable contacts that are not shown are made of brass and have small damage from small sparking. The conclusion is that due to poor contact there is overheating, coking with further development of temperature and sparking appearance which made damage on contact surfaces which can ultimately lead to strong electrical discharges. In this and other cases more significant damages are on brass parts than on copper.

Table 5 and Figure 9 show the fault case D+T2 confirmed by visual inspection [14].

TABLE 5 –DGA CASE

Date	H_2 (ppm)	CH_4 (ppm)	C_2H_2 (ppm)	C_2H_4 (ppm)	C_2H_6 (ppm)	CO (ppm)	CO_2 (ppm)
-	550	80	141	125	40	83	1634

Figure 9 – Flashover marks, overheating and triangle

From Figure 9 on the left it can be seen that it was an electrical discharge (flashover) in accordance with the Buchholz trip. Figure 9 in the middle shows the overheating which was also present at other places. Figure 9 on the right shows points in the Improved Triangle and Duval Triangle 1. This fault is located near the area D2 of the Improved Triangle indicating that the fault is the dominant D type (in this case D2+T2 type). Because of non-recognition of thermal fault beside electrical fault incorrect interpretations give Duval Triangle 1 with interpretation D2, Doernenburg[1] as an electric arc, the Rogers[1] as high energy discharging, and the IEC 60599 and MSS as low energy discharging.
Table 6 and Figure 10 show the fault case D+T2 confirmed by visual inspection [15].

TABLE 6 – DGA CASE

Date	H_2 (ppm)	CH_4 (ppm)	C_2H_2 (ppm)	C_2H_4 (ppm)	C_2H_6 (ppm)	CO (ppm)	CO_2 (ppm)
20061018	2480	5126	32	6035	1782	634	1636
20060607	171	782	11	1423	609	148	814

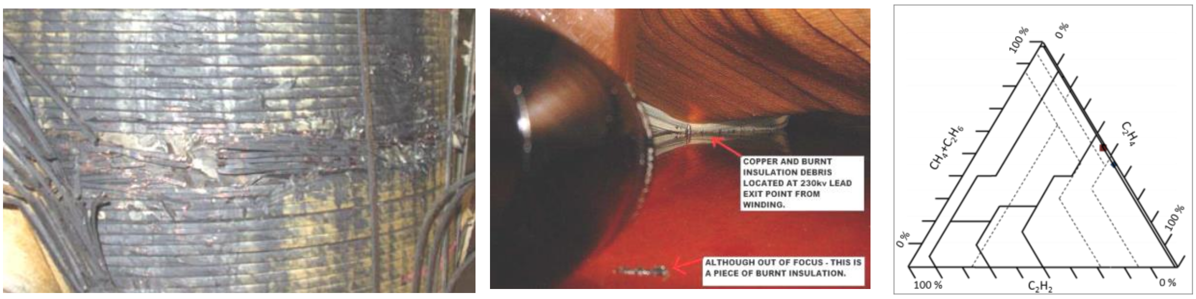

Figure 10 – Electrical discharges, overheating and triangle

Figure 10 on the left shows obvious electrical discharges even though there was no Buchholz alarm and/or trip. Dust and pinhead sized copper particles have been found. This indicates that the electrical discharges were smaller and long-term without free gases because gases dissolved in oil or collected in vessel pockets. Figure 10 in the middle shows overheating that was present at other places, too. Figure 10 on the right shows the points in the Improved Triangle and Duval Triangle 1 for DGA result from the first row of Table 6 as of 20061018. The fault can be interpreted as a fault of D1+T2 type. Duval triangle 1 gives incorrect interpretation for both DGAs from Table 6 by setting points in the T3 area, because both DGAs are of D+T fault with the dominant thermal fault. For Doernenburg, Rogers, IEC 60599 and MSS there is a wrong interpretation of the T type of fault.
Many DGA cases with a small amount of Acetylene and large amounts of "thermal" gases are interpreted as T type of fault. Only the Improved Triangle places such cases in the D+T areas, which instructs the user to perform additional checking for the possible uncertainty of the laboratory or oil testing equipment or possible oil contamination by fault gases from OLTC or through a common conservator. After checking the data the user will, if necessary, take a repeat sample for DGA. The cases in Table 4 and 6 as well as two examples from [3] show misinterpretation of all methods except the Improved Triangle.
Table 7 and Figures 11 and 12 show fault D+T2 confirmed by the visual inspection and the frequent DGAs [16].

TABLE 7 – DGA CASE

Date	H_2 (ppm)	CH_4 (ppm)	C_2H_2 (ppm)	C_2H_4 (ppm)	C_2H_6 (ppm)	CO (ppm)	CO_2 (ppm)
20051118	2800	1950	1450	1600	400	1300	-

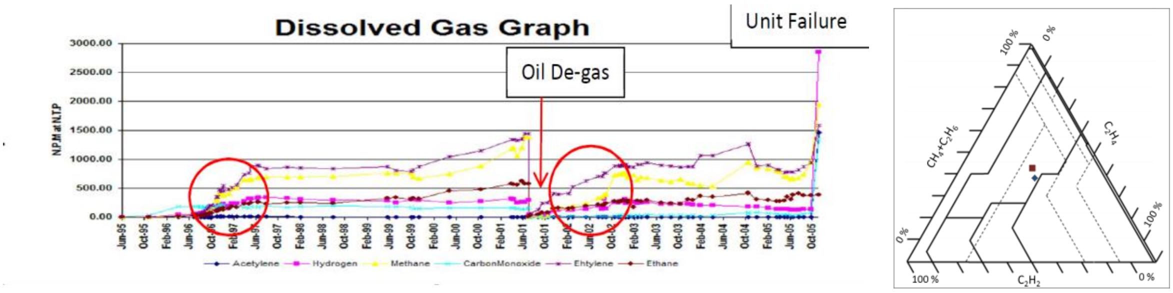

Figure 11 – Changes in gases quantities and last point in triangle

In Figure 11 on the left changes in gases quantities are shown. Obviously there was a thermal fault before the failure of the transformer. The sample was taken after the transformer trip due to the operation of protective devices. Table 7 shows the last right point from Figure 11 on the left. Figure 11 on the right shows the points in the Improved Triangle and Duval Triangle 1.

Figure 12 – Electrical discharges and overheating

Figure 12 on the left shows the location of a strong electrical discharge. Figure 12 in the middle and the right shows places of overheating. Visual inspection and frequent DGAs confirm that the fault is type D+T (D2+T2). Duval triangle 1 has incorrect interpretation setting a point into D2 area, Doernenburg as an electric arc, Rogers, IEC 60599 and MSS as high energy discharging. In this case there is no dominant fault.

CONCLUSION

Considerations of a large number of DGA cases and the revision of existing methods have led to introduction of Ethane together with Methane on one side of triangle, to new borders and areas D+T1, D+T2 and D+T3 in the Improved Triangle.
DGA cases with a detailed visual inspection, frequent sampling, monitoring and different tests show that a large number of cases of D+T faults are not recognized as fault by most of the existing methods or misinterpreted as D or T type of fault. By comparing with other methods, the Improved Triangle gives the best interpretation of DGA results and the next in quality is the Duval Triangle 1. The other methods discussed here are far worse both in terms of the percentage of recognition of the faults and the percentage of the correct interpretation of the faults.
D+T fault cases shown here, like many others, clearly show that using Improved Triangle gives a more accurate interpretation of the faults.
Consideration of additional DGA cases will lead to further upgrading of borders of the Improved Triangle.
The next field of research is the thermal triangle with new borders.

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