

Dissolved Gas Analysis (DGA) for Natural Ester-Filled Transformers

As the adoption of natural ester continues to grow in momentum due to its multiple benefits, it is also becoming increasingly important to understand the application of dissolved gas analysis (DGA) for natural ester-filled transformers, particularly since the fluid has also been widely used in power transformers which rely heavily on DGA for condition monitoring and maintenance.

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Based on the properties and gassing pattern of natural ester fluid as compared to conventional mineral oil, this article reviews how the commonly used methodologies for interpreting DGA results can be applied to natural ester-filled transformers.

IMPORTANCE OF DEVELOPING DISSOLVED GAS ANALYSIS (DGA) CAPABILITY FOR NATURAL ESTER TRANSFORMERS

Since its introduction in the 1960s, DGA has become one of the most widely used non-destructive diagnostic tool for condition monitoring of transformers. While in general DGA is capable of providing a reliable and economical method for evaluating conditions and detecting possible faults in transformers, interpretation of DGA results is also fundamentally more difficult than many of the other used fluid analysis tests due to the susceptibility to interference of normal variations of gas concentrations caused by the changeable loading and environmental conditions, as well as the unavoidable random errors in sample taking, handling and testing, etc.. To better detect, identify and assess the genuine equipment faults and the severity, gas concentrations and generation rate (derived from trending of past DGA results) would have to be evaluated using established methods in conjunction with the operation and maintenance records as well as experience from industrial practice.

Based on large amount of DGA data collected from mineral oil transformers over the decades, technical guides are widely available to aid the interpretation of DGA results for fault identification [1-4]. On the other hand, as natural ester-filled transformers have only been in commercial use since the 1990s, the opportunities to evaluate the actual equipment faults are obviously limited.

As natural ester fast becomes the preferred choice of dielectric fluid in most applications including power grade transformers up to 750kV due to its intrinsic sustainability as a biobased fluid from renewable source and the other benefits in improving the safety, reliability and loading capacity of transformers [5-7], there is also a pressing need to interpret DGA results from in-service natural ester fluid with high level of confidence. With consideration to the different properties and gassing pattern observed from the relevant fluid samples, DGA guides for non-mineral oil fluids have been developed to enable the commonly used diagnostic and fault identification methods to be adopted for natural ester-filled transformers [8-9].

KEY DIFFERENCES IN THE GASSING OF NATURAL ESTER AND MINERAL OIL

While the same sampling and testing methods can be used for DGA of natural ester fluid, its very different molecular structure (Figure 1) means that the ratio and the generation rate of the various key gases can be very different,

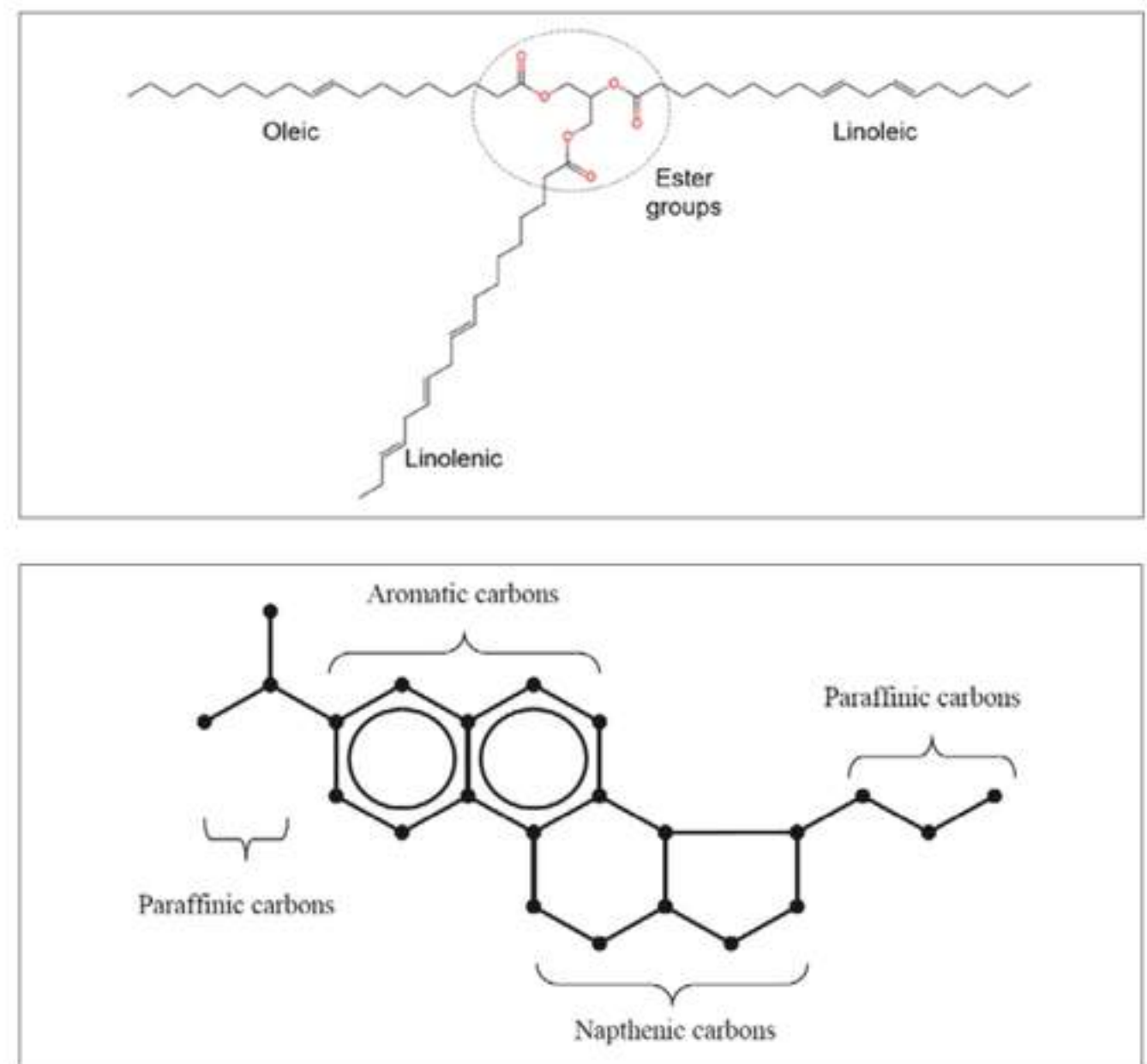


Figure 1 Typical molecular structure of natural ester (top) and mineral oil (below)

and the common methods of interpretation for mineral oil would therefore need to be modified.

Comparing the thermal decomposition test results obtained from mineral oil and the most commonly used natural ester fluid derived from soybean crop (Table 1), it is clear that the gassing tendency of the latter is in general significantly higher [10]. This is particularly so for ethane (C₂H₆), hydrogen (H₂) and carbon oxides (CO and CO₂), and in such cases the inceptions of gas generation also start at much lower temperature.

Stray gassing tests conducted according to the ASTM standard (air sparge at 120 °C for 24 hours) [11] and the CIGRE testing regime [12] confirms the tendency for natural ester to evolve ethane (C₂H₆), hydrogen (H₂) and carbon oxides (CO and CO₂) as the main stray gases [8]. In addition, as the generation of ethane gas is primarily due to the oxidation of linolenic acid, the stray-gassing tendency of rapeseed-

Temperature (°C)		250	350	450	500	550	600	650	700
H ₂ (ppm)	Mineral oil	0	65	308	635	3,415	112,760	1,349,634	7,248,321
	Natural ester	183	453	14,578	92,064	449,630	951,663	1,898,615	5,336,773
CH ₄ (ppm)	Mineral oil	15	77	281	1,135	14,060	525,596	5,562,060	18,288,865
	Natural ester	9	36	5,427	32,265	426,389	2,555,117	5,176,221	15,591,740
C ₂ H ₆ (ppm)	Mineral oil	0	9	181	606	7,688	403,924	2,989,009	7,135,061
	Natural ester	321	495	12,584	46,790	518,002	2,666,376	5,163,518	11,721,018
C ₂ H ₄ (ppm)	Mineral oil	0	2	26	502	8,254	528,885	5,156,563	15,505,831
	Natural ester	2	9	12,620	66,570	549,371	6,377,429	13,599,997	37,426,253
C ₂ H ₂ (ppm)	Mineral oil	0	0	0	0	0	0	1,506	4,140
	Natural ester	0	0	0	0	0	3,573	8,213	33,494
CO (ppm)	Mineral oil	23	156	220	256	166	478	5,458	12,096
	Natural ester	138	388	159,834	846,321	4,476,588	8,535,474	9,782,953	15,715,859
CO ₂ (ppm)	Mineral oil	392	540	699	653	866	4,524	51,091	121,840
	Natural ester	528	660	150,631	663,328	3,110,067	5,863,817	6,839,063	9,506,162

Table 1 Gassing tendency of soybean based natural ester fluid in laboratory pyrolysis test as compared to mineral oil

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based fluid, another commonly found natural ester which contains higher level of linolenic acid, is also significantly higher than the soybean based product (Table 2 and Figure 2).

Natural ester type	Soybean based	Rapeseed based
Linolenic acid content	~7%	~9%
H ₂ (ppm)	316	289
CH ₄ (ppm)	10	60
C ₂ H ₆ (ppm)	563	3,694
C ₂ H ₄ (ppm)	7	19
C ₂ H ₂ (ppm)	0	0
CO (ppm)	408	503
CO ₂ (ppm)	1,330	1,696

Table 2 Stray gassing of soybean based and rapeseed based natural ester fluids under the ASTM testing regime (air sparge at 120 °C for 24 hours) [8]

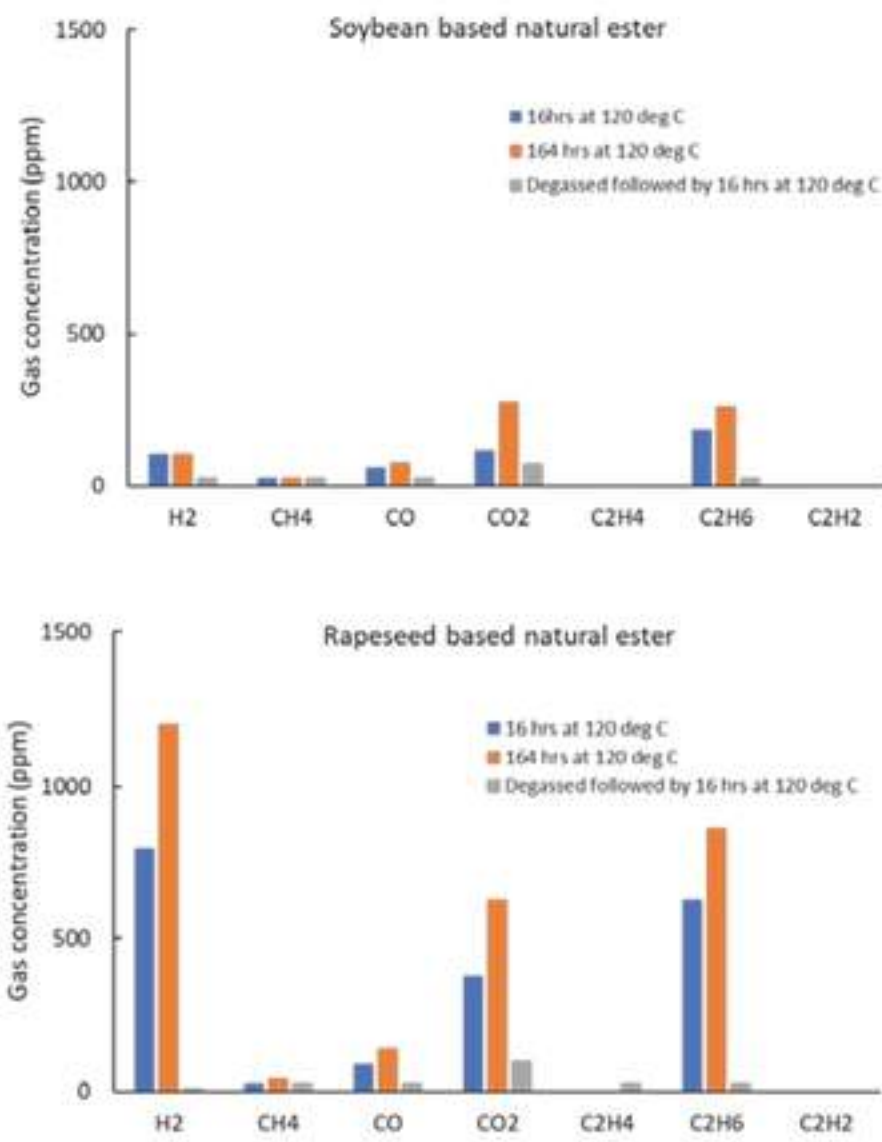


Figure 2 Stray gassing of soybean based (above) and rapeseed based natural ester fluids under the CIGRE testing regime [12-13]

ASSESSMENT OF DGA RESULTS FROM NATURAL ESTER TRANSFORMERS

Based on the latest version of the IEEE DGA Guide for mineral oil [1], the key steps of assessing DGA results are essentially about categorising them into one of the three status level using the threshold (90th and 95th percentile) values derived from historical data obtained from the same type of fluid as shown in Figure 3.

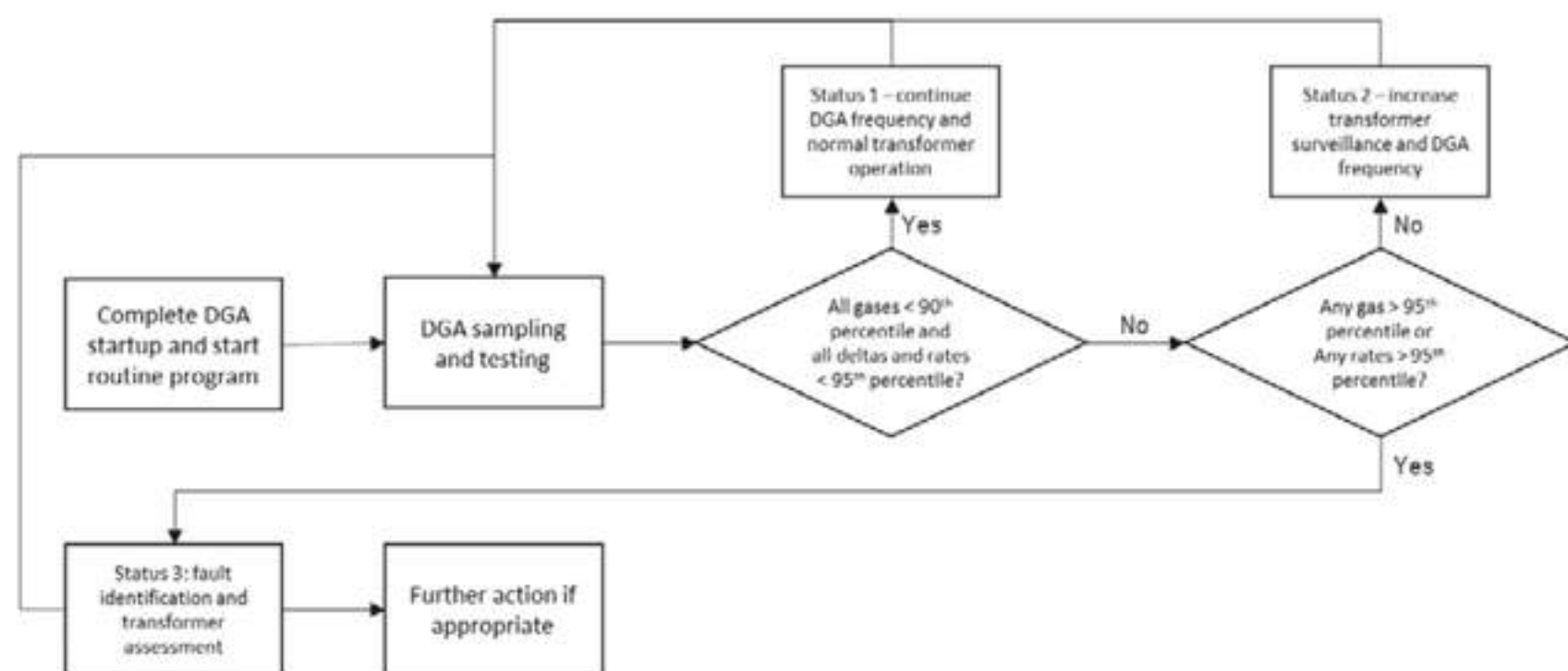


Figure 3 Categorisation of DGA results based on the threshold (percentile) values of absolute gas concentrations and increase rate

Gas	90 th percentile (ppm)				95 th percentile (ppm)			
	Mineral oil (O ₂ /N ₂ ratio ≤0.2)	Mineral oil (O ₂ /N ₂ ratio >0.2)	Soy based natural ester		Mineral oil (O ₂ /N ₂ ratio ≤0.2)	Mineral oil (O ₂ /N ₂ ratio >0.2)	Soy based natural ester	
			Threshold	95% CI			Threshold	95% CI
H ₂ (ppm)	80	40	112	105-118	200	90	171	160-188
CH ₄ (ppm)	90	20	20	19-22	150	50	41	34-39
C ₂ H ₆ (ppm)	90	15	232	219-247	175	40	389	351-444
C ₂ H ₄ (ppm)	50	50	18	17-20	100	100	36	33-44
C ₂ H ₂ (ppm)	1	2	1	1-1	2	7	3	2-3
CO (ppm)	900	500	161	150-179	1,100	600	462	385-562
CO ₂ (ppm)	9,000	5,000	-	-	12,500	7,000	-	-

Table 3 Percentile-based key gases thresholds for soybean based natural ester fluid as compared to mineral oil [8]

As the most widely used dielectric fluid in the market apart from mineral oil, the percentile-based threshold gas values for soybean based natural ester are by far the most robust among the alternative fluids as indicated by the narrow range of variability (the 95% confidence interval (CI)) as shown in Table 3 [8]. It is therefore highly feasible to use the same criteria as shown in Figure 3 to assign the status level of the DGA results from in-service soybean based natural ester fluid based on the corresponding 90th and 95th percentiles. Even though the threshold values for the gas generation rate in natural ester fluid are not yet established, by comparing the percentile threshold values of the two fluids as shown in Table 3, the thresholds of the gas generation rate in mineral oil can still be applied to help to assess the DGA results of natural ester fluid, maybe with the exception of ethane (C₂H₆) gas.

More recently a new approach was also proposed to assess DGA results from mineral oil transformers using the normalised energy intensity (NEI) [14]. Based on this methodology, the NEIs (in kJ/kl) for oil and paper insulations are calculated from the relevant key gases' concentrations (in ppm) and the energy (enthalpies) (in kJ/mole) required to generate the individual gas from n octane:

$$NEI_{oil} = (77.7[CH_4] + 93.5[C_2H_6] + 104.1[C_2H_4] + 278.3[C_2H_2]) / 22400 \quad \text{(Equation 1)}$$

$$NEI_{paper} = (101.4[CO] + 30.2[CO_2]) / 22400 \quad \text{(Equation 2)}$$

Due to the robust DGA percentile threshold data for soybean based natural ester fluid, the corresponding normalised energy intensity (NEI_{NE}) threshold values can be calculated with high level of confidence in the same way as mineral oil using Equation 3 (Table 4).

$$NEI_{NE} = (105[CH_4] + 114[C_2H_6] + 486[C_2H_4] + 846[C_2H_2]) / 22400 \quad \text{(Equation 3)}$$

Against the threshold values of L1-3 as shown in Table 4, the NEI_{NE} calculated from any sets of DGA results from natural ester transformers using equation 3 can be evaluated to obtain the gas scores as shown in Table 5 which provide insight to the equipment condition and the response actions that to be considered [14].

N ₂ /O ₂ ratio	Mineral oil			Natural ester fluid		
	L1 (90 th percentile)	L2 (95 th percentile)	L3 (98 th percentile)	L1 (90 th percentile)	L2 (95 th percentile)	L3 (98 th percentile)
<5.94	0.39	0.72	1.98	1.70	3.07	7.74
≥5.94	1.02	1.87	4.00			

Table 4 NEI_{oil} percentile values for mineral oil and soybean based natural ester fluid

Criteria	Gas score	Condition/recommended response actions
NEI ≥ L3	4.0	Emergency, advanced deterioration
L2 ≤ NEI < L3	3 + (NEI - L2)/(L3 - L2)	Higher urgency investigation and testing
L1 ≤ NEI < L2	2 + (NEI - L1)/(L2 - L1)	Precautionary investigation, testing
NEI < L1	1 + NEI/L1	Normal operation

Table 5 Criteria for evaluating the NEI values from DGA results [14]

FAULT TYPE IDENTIFICATION FOR NATURAL ESTER TRANSFORMERS

The prerequisite for applying fault type identification is the confirmation of an existing fault based on the threshold gas concentrations and the gas generation rates as described above [1]. While most of the commonly used fault type identification methods based on key gas concentrations or simple gas ratios as shown in Table 6 [1-2] can be applied to natural ester fluid to a certain extent, interpretation would need to be made with caution since the potentially higher concentration of ethane and hydrogen gases would affect the resultant gas ratios.

Method	Analysis	Applicability to natural ester
Key gas	Proportions of C ₂ H ₄ , CO, H ₂ , C ₂ H ₂	Applicable, typically higher proportion of C ₂ H ₆
Rogers Ratios	C ₂ H ₂ /C ₂ H ₄ ; CH ₄ /H ₂ ; C ₂ H ₄ /C ₂ H ₆	Not reliable in identifying existing faults
Doerenburg Ratios	CH ₄ /H ₂ ; C ₂ H ₂ /C ₂ H ₄ ; C ₂ H ₂ /CH ₄ ; C ₂ H ₆ /C ₂ H ₂	Often not applicable
Duval Triangle/Pentagon	Proportions of H ₂ , CH ₄ , C ₂ H ₆ , C ₂ H ₄ , C ₂ H ₂	Most reliable
IEC Basic Ratios	C ₂ H ₂ /C ₂ H ₄ ; CH ₄ /H ₂ ; C ₂ H ₄ /C ₂ H ₆	Applicable, impacted by higher C ₂ H ₆ level
IEC Simplified Ratios	C ₂ H ₂ /C ₂ H ₄ ; CH ₄ /H ₂	Applicable
Carbon oxides ratio	CO ₂ /CO	Applicable

Table 6 Commonly used fault type identification methods and their applicability to natural ester transformers

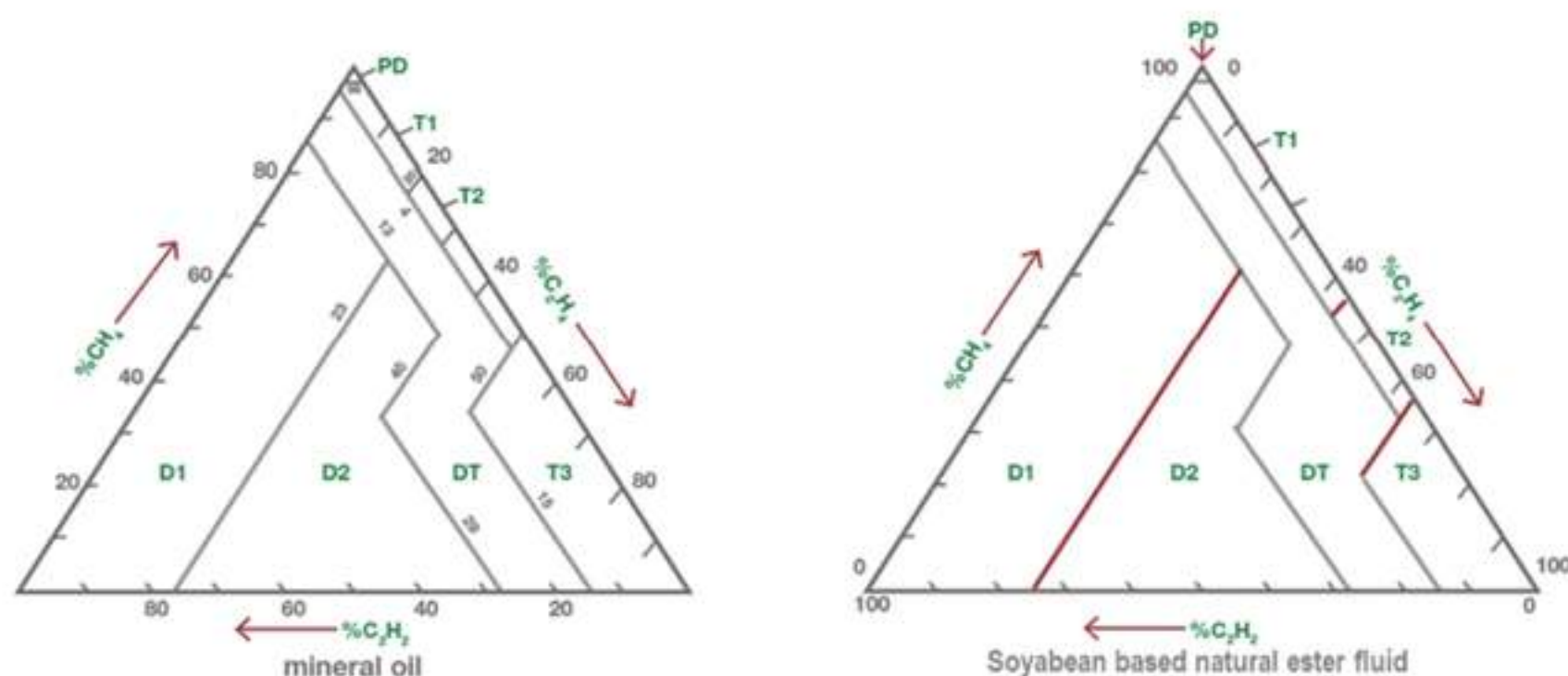


Figure 4 Duval Triangle 1 (left) and 3 (right) for basic fault type identification for mineral oil and soybean based natural ester fluid

Fault type	% CH ₄	% C ₂ H ₄	% C ₂ H ₂
PD (Corona type partial discharges)	>98	-	-
D1 (low energy discharges or sparking partial discharges)	-	<25	>13
D2 (high energy discharges)	-	25<y<40	>13
T1 (<300 °C thermal fault)	<98	<43	<4
T2 (300-700 °C thermal fault)	-	43<y<63	<4
T3 (>700 °C thermal fault)	-	>63	<15
DT (mixed electrical and thermal faults)	-	<63	4<x<13
	-	40<y<63	4<x<29
	-	>63	15<x<29

Table 7 Fault type identification for soybean based natural ester fluid based on Duval Triangle 3 gas proportions

When applying to DGA results from soybean based natural ester transformers that are above the threshold values, Duval Triangle 3 in general provides the most reliable method in identifying the basic fault types in the same way as Duval Triangle 1 for mineral oil transformers (Figure 4 and Table 7) [8-9]. Comparing to the other gas ratios methods, the main advantage of the Duval Triangle method is that it provides a close system that would always propose

a diagnostic result. On the other hand, it is particularly important to confirm the existence of a fault in the first place, otherwise applying such fault identification method on samples with very low gas concentrations could be misleading and would lead to unreliable and inaccurate diagnosis.

Similar to the case of mineral oil, specific sub-types of faults, including stray gassing (S), overheating (O) and carbonisation of

cellulose paper (C) can also be identified in soybean base natural ester fluid using Duval Triangle 6 and 7 (for low and medium/high temperature faults respectively) and Pentagon 3 as shown in Figure 5 [15-16].

DGA AS THE KEY DIAGNOSTIC TOOL FOR NATURAL ESTER TRANSFORMERS

Based on the similarity of key gases generation by internal fault conditions, methods for DGA sampling and testing as well as the general interpretation principle for mineral oil are very much applicable for natural ester fluids. Due to its higher stray-gassing tendency particularly with respect to ethane, hydrogen and carbon oxide gases, special attention would be required on assessing the different gas ratios and gassing rate.

As mentioned in the beginning, for the interpretation of DGA results from all types of fluids, it is important to bear in mind that most of the time condition assessment and fault diagnosis would need to be carried out considering the operation, maintenance, and testing histories of the transformers. And even then, in most cases, fault type(s) and equipment condition would still need to be confirmed by inspection and the relevant tests. However, with the highly robust threshold values for the key gases generated in in-service soybean based natural ester fluids and the well-established Duval Triangle and Pentagon fault type identification methods, it is no doubt that DGA will continue to be regarded as one of the most useful non-destructive diagnostic tools for the rapidly growing number of natural ester-filled transformers.

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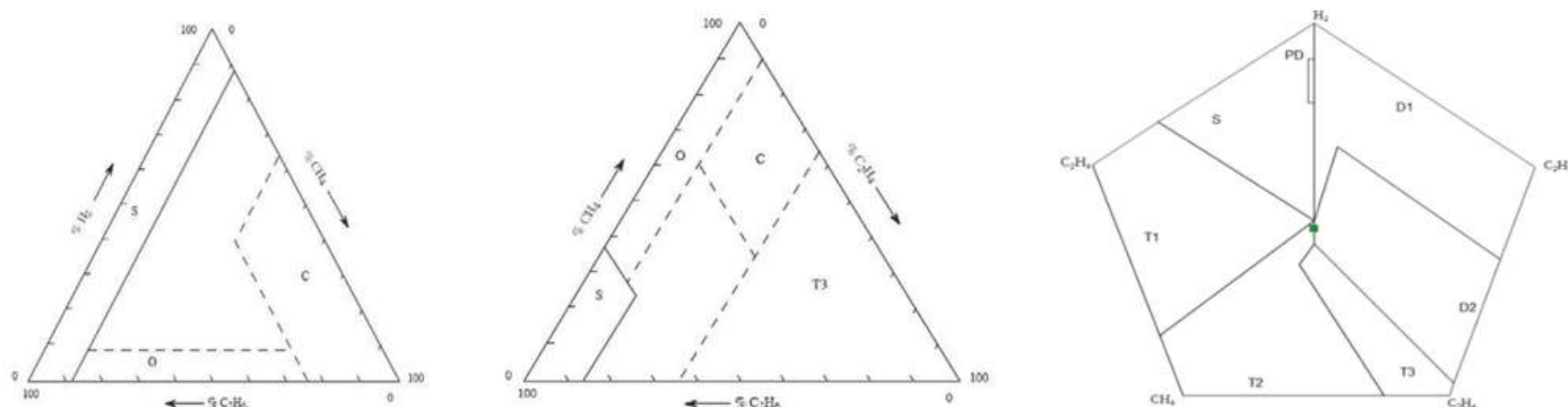



Figure 5 Duval Triangle 6 (left), Triangle 7 (middle) and Pentagon 3 (right) for soybean based natural ester fluid

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