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A Methodology for the Calculation of Typical Gas Concentration Values and Sampling Intervals in the Power Transformers of a Distribution System Operator †

Sergio Bustamante *, Mario Manana, Alberto Arroyo, Raquel Martinez and Alberto Laso

School of Industrial Engineering, University of Cantabria, Av. Los Castros s/n, 39005 Santander, Spain; mananam@unican.es (M.M.); arroyoa@unican.es (A.A.); raquel.martinez@unican.es (R.M.); alberto.laso@unican.es (A.L.)

* Correspondence: bustamantes@unican.es

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Abstract: Predictive maintenance strategies in power transformers aim to assess the risk through the calculation and monitoring of the health index of the power transformers. The parameter most used in predictive maintenance and to calculate the health index of power transformers is the dissolved gas analysis (DGA). The current tendency is the use of online DGA monitoring equipment while continuing to perform analyses in the laboratory. Although the DGA is well known, there is a lack of published experimental data beyond that in the guides. This study used the nearest-rank method for obtaining the typical gas concentration values and the typical rates of gas increase from a transformer population to establish the optimal sampling interval and alarm thresholds of the continuous monitoring devices for each power transformer. The percentiles calculated by the nearest-rank method were within the ranges of the percentiles obtained using the R software, so this simple method was validated for this study. The results obtained show that the calculated concentration limits are within the range of or very close to those proposed in IEEE C57.104-2019 and IEC 60599:2015. The sampling intervals calculated for each transformer were not correct in all cases since the trend of the historical DGA samples modified the severity of the calculated intervals.

Keywords: asset management; dissolved gas analysis; maintenance management; oil insulation; power transformers; predictive maintenance

1. Introduction

Transmission System Operators (TSOs) and Distribution System Operators (DSOs) face asset maintenance management as a critical issue. DSOs and TSOs aim to operate the network reliably, and this is accomplished through good asset maintenance. The direction in asset maintenance is the application of predictive maintenance strategies [1–3] that allow foreseeing malfunctions or faults in assets.

Power transformers are critical assets within the network due to their function and the costs of replacement and maintenance [4–6], therefore they are the most important assets of DSOs and TSOs. Predictive maintenance for transformers intends to manage risk. Understanding the risk index as a function of the consequence of failure (CoF) and the probability of failure (PoF) [1,4,7–9]. The CoF is related to the location of the asset, so it can be assumed that it is fixed as long as the asset is not relocated. The PoF is obtained from the health index of the transformer, which is determined using the available variables obtained by field and laboratory tests, such as oil analysis, electrical tests and visual inspection. To obtain the most accurate health index, it is necessary to have a high number of parameters, the more the better.

Dissolved gas analysis (DGA) is an important parameter in the calculation of the transformer health index [4,10–13]. The use of online DGA monitoring equipment is the current trend, while specific laboratory analyses continue to be carried out [14,15]. Both types of measurements are performed either to establish a correlation of measurements between the DGA equipment and the laboratory results or because the DGA equipment only measures one or two gas concentrations. Online DGA monitoring equipment allows detecting or diagnosing incipient faults in the liquid or solid insulation of the transformer almost instantaneously [14,16,17]. Achieving a successful DGA program is a critical element; to achieve this, it is necessary to establish the appropriate alarm limits together with appropriate actions in the event of an alarm.

This paper updates a previous work [18] by applying the new IEEE guide [19]. In this study, the typical gas concentration values and the typical rates of gas increase for 195 transformers that are in service in the north of Spain were calculated based on the DGA results obtained in the laboratory to determine an optimal sampling interval for each transformer. The improvements over the previous work [18] were that the number of DGA samples used in this study was increased by 50, the results were compared with the new limits established in the IEEE guide [19] and the acetylene concentrations used to calculate their typical concentrations and increases were separated into two groups in a similar way as indicated in the IEC guide [15]. The first group included the DGA samples from transformers without OLTC or without communicating OLTC, while the second group consisted of the DGA samples from transformers with communicating OLTC.

The main objective of this study was to obtain the 90th and 95th percentiles of the typical gas concentrations values and the typical rates of gas increase and the optimal theoretical sampling intervals.

As the IEEE and IEC guides [15,19] indicate, not only should maintenance actions be performed within the limits established in the guides, but also electric utilities should calculate their own limits. The procedure to calculate the percentiles was the nearest-rank method [20–23]. The nearest-rank method is a very simple method, so the R software [24] and its quantile function were used to validate the results obtained. Subsequently, a brief comparison with the limits of the guidelines was performed.

Finally, the optimal theoretical sampling intervals from the calculated 90th percentiles and the pre-failure concentration values were calculated. The theoretical sampling intervals were compared with the sampling intervals that had actually been used by maintenance technicians. This last comparison presents a real view of what is currently done with respect to what the theory indicates.

2. Background Theory

The guides [15,19] propose limits for dissolved gas concentration in transformer oil to monitor and identify electrical or thermal faults. These limits are shown in Tables 1–3. The reference limits were determined for transformers with specific typologies under specific conditions of installation and location. Therefore, the maintenance of transformers by an electric utility can be supported within the limits of the standards. However, it cannot be fully achieved by following only these limits. Tables 4 and 5 show the typical rates of gas increase presented in the IEEE [19] and IEC [15] guides.

Tables 3 and 5 differentiate the acetylene values depending on the on-load tap-changer (OLTC). When talking about power transformers without OLTC or without communicating OLTC, the typical concentration and annual increase of acetylene are less than in the case of power transformers with communicating OLTC.

The guides [15,19] encourage electric utilities to calculate their own limits for both gas levels and annual increases in the concentration of gases. In [20–23], a method for calculating these limits is proposed. This method [20–23] uses a simplification of the percentile calculation, called the nearest-rank method. The nearest-rank method obtains the value below which a given percentage of samples falls. The method places each combustible gas in a column in increasing order; the 90th percentile of the typical gas concentration corresponds to row $0.9n$, where n is the total number of samples.

Another way to calculate the percentiles is to use the functions defined in software. For example, the R software [24] has the quantile function, which generates sample quantiles corresponding to the given probabilities. The probabilities vary from 0 to 1, correspond to the smallest and largest observation, respectively. There are nine types of quantile function in R software; each quantile type i is defined as follows:

$$Q[i](p) = (1-\gamma)x[j] + \gamma x[j+1] \quad (1)$$

where $1 \leq i \leq 9$, $(j-m)/n \leq p < (j-m+1)/n$, $x[j]$ is the jth order statistic, n is the sample size, the value of γ is a function of $j = floor(np+m)$ and $g = np+m-j$ and m is a constant determined by the sample quantile type [24].

Table 1. Typical gas concentration (90th percentile) from IEEE C57.104-2019 [19] (ppm).

Gas	O_2/N_2 Ratio ≤ 0.2				O_2/N_2 Ratio > 0.2			
	Transformer Age (Years)				Transformer Age (Years)			
	Unknown	1–9	10–30	>30	Unknown	1–9	10–30	>30
Hydrogen (H_2)	80	75	75	100	40	40	40	40
Methane (CH_4)	90	45	90	110	20	20	20	20
Ethane (C_2H_6)	90	30	90	150	15	15	15	15
Ethylene (C_2H_4)	50	20	50	90	50	25	60	60
Acetylene (C_2H_2)	1	1	1	1	2	2	2	2
Carbon monoxide (CO)	900	900	900	900	500	500	500	500
Carbon dioxide (CO_2)	9000	5000	10,000	10,000	5000	3500	5500	5500

Table 2. Typical gas concentration (95th percentile) from IEEE C57.104-2019 [19] (ppm).

Gas	O_2/N_2 Ratio ≤ 0.2				O_2/N_2 Ratio > 0.2			
	Transformer Age (Years)				Transformer Age (Years)			
	Unknown	1–9	10–30	>30	Unknown	1–9	10–30	>30
H_2	200	200	200	200	90	90	90	90
CH_4	150	100	150	200	50	60	60	30
C_2H_6	175	70	175	250	40	30	40	40
C_2H_4	100	40	95	175	100	80	125	125
C_2H_2	2	2	2	4	7	7	7	7
CO	1100	1100	1100	1100	600	600	600	600
CO_2	12,500	7000	14,000	14,000	7000	5000	8000	8000

Table 3. Typical gas concentration (90th percentile) from IEC 60599-2015 [15] (ppm).

Gas	All Transformers	Not OLTC	Communicating OLTC
H_2	50–150		
CH_4	30–130		
C_2H_6	20–90		
C_2H_4	60–280		
C_2H_2		2–20	60–280
CO	400–600		
CO_2	3800–14,000		

Table 4. Absolute values of changes in level between successive laboratory DGA samples (95th percentile) from IEEE C57.104-2019 [19] (ppm).

Gas	O_2/N_2 Ratio ≤ 0.2	O_2/N_2 Ratio > 0.2
H_2	40	25
CH_4	30	10
C_2H_6	25	7
C_2H_4	20	20
C_2H_2	Any increase	Any increase
CO	250	175
CO_2	2500	1750

Table 5. Typical rates of gas increase (90th percentile) from IEC 60599-2015 [15] (ppm/year).

Gas	All Transformers	Not OLTC	Communicating OLTC
H_2	35–132		
CH_4	10–120		
C_2H_6	5–90		
C_2H_4	32–146		
C_2H_2		0–4	21–37
CO	260–1060		
CO_2	1700–10,000		

The difference between using the nearest-rank method or the quantile function of R software is that the first one uses rounding to obtain the calculated range, while the second one obtains the percentiles by interpolation between contiguous values in the dataset in order to improve the accuracy.

From the gas limits obtained by any of the methods presented above, and the pre-failure values in [20–22], as shown in Table 6, it is possible to calculate the theoretical DGA sampling interval for each transformer of the electric utility. The theoretical DGA sampling interval is obtained by creating a graph. The pre-failure values associated with a theoretical DGA sampling interval of 1 h are placed on the left y-axis. The 90th percentile values of the typical gas concentrations associated with a theoretical one-year DGA sampling interval are placed on the right y-axis. The x-axis indicates the theoretical DGA sampling interval. All axes are logarithmic.

Table 6. Average pre-failure values [20–22].

	Gas Concentration Values (ppm)	Rates of Gas Increase (ppm/Year)
H_2	725	1095
CH_4	400	1825
C_2H_6	900	4015
C_2H_4	800	1825
C_2H_2	450	182
CO	2100	17,000
CO_2	50,000	150,000

To achieve greater accuracy in the theoretical DGA sampling interval than that obtained from the graph, the following formula is used for each of the gases:

$$log\ G = -a\ log\ t + log\ b \tag{2}$$

where G is the gas concentration obtained in the DGA result (ppm) and t is the theoretical DGA sampling interval (hours). a and b are obtained using Equation (2) with the pre-failure values for each gas (G_P) and the 90th percentile values of the typical gas concentrations (G_T) and t is the theoretical DGA sampling intervals of 1 h and one year, respectively.

The theoretical DGA sampling interval can also be obtained from the annual increases in the concentration of gases. As explained above, the annual increases in the concentration of gases are used instead of the 90th percentile values of the typical gas concentrations. The average pre-failure values of the annual increases in the concentration of gases collected in [20–22] are shown in Table 6.

3. Methodology

The methodology used in this study is made up of four steps, as shown in Figure 1.

Step 1: *Data collection and cleaning*

The first step is the acquisition of gas concentrations from the DGA results obtained in the laboratory. Next, the gas concentrations are reviewed and validated to identify abnormal concentration values, following the indications of the IEEE guide [19].

The acetylene concentration dataset is divided into two groups depending on the OLTC, since acetylene concentrations are different in both cases. Power transformers without OLTC or without communicating OLTC are in the first group, and those with communicating OLTC are in the second group.

Step 2: *Application and comparison of methods*

Once the dataset is validated, the 90th and 95th percentiles of typical gas concentrations and typical rates of gas increase are calculated using the nearest-rank method and the nine quantile function types of the R software.

The increase between consecutive DGA data from the same transformer is calculated and extrapolated an annualised value. These values are used to obtain the 90th and 95th percentiles of the typical rates of gas increase through the two methods.

The percentile results of the methods are compared to validate the nearest-rank method.

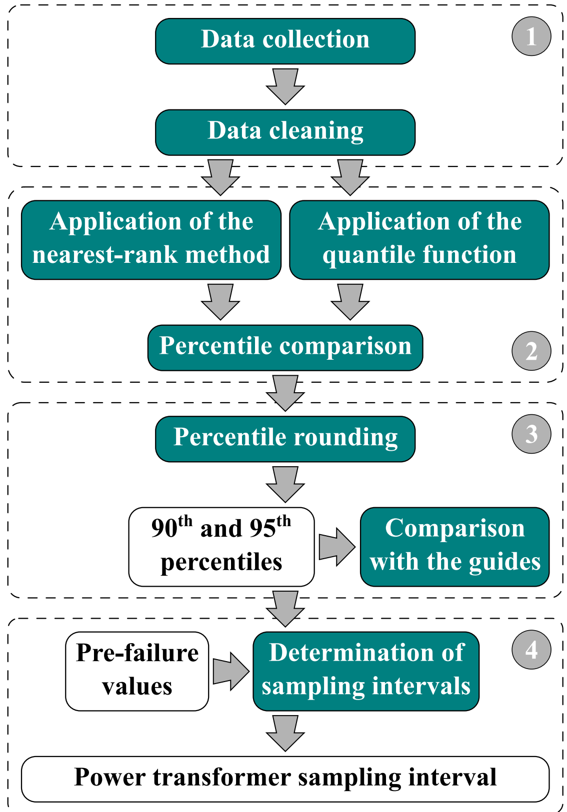

Figure 1. Outline of the methodology followed.

Step 3: Determination of percentiles and comparison with the guides.

Following the guide [19], the results of the nearest-rank method obtained in the previous step are rounded using the following rounding scheme:

- 1–10 : Unit
- 10–50: Nearest 5
- 50–100: Nearest 10
- 100–250: Nearest 25
- 250–500: Nearest 50
- 500–1000: Nearest 100
- 1000–2500: Nearest 250
- 2500–5000: Nearest 500
- Above 5000: Nearest 1000

Once rounded, these are the 90th and 95th percentiles of typical gas concentrations and typical rates of gas increase of the DSO transformer population.

Finally, these percentiles are compared with those indicated in the guides [15,19] (Tables 1–5).

Step 4: Determination of sampling interval of power transformers

Using the pre-failure values (Table 6) and the calculated 90th percentile of typical gas concentrations, the theoretical DGA sampling intervals of each power transformer are obtained through the creation of the graph explained above or the application of Equation (2). For each DGA sample, the sampling interval is obtained due to the 90th percentile of typical gas concentrations. For the same DGA sample, different DGA sampling intervals can be obtained due to gas concentrations, so the lowest sampling interval is chosen.

4. Study Characteristics

This study was performed using 417 laboratory DGA samples from 195 transformers of a DSO that were obtained between the end of 2017 and the middle of 2019. All 417 DGA samples were provided by a DSO. All samples were actual raw data, so data cleaning had to be done following the indications provided by the IEEE guide [19], as noted below. Figure 2 shows these transformers divided by age, voltage class and power rating. The voltage of 74 transformers is equal to or greater than 132 kV, which is not in the common range used in distribution networks; this is because these transformers are connected on the high voltage side to the transmission grid.

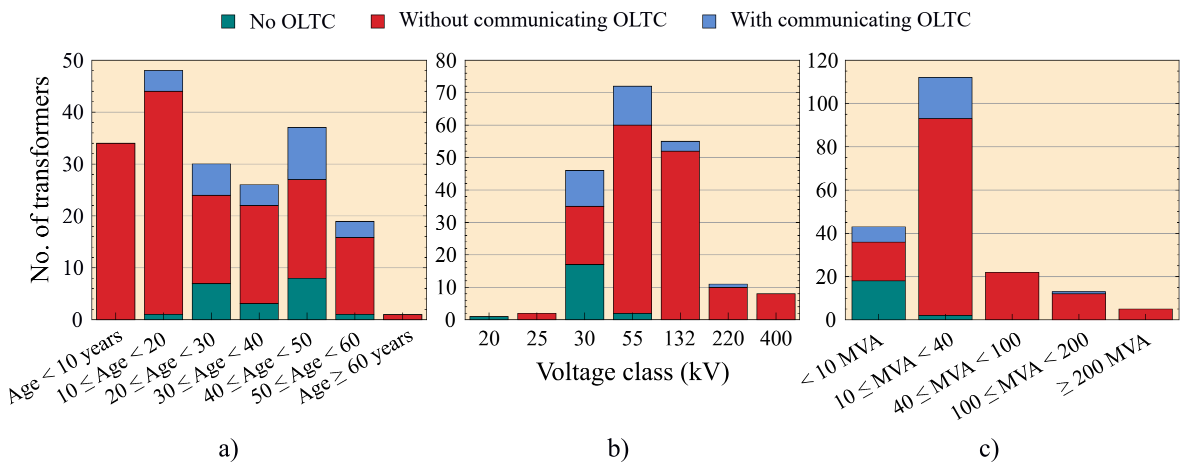

Figure 2. Power transformers according to: (**a**) age; (**b**) voltage class; and (**c**) power rating.

In addition, Figure 2 shows the number of transformers without OLTC, without communicating OLTC or with communicating OLTC. Power transformer with communicating OLTC means that there is an exchange of oil or gases between the main tank and the OLTC compartment, or between the respective oil conservators. The concentration limit of acetylene will differ depending on this classification, as is shown below. Another important classification is whether the transformer is sealed or air-breathing; however, it was not necessary to collect such information for this study because the DSO transformers in this case study were all air-breathing.

Figure 3 shows the DGA results ordered from lowest to highest gas concentration and the 90th percentile ranges of gas concentrations from the IEEE and IEC guides. The sampling interval is performed annually. In the case of high gas concentrations, the sampling interval is decreased to approximately six months, and it decreases to two months in the case of exceptional gas concentration values. The DGA data for acetylene concentrations were divided into two groups as explained above (Figure 3b,c).

The O_2/N_2 ratios for all DGA samples were calculated because the IEEE guide [19] classifies the limits for concentrations and increases based on this ratio. All the calculated O_2/N_2 ratios were greater than 0.2 except 10 out of 417 DGA samples which were lower; therefore, the results obtained in this study were compared with the limits in Tables 1, 2 and 4 that have O_2/N_2 ratio greater than 0.2.

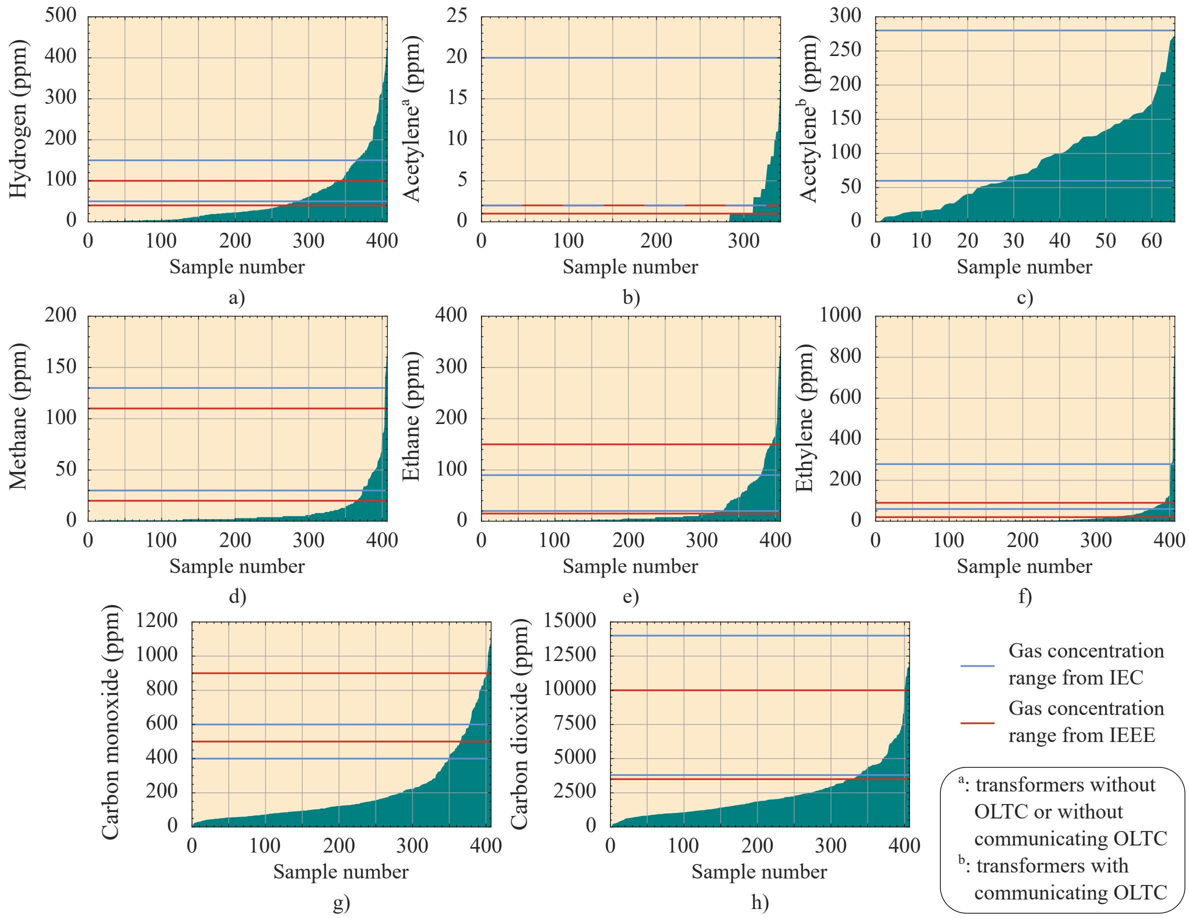

Figure 3. Gas concentration data: (**a**) hydrogen; (**b**) acetylene (transformers without OLTC or without communicating OLTC); (**c**) acetylene (transformers with communicating OLTC); (**d**) methane; (**e**) ethane; (**f**) ethylene; (**g**) carbon monoxide; and (**h**) carbon dioxide.

5. Results

Following the methodology indicated in Section 3, the results explained in this section were obtained.

Step 1: Data collection and cleaning

From the validation performed, following the indications of the IEEE guide [19], 10 DGA samples were eliminated due to abnormal concentration values.

Acetylene concentrations were divided into two groups. In the group of transformers without OLTC or without communicating OLTC, 342 DGA samples were used, and, in the group of transformers with communicating OLTC, the remaining 65 DGA samples were used.

Step 2: Application and comparison of methods

The 90th and 95th percentiles of the typical gas concentration values and 90th and 95th percentiles of the typical rates of gas increase were calculated by the nearest-rank method and the nine quantile function types of the R software. Tables 7 and 8 show the calculated percentiles.

Table 8 shows the ranges of the 90th and 95th percentiles of the typical gas concentration values and the 90th and 95th percentiles of the typical rates of gas increase returned by the quantile function.

The lowest and highest values in Table 8 correspond to those obtained with Type 3 and Type 6 quantile algorithms, respectively. The results of the other seven types of quantile algorithm are within this range.

According to the results presented in Tables 7 and 8, the values calculated using the nearest-rank method were within the ranges obtained through the R software, thus this method was adequate for this study.

Table 7. Typical gas concentration values and rates of gas increase (90th and 95th percentile) calculated by the nearest-rank method (ppm and ppm/year, respectively).

	Gas Concentration Values		**Rates of Gas Increase**	
	90th	**95th**	**90th**	**95th**
H_2	153	198	56.78	168.02
CH_4	21	48	9.97	9.97
C_2H_6	73	132	4.75	21.96
C_2H_4	49	82	11.59	30.05
C_2H_2 [a]	1	5	1.62	3.81
C_2H_2 [b]	168	219	99.55	164.91
CO	509	729	151.69	257.93
CO_2	4655	6492	1213.63	1549.36

[a] Transformers without OLTC or without communicating OLTC; [b] transformers with communicating OLTC.

Table 8. Typical gas concentration values and rates of gas increase (90th and 95th percentile) obtained with R software using Type 3 and Type 6 quantile algorithms (ppm and ppm/year, respectively).

	Gas Concentration Values		**Rates of Gas Increase**	
	90th	**95th**	**90th**	**95th**
H_2	153–154.4	198–217.8	56.78–64.11	168.02–196.19
CH_4	21–21.2	48	9.97–10.42	20.98–21.68
C_2H_6	73–75	132–133.8	4.75–5.33	21.96–29.78
C_2H_4	49–51	82–82.6	11.59–13.99	30.05–30.62
C_2H_2 [a]	1	5–5.85	1.62–1.82	3.81–4.31
C_2H_2 [b]	160–170	219	99.55–158.25	164.91–276.01
CO	509–531.8	729–732	151.69–157.45	257.93–269.88
CO_2	4655–4700.4	6492–6500.4	1213.63–1253.61	1820.49–2057.55

[a] Transformers without OLTC or without communicating OLTC; [b] transformers with communicating OLTC.

Step 3: Determination of percentiles and comparison with the guides.

Following the guide [19], the results of the 90th and 95th percentiles of the typical gas concentration values and the typical rates of gas increase were rounded, as shown in Table 9.

Comparing the 90th percentile of the typical gas concentration values and the typical rates of gas increase calculated (Table 9) with the IEC limits [15] (Tables 3 and 5), the values obtained are within the typical ranges, except the rate of acetylene increase in the transformers with communicating OLTC. Although this value is very high compared to the IEC limits, it is necessary to note that the rate of acetylene increase was calculated using a very small number of DGA samples.

The calculated values (Table 9) were compared with the concentration values published by the IEEE [19] (Tables 1 and 2) using a general comparison because the results obtained in this study were not classified by transformer age owing to the low number of DGA samples. The values obtained for the 90th and 95th percentiles are very similar to those proposed by the guide [19] for methane, ethylene, acetylene (without OLTC or without communicating OLTC), carbon monoxide and carbon dioxide concentrations.

The values obtained for the 90th percentiles of hydrogen and ethane are approximately four times higher than those listed in Table 1; those obtained for the 95th percentile are approximately double or triple those listed in Table 2. It was not possible to compare the acetylene concentrations of transformers with communicating OLTC due to the IEEE guide not considering it.

Table 9. Typical gas concentration values and rates of gas increase (rounded 90th and 95th percentile) calculated for DSO power transformers (ppm and ppm/year, respectively).

	Gas Concentration Values		Rates of Gas Increase	
	90th	**95th**	**90th**	**95th**
H_2	150	200	60	175
CH_4	20	50	10	10
C_2H_6	70	125	5	20
C_2H_4	50	80	10	30
C_2H_2 [a]	1	5	2	4
C_2H_2 [b]	175	225	100	175
CO	500	700	150	250
CO_2	4700	6000	1250	1500

[a] Transformers without OLTC or without communicating OLTC; [b] transformers with communicating OLTC.

The 95th percentile of the typical rates of gas increase is similar to those collected by the IEEE (Table 4); except for the case with typical concentrations, the typical rate of hydrogen increase was much higher and the typical rate of ethane increase was slightly higher than the values shown in Table 4.

Figure 4 shows the location of the 90th and 95th percentile results on the historical distribution of DGA data. Most of the time the gas concentrations were concentrated on the left side of the distribution, while few samples were concentrated on the right side above the 90th and 95th percentiles.

Step 4: Determination of sampling interval of power transformers

Figure 5 shows the graph to calculate the theoretical DGA sampling interval from the latest DGA results. The graph was obtained from the pre-failure concentrations of each gas (Table 6) and the 90th percentile of the calculated typical gas concentrations (Table 9).

Using Equation (2) and the data in Tables 6 and 9, gas concentrations relative to each sampling interval were obtained, as shown in Table 10. Table 11 shows the number of power transformers and their sampling interval for each type of gas. Some of the transformers had several gas concentrations above the 90th percentile values, so different sampling intervals would be obtained. In this case, the lowest sampling interval would be selected. The row of totals indicates the number of transformers that correspond to each sampling interval according to the results by the last DGA evaluation.

Table 10. Calculated sampling intervals based on the 90th of the typical gas concentration values (ppm).

	Hydrogen (H_2)	**Methane** (CH_4)	**Ethane** (C_2H_6)	**Ethylene** (C_2H_4)	**Acetylene** [a] (C_2H_2)	**Acetylene** [b] (C_2H_2)	**Carbon Monoxide** (CO)	**Carbon Dioxide** (CO_2)	**Sampling Interval**
Typical	150	20	70	50	1	175	500	4700	annually
	158	22	76	55		180	523	5066	9 months
	169	25	85	62	2	188	558	5630	6 months
	191	32	103	76	3	202	623	6744	3 months
	231	45	141	107	5	227	741	8978	monthly
	298	74	213	167	14	264	934	13,163	weekly
	418	140	368	303	53	323	1271	21,851	daily
Pre-failure	725	400	900	800	450	450	2100	50,000	hourly

[a] Transformers without OLTC or without communicating OLTC; [b] transformers with communicating OLTC.

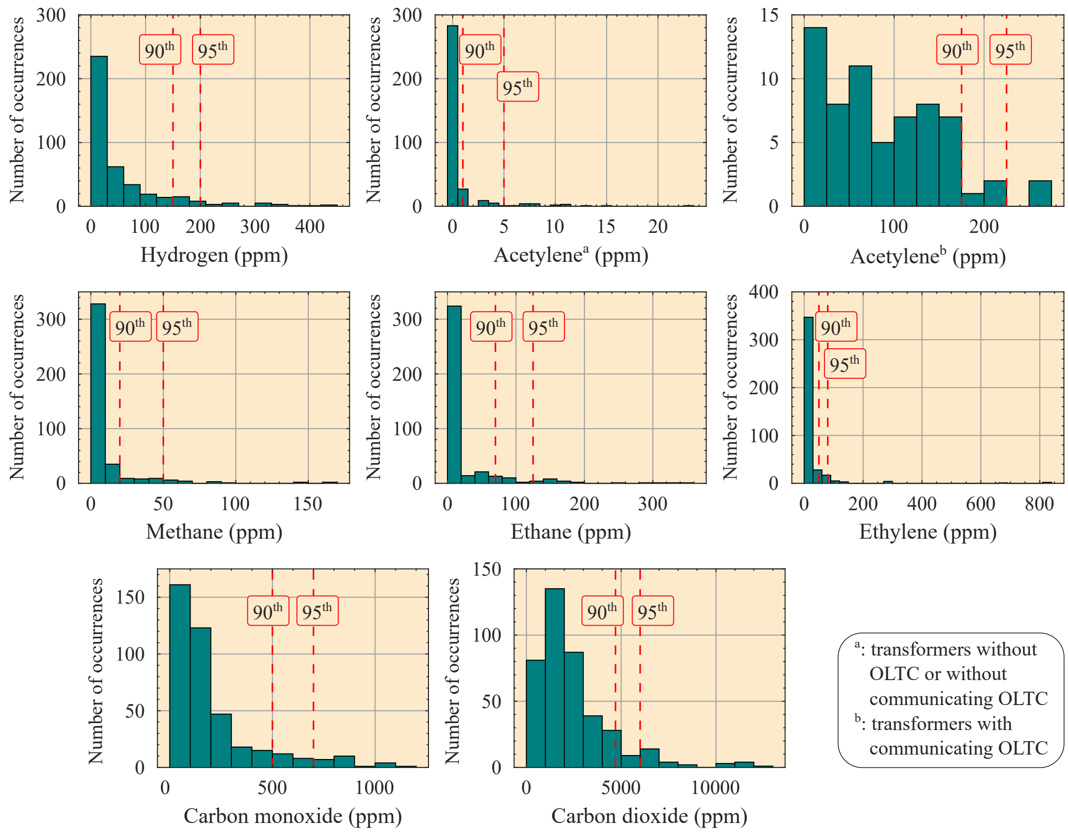

Figure 4. Distribution of gas concentrations and calculated 90th and 95th percentiles: (**a**) hydrogen; (**b**) acetylene (transformers without OLTC or without communicating OLTC), (**c**) acetylene (transformers with communicating OLTC); (**d**) methane; (**e**) ethane; (**f**) ethylene; (**g**) carbon monoxide; and (**h**) carbon dioxide.

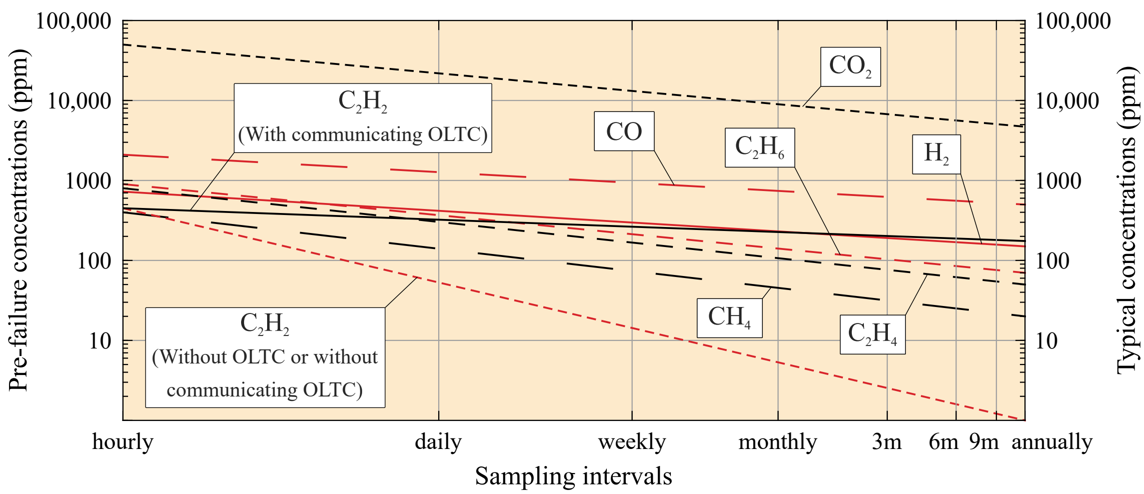

Figure 5. Determination of DGA sampling intervals.

Table 11. Number of transformers per sampling interval based on the 90th of the typical gas concentration values.

Gas	Annually	9 Months	6 Months	3 Months	Monthly	Weekly	Daily	Hourly
Hydrogen (H_2)	182	2	1	4	4	2		
Methane (CH_4)	178	2	2	2	6	4	1	
Ethane (C_2H_6)	180	5	2	1	5	2		
Ethylene (C_2H_4)	176	3	3	6	3		2	2
Acetylene [a] (C_2H_2)	147			6	6	6		
Acetylene [b] (C_2H_2)	26				2	2		
Carbon monoxide (CO)	177	2	4	2	9	1		
Carbon dioxide (CO_2)	177	6	4	5	2	1		
TOTAL	131	9	5	12	20	13	3	2

[a] Transformers without OLTC or without communicating OLTC; [b] transformers with communicating OLTC.

6. Discussion

As indicated in the results (Tables 7 and 8), the nearest-rank method despite being a simple approach provides the results in the same range as those obtained with the quantile function of the R software. The validation of the nearest-rank method through the comparison of the results of the quantile function indicated that the results obtained using this method were considered reliable.

The most urgent theoretical sampling intervals obtained for each gas (Table 11) are discussed below. As mentioned, the same transformer could have different sampling intervals due to the different gas concentrations, from which the most restrictive sampling interval was selected. In this section, the critical sampling intervals obtained due to gas concentrations were evaluated even for the same transformer.

Table 12 shows the DGA samples from six power transformers with weekly and monthly sampling intervals due to the high hydrogen concentration obtained in the last DGA sample. As shown in Table 12, all six transformers had high hydrogen concentrations in all of their DGA samples and were stable. Therefore, it was decided that the next DGA sampling would be carried out in about six months to control the trend of the hydrogen concentration. Comparing the decision to perform the DGA sampling in half a year with the result obtained in this study, it turns out that this result is too restrictive with respect to the best practices performed by maintenance technicians based on the knowledge of the transformers and the network.

The high concentrations of methane forced the need for a daily sampling interval in one of the transformers and a weekly interval in four others, as shown in Table 13. Transformer 7 was 52 years old, and methane and ethane concentrations were high but stable in all its DGA samples. Thus, it was normal for their concentrations to be high. The methane concentration required the daily sampling interval, while the ethane concentration was the reason for the weekly sampling interval. Although the methane concentration was high, its next DGA sampling would be in approximately six months to control the trend of the gases.

The remaining four transformers did not have the methane concentration as high as the previous transformer. Transformers 8 and 10 were sampled in one year and Transformers 9 and 11 in half a year to control the trend of gases. The reasons for the reduced interval were the high concentrations of ethylene for Transformer 9 and the young age of only 10 years for Transformer 11.

Table 12. Transformers DGA results with shorter sampling interval due to high hydrogen concentrations (ppm).

Sample Date	Transf. No.	Age (Years)	H_2	CH_4	C_2H_2 [a]	C_2H_2 [b]	C_2H_4	C_2H_6	CO	CO_2	Sampling Interval
01/04/2019	1	19	310	4		41	14	10	125	2581	weekly
09/10/2018			326	5		59	18	16	219	3629	
17/04/2018			264	4		57	23	15	244	3792	
25/04/2019	2	33	304	2	0		1	2	187	2296	weekly
09/10/2018			314	2	1		2	2	253	2453	
08/05/2018			340	2	0		2	2	221	2043	
01/04/2019	3	20	260	3		15	4	2	46	1074	monthly
28/01/2019			231	1		14	2	2	57	980	
08/05/2018			358	2		7	2	2	57	1080	
01/04/2019	4	49	248	25		219	123	5	462	5976	monthly
17/10/2018			157	20		144	113	5	490	6253	
17/04/2018			168	17		114	115	8	438	6492	
28/01/2019	5	48	244	15		219	83	3	286	2974	monthly
09/10/2018			164	15		192	82	2	388	3482	
08/05/2018			198	13		150	79	3	324	3181	
25/04/2019	6	46	236	22	3		33	70	153	1645	monthly
28/01/2019			269	10	4		8	55	167	1563	
09/10/2018			311	16	3		16	73	271	2019	
08/05/2018			168	7	3		8	57	154	1438	

[a] Transformers without OLTC or without communicating OLTC; [b] transformers with communicating OLTC.

Transformers 12–16, shown in Table 14, had acetylene concentrations in the 10–13 ppm range and they had no communicating OLTC. The low concentrations of acetylene were the reason for the weekly sampling intervals, since they are very far from the pre-failure concentration of acetylene. Their final sampling interval was approximately one year. Transformer 9 (Table 13) was in the same situation, its sampling interval was annual.

Transformers 17 and 18 (Table 14) had communicating OLTC, so the acetylene concentration values were high, as expected. Although these concentrations can be considered normal in transformers with communicating OLTC, the increase in acetylene concentration was high. The number of operations performed by the OLTCs of these transformers was in the range of 2000–4000 operations/year each, so the oil sampling of the OLTCs was programmed to confirm the communication between the main tank and the OLTC compartment. The next DGA sampling for Transformers 17 and 18 and their OLTCs was established in one year.

Table 13. Transformers DGA results with shorter sampling interval due to high methane concentrations (ppm).

Sample Date	Transf. No.	Age (Years)	H_2	CH_4	C_2H_2 [a]	C_2H_2 [b]	C_2H_4	C_2H_6	CO	CO_2	Sampling Interval
17/10/2018	7	52	57	147	1		66	312	699	3080	daily
08/05/2018			56	160	1		75	326	725	2716	
15/06/2017			54	166	0		79	354	695	2621	
24/05/2018	8	52	18	62	0		115	5	806	3527	weekly
25/09/2017			2	8	0		62	15	444	2504	
09/04/2019	9	31	24	85	13		812	247	113	5403	weekly
17/10/2018			24	174	17		1010	286	153	6325	
24/05/2018			85	291	7		1127	292	161	5673	
07/06/2019	10	27	4	93	0		10	88	86	2988	weekly
17/10/2018			11	87	0		10	83	83	3872	
28/02/2018			9	86	0		10	78	75	3543	
25/09/2017			0	59	0		10	82	77	3241	
01/04/2019	11	10	29	66	0		2	158	147	3167	weekly
09/10/2018			28	59	1		2	132	146	3408	
01/02/2018			23	62	0		2	147	166	3144	
25/09/2017			11	34	0		2	121	103	2409	

[a] Transformers without OLTC or without communicating OLTC; [b] transformers with communicating OLTC.

Table 14. Transformers DGA results with shorter sampling interval due to high acetylene concentrations (ppm).

Sample Date	Transf. No.	Age (Years)	H_2	CH_4	C_2H_2 [a]	C_2H_2 [b]	C_2H_4	C_2H_6	CO	CO_2	Sampling Interval
19/06/2019	12	24	73	2	11		2	2	68	1708	weekly
05/06/2018			43	1	8		1	1	51	1237	
01/04/2019	13	35	54	34	10		25	78	478	2342	weekly
17/10/2018			80	48	7		29	87	537	2724	
17/04/2018			52	35	3		29	88	456	2385	
27/05/2019	14	30	0	1	15		2	3	63	1535	weekly
09/05/2018			20	1	11		2	3	67	1417	
15/05/2019	15	50	198	3	10		4	1	165	11,027	weekly
24/05/2018			98	2	4		4	5	96	7375	
15/05/2019	16	46	1	1	11		2	0	58	995	weekly
24/05/2018			3	1	0		1	3	55	827	
09/10/2018	17	35	33	8		273	35	8	92	2506	weekly
12/04/2018			5	4		125	20	5	49	1903	
09/10/2018	18	35	25	8		265	41	18	81	2449	weekly
12/04/2018			19	5		126	25	16	48	2021	

[a] Transformers without OLTC or without communicating OLTC; [b] transformers with communicating OLTC.

Table 15 shows the results of the new DGA samples of the transformers and their OLTCs. These samples were not used in the procedure described in this paper because they belonged to the next sampling campaign. These DGA samples were added to the study to serve as the basis for discussion of DGA results from transformers with communicating OLTC. Both OLTCs were of the arc-breaking in oil type with the diverter switch and tap selector in the same oil compartment. The gas pattern of the OLTCs oil samples shown in Table 15 indicated that the OLTCs operate normally. Since the solubility of acetylene is greater than the solubility of hydrogen, when electrical discharge is generated in the OLTC compartment (normal operation), acetylene spreads more quickly out of the OLTC tank. This results in the acetylene concentration being greater than the hydrogen concentration, as shown in the DGA samples of Transformers 17 and 18 (Tables 14 and 15).

Transformers 4 and 5 (Table 12) were at the same stage with regard to acetylene concentrations; in this case, their next sampling was established in half a year to control the gas trend.

Table 15. New DGA results of Transformers 17 and 18 and their OLTCs (ppm).

Oil Sample Origin	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2
Transformer 17	29	5	138	29	15	58	1422
OLTC	437	46	616	132	64	76	1326
Transformer 18	24	5	254	39	15	63	1910
OLTC	189	42	785	119	51	75	1926

Table 16 shows the DGA samples from three power transformers with hourly and daily sampling intervals due to the high ethylene concentration obtained in the last DGA sample. The three transformers are old, 45–52 years, so it is normal for gas concentrations to accumulate over time; this occurs in Transformers 19 and 21. Transformer 9, shown in Table 13, was also in this situation. For these three transformers, the next DGA sampling was scheduled in six months to observe the gas trend. In Transformer 20, an increase in the ethylene concentration is observed, approximately 250 ppm/year, since both the concentration and the annual increase were far from the pre-failure values (Table 6). The maintenance technicians decided to carry out the next sampling in approximately six months to control the evolution of the ethylene concentration since this gas pattern may indicate the existence of a thermal fault (>700 °C).

Table 16. Transformers DGA results with shorter sampling interval due to high ethylene concentrations (ppm).

Sample Date	Transf. No.	Age (Years)	H_2	CH_4	C_2H_2 [a]	C_2H_2 [b]	C_2H_4	C_2H_6	CO	CO_2	Sampling Interval
01/04/2019	19	52	35	48		107	661	148	132	2312	hourly
17/10/2018			45	68		125	813	194	175	2691	
17/04/2018			112	118		111	1020	227	195	2853	
07/06/2019	20	45	12	4	0		274	3	535	2868	daily
08/05/2018			1	4	0		2	2	145	644	
01/04/2019	21	51	168	41		159	284	67	232	3166	daily
17/10/2018			162	35		137	283	70	265	3440	
17/04/2018			144	30		100	297	98	273	3462	

[a] Transformers without OLTC or without communicating OLTC; [b] transformers with communicating OLTC.

The transformers with the lowest sampling interval due to ethane concentration were Transformers 7 and 9 (Table 13), discussed above due to other gases. The next DGA sampling was established in these transformers in six months.

Finally, the concentrations of carbon monoxide and carbon dioxide are not taken into account in real life to establish the DGA sampling interval, so it was not necessary to show the concentrations of these transformers in this section.

As a summary of this section, it was established that all the calculated sampling intervals were too strict with respect to the sampling intervals that are carried out in real life. All the calculated sampling intervals were increased between six months and one year. It should be noted that the theoretical sampling intervals calculated in this paper were correct, but knowledge of the transformers and their operating conditions by maintenance technicians is essential to establish a good DGA sampling program.

7. Conclusions

This paper updates the results of a case study [18] to which the information in the new IEEE guide was applied [19]. This study presents the application and validation of the nearest-rank method to calculate the 90th and 95th percentiles of the typical gas concentration values and theoretical DGA sampling intervals for the transformers of a DSO.

The DGA dataset used in this study comes from 417 analyses of 195 power transformers. The DGA dataset was divided into two groups regarding acetylene concentrations due to OLTC. DGA samples from transformers without OLTC or without communicating OLTC were in the first group, while DGA samples from transformers with communicating OLTC were in the second group. This was done because the acetylene concentrations are different depending on the group to which the transformer belongs. It was observed that the new DGA data used for this paper made a significant change in the previous results. Due to this development, it is recommended that the outputs of this study are applied with caution. It is also recommended to update the results as new DGA data are collected.

The 90th and 95th percentiles of the typical gas concentrations limits and the 90th and 95th percentiles of the typical rates of gas increase resulting from this work are within or very close to the ranges suggested by the guides [15,19], except for hydrogen and ethane. The gas concentration limits and the rates gas increase for hydrogen and ethane at both percentiles were found to be significantly higher than the IEEE values. Although the percentiles of the typical rates of gas increase were in or close to the ranges proposed by the guides, it should be noted that the number of annualised increments used to calculate them was 217, a small number to establish the percentiles with certainty.

As a result of this case study, all transformers of a DSO were assigned new sampling frequencies. The sampling intervals obtained were a theoretical result based on the absolute value of the DGA sample; however, the trend of gas concentrations considering the age of the transformer must be carefully analysed before establishing an optimal sampling interval for each transformer. As discussed, all the theoretical sampling intervals obtained in this study were too strict when compared to what was actually done in the field. A more realistic adjustment of the calculation of sampling intervals relative to what is actually performed by maintenance technicians in the field could be a line of future research.

Although these results are correct, it must be noticed that the DGA dataset studied is small, 417 analyses from 195 transformers; therefore, this study should be repeated with a higher number of samples. With a more robust DGA sample dataset, this study could be repeated in accordance to the distribution of transformers presented in Figure 2.

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Abbreviations

The following abbreviations are used in this manuscript:

CoF	Consequence of failure
C_2H_2	Acetylene
C_2H_4	Ethylene
C_2H_6	Ethane
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
DGA	Dissolved gas analysis
DSO	Distribution system operator
H_2	Hydrogen
OLTC	On-load tap changer
PoF	Probability of failure
TSO	Transmission system operator

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