



The behavior of different transformer oils relating to the generation of fault gases after electrical flashovers



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ABSTRACT

Dissolved gas analysis is a common technique in the supervision and maintenance of transformers. It can give hints on defects and faults in oil-immersed transformers by determination and quantification of gases arising in consequence of thermal or electrical stress. Different algorithms for the assessment of transformers, which employ data obtained from dissolved gas analysis, have been published so far. However, only few investigations, dealing with the influence of the oil's composition towards the oil's tendency of releasing gases, exist. This research study presents a comparison of three commercially available transformer oils of different composition regarding that aspect. The results indicate that an oil with high percentages of paraffinic hydrocarbons forms gases to a lesser extent than naphthenic oils when it is exposed to electrical stress. This phenomenon can be explained either by a variable solubility of gases in the medium oil, or by the presumption that cyclic hydrocarbons are the main producers of gases.

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Introduction

Several defects and faults can occur in an oil-immersed power transformer in operation e.g. partial discharges, discharges of high energy, arcing, thermal incidents like hotspots, overheating and insufficient cooling. If a transformer is exposed to thermal or electrical stress, the formation of gases resulting from oil decomposition and paper degradation processes will be involved. The common representatives of those gases are: Hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), propane (C_3H_8), propylene (C_3H_6), carbon monoxide (CO) and carbon dioxide (CO_2), respectively. Therefore, the gases mentioned above can be considered as indicators for defects and faults in transformers; sometimes they are denominated as fault gases, e.g. [1]. The method of choice for the determination of fault gases in transformer oils is the so-called dissolved gas analysis (DGA). Hence, DGA represents an important diagnostic tool for detection and evaluation of defects and faults in transformers [2]. An equipment for the accomplishment of dissolved gas analyses (DGAs) consists of an extraction technique coupled with gas chromatography. Several techniques for extraction of dissolved gases from oil are available: (i) multi-cycle vacuum extraction (e.g. Toepler

pump), (ii) single-cycle vacuum extraction (partial degassing), (iii) stripping and (iv) headspace extraction. The gas chromatograph shall be equipped with two packed or PLOT columns containing stationary phases of different polarities. Moreover, the usage of a thermal conductivity detector (TCD) and a flame ionization detector (FID) enables the selective detection of all relevant gases. The sensitivity in detecting the gases CO and CO_2 can be improved by means of a methanizer fitted at the inlet to the flame ionization detector: The two carbon oxides (CO and CO_2) are converted to CH_4 , a gas, which can be registered at a lower limit of quantitation by FID [3].

The concentrations of dissolved gases, obtained by DGA, depend on the character of defects or faults emerging in transformers [4]. Above all, a variety of interpretation schemes was developed in order to derive an accurate diagnosis for transformers from raw measurement data. These interpretation schemes are based on empirical assumptions and practical knowledge gathered by experts worldwide [4]. Common interpretation schemes are: Doernenburg Ratio method [5], Key Gas method [6], Duval triangle and pentagon method [7–10], Rogers Ratio method [11] and the IEC method [2]. Additionally, various artificial intelligence systems including fuzzy logic and artificial neural networks were designed since the 1990s [12–14] to enable a more effective diagnosis on transformers.

Nevertheless, the transformer's trend to generate fault gases, in case of thermal or electrical stress, may be affected by the

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Table 1

Composition and properties of the transformer oils used for testing the trend of generating fault gases after electrical flashovers.

	NA-UI	NA-I	PA-I
Aromatic Hydrocarbons [%] ^a	5	7	1
Paraffinic Hydrocarbons [%]	48	47	75
Naphthenic Hydrocarbons [%]	47	46	24
Inhibitor [%] ^b	–	0.31	0.21
Color ^c	0.5	0.5	0.5
Breakdown Voltage [kV] ^c	75	75	88.1
Dielectric Dissipation Factor ^c	0.0020	0.0010	0.0010
Neutralization Value [mg KOH/g] ^c	0.01	0.01	0.01
Water Content [mg/kg] ^c	2	4	2
Interfacial Tension [mN/m] ^c	45.3	45.3	45.3
Sediment and Sludge [%] ^c	<0.02	<0.02	<0.02
Particles ^c	–/13/10	–/12/9	–/13/9

^a Acc. to [16].

^b Acc. to [17].

^c Acc. to [18] and references therein.

composition of the insulation liquid as well. In this manuscript, we present key experiments, in which three different transformer oils were subjected to a defined number of electrical flashovers followed by an investigation of the fault gases evolved from those flashovers.

Experimental

The experiments were performed by usage of a calibrated equipment (DTA 100 - BAUR GmbH, A-6832 Sulz, Austria) as prescribed in Ref. [15] for determining the breakdown voltage in insulating liquids. The test procedure was accomplished as described in Ref. [15] with modifications: The test cell was cleaned and flushed. The oil destined for examination was divided into three aliquots (0.5 l) and one aliquot was poured slowly in the test cell to prevent the formation of air bubbles. Then, the first aliquot was subjected to a run of 6 breakdowns. Within the next two test runs, the second aliquot was subjected to 12 breakdowns and the third aliquot was subjected to 18 breakdowns. During the entire test runs, the oil was stirred. After each test run of breakdowns, samples were taken and DGAs were performed in triplicate by means of a calibrated multi-cycle vacuum extractor coupled to a gas chromatograph (TOGA GC version 2, equipped with vacuum extractor and automatic sampling system, Energy Support GmbH, D-41468 Neuss, Germany). The transformer oils examined in this study are commercially available and they were used directly after degassing ($p < 0.5$ mbar; $T = 50$ – 60 °C) and cooling down to ambient temperature in an airtight aluminum bottle. An extra treatment or the addition of supplementary anti-oxidative substances was not done. A naphthenic oil without inhibitor (NA-UI: naphthenic uninhibited), an inhibited naphthenic oil (NA-I: naphthenic inhibited)

and a mainly paraffinic oil with inhibitor (PA-I: paraffinic inhibited) were chosen for the experiments. The selected oils are widespread in transformers all over the world and well-known manufacturers offer them. The exact composition of each transformer oil is listed in Table 1.

Results and discussion

At the beginning of our study, it was not to be expected that a significant, notable difference in the oil's trend of generating fault gases after electrical flashovers would occur. In a first attempt the oils NA-UI and PA-I, whose compositions differ a lot, were chosen. Amazingly, significant concentrations of the fault gases CO₂, C₂H₄, C₂H₂, CH₄, C₃H₆ and H₂ could be detected after 6, 12 and 18 flashovers. The fault gases C₂H₆, CO and C₃H₈ were not detected or only detected in traces. The representatives registered with the highest concentrations were carbon dioxide (CO₂), acetylene (C₂H₂), hydrogen (H₂) and ethylene (C₂H₄) for both oils. Since paper was not involved in the experiment and carbon monoxide (CO) was not found, it could be concluded that CO₂ was formed by oxidation of oil molecules or it was mainly introduced by ambient atmosphere. Moreover, the oil PA-I formed fault gases in lower quantities than oil NA-UI. An overview with the complete results received during the first attempt is depicted in Table 2. Charts are illustrated for C₂H₄ and C₂H₂ in Figs. 1 and 2.

After these astonishing results, received within the scope of the first attempt, revealing different capabilities of forming fault gases by transformer oils under electrical stress, the experiment was repeated with one modification: Instead of oil NA-UI, an inhibited naphthenic oil (NA-I) was compared to oil PA-I. Once again, significant concentrations of the fault gases CO₂, C₂H₄, C₂H₂, CH₄, C₃H₆ and H₂ were detected after several flashovers. The fault gases CO and C₃H₈ were detected in traces, ethane (C₂H₆) was not registered. The highest concentrations were found for CO₂, C₂H₂, H₂ and C₂H₄ in case of both oils. Nevertheless, the oil PA-I formed less fault gases than oil NA-I. The complete results of the second attempt are given in Table 3. Figs. 3 and 4 present graphs for C₂H₄ and C₂H₂.

The concentrations of gases in the oils received after 18 flashovers (see Table 2 and Table 3) were evaluated by application of existing interpretations schemes [2,5–11]. The results are mapped in Table 4. Interestingly, the interpretation schemes each resulted in the same diagnostic indication for all four oil samples examined.

As a quintessence of the experiments and results described above, the following statements can be made: Considering the behavior of naphthenic oils with (NA-I) and without inhibitor (NA-UI), it seems that the presence of inhibitor suppresses the generation of fault gases caused by flashovers: The concentrations of all relevant fault gases are lower for oil NA-I compared to oil NA-UI (see Fig. 5). Anyway, the differences between oil NA-UI and NA-I concerning the volumes of generated fault gases are marginal.

Table 2

DGAs of oils NA-UI and PA-I after 6, 12 and 18 flashovers (first attempt; room temperature).

Gas ^a	0 flashovers		6 flashovers		12 flashovers		18 flashovers	
	NA-UI	PA-I	NA-UI	PA-I	NA-UI	PA-I	NA-UI	PA-I
CO ₂	20.7	29.2	117.7	82.6	149.3	109.3	243.0	130.3
C ₂ H ₄	n.d.	n.d.	3.1	2.9	11.3	6.7	16.1	12.6
C ₂ H ₂	n.d.	n.d.	19.8	14.3	68.5	28.4	103.7	51.0
C ₂ H ₆	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
CH ₄	n.d.	n.d.	1.5	1.1	5.3	2.5	7.2	4.5
CO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
C ₃ H ₆	n.d.	n.d.	1.5	1.5	4.8	2.7	7.1	6.2
C ₃ H ₈	n.d.	n.d.	0.1	0.1	0.3	0.1	0.3	0.3
H ₂	n.d.	n.d.	5.2	4.9	18.7	11.9	23.4	18.7

^a The concentrations of gases are given in [μl gas/l oil]; n.d.: not detected.

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