Abstract At a time when the optimal utilization of resources is becoming ever more important, the condition monitoring of electrical equipment is also becoming increasingly essential. The dissolved gas analysis (DGA), an internationally accepted method for the condition assessment of transformers, plays a key role in this respect. By continuously monitoring the key gases in a transformer, incipient faults can be detected at an early stage and suitable maintenance measures can be initiated. This ability to plan maintenance measures may provide the key to cutting costs and increasing the overall system reliability. In free-breathing transformers, degassing or gas dissolving can occur over time, which may influence the interpretation basis of the DGA. The reason for this is that molecules always strive for equal distribution in a chemical-physical system. Various theories, which are based on the determination of physical and chemical material properties, can be used to describe these processes. Here, the Henry constants describe the concentration equilibrium at the phase interfaces and the diffusion coefficients describe the movement of the gas molecules dissolved in mineral oil. This paper presents mathematically or experimentally determined values and compares them with the literature. Furthermore, it describes the influence of the key gases investigated and the temperature dependence.

Keywords Transformer · Online DGA · Condition monitoring · Henry constants · Diffusion coefficients

Zusammenfassung In einer Zeit, in der die optimale Verwertung von Ressourcen in den Vordergrund rückt, wird auch die Zustandsüberwachung elektrischer Betriebsmittel immer wichtiger. Hierbei übernimmt die Gas-in-Öl-Analyse als weltweit anerkannte Methode zur Zustandsbewertung von Transformatoren eine wesentliche Schlüsselrolle. Mithilfe eines kontinuierlichen Monitorings der Schlüsselgase in einem Transformator können sich anbahnende Defekte frühzeitig erkennen und geeignete Maßnahmen eingeleitet werden. Durch diese ermöglichte Planung von Instandhaltungsmaßnahmen werden Kosten eingespart und die Gesamtsystemzuverlässigkeit erhöht. Bei frei-atmenden Transformatoren kann es mit der Zeit zu einer Entgasung bzw. zu einer Gasrückwärtigung kommen, welche die Interpretationsgrundlage der Gas-in-Öl-Analyse beeinflussen kann. Grund hierfür ist, dass frei bewegliche Moleküle in einem physikalisch-chemischen System stets eine Gleichverteilung anstreben. Zur Beschreibung dieser Vorgänge können verschiedene Theorien herangezogen werden. Die Bestimmung der physikalischen und chemischen Stoffeigenschaften stellt das Fundament dieser Theorien dar. Hierbei dienen die Henry-Konstanten zur Beschreibung des Konzentrationsgleichgewichts an Phasengrenzflächen und die Diffusionskoeffizienten zur Beschreibung der Bewegung der im Mineralöl gelösten Gasmoleküle. In diesem Beitrag werden rechnerisch bzw. empirisch ermittelte Werte präsentiert und mit der Literatur verglichen. Darüber hinaus wer-
den der Einfluss der untersuchten Schlüsselgase und die Abhängigkeit von der Temperatur beschrieben.

Schlüsselwörter Transformatoren · Kontinuierliche Gas-in-Öl-Analyse · Zustandsüberwachung · Henry-Konstanten · Diffusionskoeffizienten

1 Introduction

Optimal use of monetary resources is an issue of ever greater importance in the world today, and asset management in the energy sector is also gaining significance. An essential task that goes hand in hand with this, is evaluating the current condition of electrical equipment is. Dissolved gas analysis (DGA) is an accepted procedure worldwide for condition assessment and condition monitoring of transformers. In addition, DGA is the most frequently used procedure to detect incipient faults at an early stage and one that also has the capability to initiate appropriate maintenance measures [1, 2].

Naphthenic mineral oil consists primarily of a mixture of hydrocarbon chains (C12H26, 11.6%) and alkanes—A cycloalkane (C14H28, 15.5%), bicyclic alkanes (C13H24, 28.5%), tricyclic alkanes (C16H28, 23.3%) and tetracyclic alkanes (C16H26, 9.7%) (Fig. 1; [3]). Electrical and/or thermal stresses in the transformer can exceed the binding energy of the carbon-carbon or carbon-hydrogen bonds. The bonds break and the resulting instable decomposition products then combine again to form gaseous molecules, which can be present in dissolved and/or free form. The resulting key gases are H2, CH4, C2H2, C2H4 and C2H6. In addition, CO and CO2, which are produced in combination with atmospheric oxygen and cellulose degradation, as well as O2 are also among the key gases [4, 5].

With DGA, the presence or concentration of the key gases is detected within the mineral. There is the possibility of manual sampling including subsequent analysis in the laboratory and the possibility of continuous monitoring systems (online DGA, Fig. 2). In general, the measurement starts with sampling and extraction of the gases dissolved in the oil. A distinction is made between the different extraction methods, with vacuum extraction being the most accurate and the headspace method the most commonly used. In the headspace method, a gas phase consisting of carrier gas is located above the mineral oil to be analysed, into which the dissolved gases diffuse. After the extraction of the gases, their composition is analysed. In most cases, this is done using gas chromatography. Here, the gas mixture (carrier gas + key gases) is forced through a system of tubes and detected on a thermal detector. The gas molecules migrate through the columns of the GC tube at different speeds and then hit the detector at a defined point in time, depending on the physical and chemical properties. Other methods with their own specific advantages and disadvantages are also in use, such as infrared spectroscopy. In this method, the reflection of an infrared light source

![Molecular structures of main components of naphthenic mineral oil, following [3]](image1)

![Transformer with online DGA system](image2)
is analysed depending on the gases present. Different gas molecules absorb different frequencies of the IR spectrum to different degrees. The great advantage of this method is very high long-term stability and the maintenance-free nature of the device itself, but not all key gases can be directly detected with this method [6, 7].

2 Condition assessment of transformers by DGA

It is possible to determine the present condition of the transformer by analysing the gases dissolved in the oil. There are various approaches for data interpretation [8]. One frequently used method is to compare identically designed transformers and define a threshold value at 90% of the maximum gas concentrations. It is assumed, that the probability of a fault occurring in a transformer at gas concentrations below this threshold is low. If one of these gas thresholds is exceeded, the transformer should be inspected more precisely. If the fleet of transformers is too small or no comparative data is available, reference values from the literature and standards can be used. Trends of recent years have shown that a condition assessment based on absolute gas concentrations can often be insufficient, the rates of gas change are thus increasingly used as an assessment criterion. Here, also, the 90% value of the gas change rate is defined or reference values can be used [4, 9, 10]. The procedure defined in IEEE C57.104 goes one step further and makes recommendations for action directly on the individual gas concentrations and gas change rates (Table 1; [11]).

Table 1  Recommendations for action related to percentage of total combustible gases (TCG) [11]

| TCG (%) | TCG rate (%/day) | Sampling Interval | Operating Procedures |
|---------|----------------|------------------|---------------------|
| Condition 4 | ≥5 | >0.3 | Daily | Consider removal from service; |
| | | | 0.01–0.3 | Daily | Advise manufacturer |
| | | <0.01 | Weekly | Exercise extreme caution; |
| | | | | Analyse for individual gases; |
| | | | | Plan outage; |
| | | | | Advise Manufacturer |
| | 2–5 | >0.3 | Weekly | Exercise extreme caution; |
| | | | | Analyse for individual gases; |
| | | | | Plan outage; |
| | | | | Advise manufacturer |
| | | | | Monthly | Exercise caution; |
| | | | | Analyse for individual gases; |
| | | | | Determine load dependence |
| Condition 2 | 0.5–2 | >0.3 | Monthly | Exercise caution; |
| | | | 0.01–0.3 | Monthly | Analyse for individual gases; |
| | | | | Determine load dependence |
| | | | | Quarterly | Exercise caution; |
| | | | | Analyse for individual gases; |
| | | | | Determine load dependence |
| | | | | | Continue normal operation |
| | | | | | Annual |

In recent years proof has been provided that knowing the history of a transformer and detecting incipient faults from an early stage is a great advantage. Through continuous monitoring, the condition of a transformer can be determined more accurately and maintenance measures can be more effectively planned (Fig. 4). This leads to better allocation of available monetary and material resources and an increase in overall system reliability [1, 14]. An essential part of this is to know exactly the rates of change of dissolved gases in a transformer—they are considered a more important indicator than the absolute gas concentrations [9]. The assessment of the transformer condition based on absolute gas concentrations can lead to incorrect estimates. The same amount of dissolved gas can be assessed with a different criticality in different transformers [4, 13, 14]. Furthermore, gas concentrations in different transformers can be attributed to different causes. There are transformers with highly increased gas concentrations that have been operating stably for many years and show no or only very small further increases. This might indicate an inactive fault, which can lead to a failure within a short time if it begins to evolve again. It is advisable to aim for continuous monitoring of the transformer. Other transformers show very rapid increases in dissolved gases in a very short time, which cannot be detected in time by regular sampling [9].

The fact that the condition of a transformer can change rapidly is shown by the case of a 23.5/432 kV generator step-up transformer, where a multi-gas DGA monitoring system was installed in 2010. Up to that time, the transformer did not show any significant gas concentrations. Shortly after installation, there was a sharp increase in H2 and C2H2, indicating an electrical fault (Fig. 5). For safety reasons, the transformer was taken off the grid, subjected to electrical tests and maintenance work. The electrical tests did not lead to a result, but forensic examinations showed a developing electrical fault in the winding with an already advanced decomposition of the paper insulation (degree of polymerisation, DP < 200) [13]. The DP value corresponds to the number of interconnected glucose rings of the cellulose. It provides information about the current condition of the paper insulation and has a direct correlation to the remaining service life. The number of interconnected
Fig. 3 Distribution of key gases for different faults in percentage (a) and Duval triangle one (b).

Fig. 4 380/110-kV transformer with a DGA monitoring system (a) and the DGA monitor itself (b).

Fig. 5 Time dependent dissolved gas concentrations in a 23.5/432 kV GSU transformer, based on [13].

Fig. 6 Time dependent dissolved gas concentrations in a 345 kV GSU transformer, based on [12].
glucose rings in new transformers is in the range of 1000 to 1200. When this value is less than 200, it can be assumed that the paper quality is no longer sufficient for reliable operation [8].

In [14], five cases are described in which a DGA monitoring system was able to successfully identify incipient faults at an early state. Of particular interest is the case of a 735/230 kV transformer where a fault in the bushing area was detected in time by an increase in H₂. Consequently, the transformer load was reduced and the transformer could be taken off the grid and maintained within 40 days as planned. The estimated cost saving due to the early detection of the fault and the corresponding repair of the transformer is estimated to be around $4,000,000.

A somewhat more recent example from [12] also shows that gas concentrations can increase rapidly within a short time (Fig. 6). The evaluation of the data with all methods showed that there is a thermal fault and the scenario described in [11] requests immediate action. The integrated Buchholz relay did not trigger in this case and the transformer was manually taken off the grid. The inspection carried out showed severe carbonisation of the paper insulation.

In general, any incipient fault is accompanied by the formation of hydrogen (compare Fig. 3a). In many cases, a hydrogen sensor is sufficient for monitoring and enables a simple realisation of a monitoring system. The interpretation basis for a developing fault and also its classification is strongly limited, however, since historical data is only available for H₂ or a few other gases. Hydrogen is not always available in sufficient quantities for thermal defects such as those that occur with broken or loose connections, overheating cores, poor cooling, eddy currents, etc. The so-called “hot metal gases” (CH₄, C₂H₆ and C₂H₄) are of central importance here. Furthermore, the increase of C₂H₂ as a significant sign for electrical discharges is not present. C₂H₂ can indicate a significant fault from concentrations of a few ppm. In the case of stray gassing, there is also a large increase in H₂, although this is not a defect with consequences [12]. It can thus be stated that monitoring with an H₂ sensor is better than no monitoring at all, but each additional key gas increases the overall system reliability and prevents costly failures. The recognised disadvantage of multigas monitoring systems is the purchase price, but this is negligible compared to the cost of a power transformer failure.

4 Gas balance of transformers for DGA interpretation

4.1 Degassing at the phase interface

In the case of free-breathing transformers, which are primarily used in Europe, gas exchange occurs at the phase interface between the mineral oil and the gas phase above [15, 16]. This exchange can be explained by the desired equal distribution of free moving molecules in a closed chemical-physical system. After the appearance of an electrical or thermal fault, very high gas concentrations are formed locally at the point of the fault due to the decomposition of the mineral oil and possibly of the cellulose. Subsequently, the dissolved and free gas molecules are distributed throughout the entire system. This balancing process is composed of free diffusion and superimposed convection flows. Consequently, an equilibrium is established between the gas phase and the mineral oil, which means that key gases are degassed into the gas phase and gases from the gas phase dissolve in the mineral oil [2, 15, 17].

Although this method is not generally recommended today, the condition of a transformer, as well as its warning and alarm gas values, are determined using the absolute gas concentrations [9, 11]. Due to the continuous degassing with simultaneous gas formation, a state of equilibrium is established between these two processes. This equilibrium does not necessarily reflect the actual state of the transformer [15, 18, 19]. Fig. 7 shows the concentrations of dissolved gases in the case of a continuous surface discharge over time in a laboratory experiment. It can be seen that in the free-breathing configuration, an equilibrium between degassing and gas formation already occurs, whereas this does not occur in the hermetically sealed configuration. Furthermore, the degassing of H₂ and CH₄ takes place so quickly that no measurable concentrations arise in the test object. This may also lead to a different interpretation of the defect [17].

4.2 Dissolving air gases and their temperature behaviour

The opposite case to the degassing of transformers is the dissolving of ambient air gases from the atmospheric ambient air during initial commissioning or after degassing of the mineral oil [16]. Own measurements showed a saturation concentration of about
Dissolving of \( \text{N}_2\), \( \text{O}_2\) and \( \text{CO}_2\) from ambient air in mineral oil of a 200 l transformer model in the laboratory (a) and temperature and concentration of dissolved \( \text{CO}_2\) over time of a in service 110/380 kV transformer (b).

63,000 ppm for \( \text{N}_2\), 18,000 ppm for \( \text{O}_2\) and 500 ppm for \( \text{CO}_2\) (Fig. 8a). It can also be seen that different gases dissolve in the mineral oil with different velocities.

In addition, different concentrations of dissolved gases can occur depending on temperature fluctuations due to changes in the load or the ambient temperature. On the one hand, this is due to the temperature dependence of Henry’s constant, which describes the gas solubility in mineral oil, and the gas storage capacity of cellulose. Fig. 8b shows this behaviour based on measurements at a 110/380 kV transformer.

The concentration of \( \text{CO}_2\) is stated in p. u. with reference to the maximum value of the concentration in the period under consideration.

5 Current research on chemical and physical properties for DGA interpretation

5.1 General

As mentioned above, gas exchange occurs in the area of the phase interface. Dissolved gas molecules in the mineral oil diffuse into the gas phase and gas molecules from the air or the gas cushion dissolve in the mineral oil. Since different substances have varying solubilities, different gases degas at unequal rates. This leads to a shift in the relative proportions of the gases and makes it difficult to identify the fault by established methods like the ratio methods or Duval triangles [17].

For decades, the DGA has been a well-suited and approved method for assessing and monitoring the condition of transformers. By taking the gas exchange into account, the DGA could be further improved. An even more precise assessment of the current condition would be possible and the accuracy of interpretation would be increased. For this purpose, a mathematical model based on the various mass transport theories is being developed and tested at the Institute of High Voltage Engineering and System Performance. In future, this model should be able to quantify the degassing at the phase interface between the mineral oil and the overlying gas blanket or the ambient air [18].

In general, all transfer and transport processes are subject to comparable physical laws and are described by similar effects. The mass transfer is understood to be a change in quantity in a time interval. The diffusion coefficients and the Henry constants are considered to be the determining parameters for the characteristics of mass transfer. The diffusion coefficients determine the relationship between concentration gradient and diffusive mass transfer. The Henry constants describe the concentration equilib-
Ostwald Coefficients

0.937

1.990

1.840

2.820

2.563 (± 0.351)

1.240

0.112 (± 0.009)

7.781 (± 2.092)

0.079 (± 0.003)

0.337

0.437 (± 0.065)

0.429

[11]

0.135 (± 0.036)

9.944 (± 0.817)

0.155 (± 0.021)

0.043

0.056

[4]

1.350

\( \eta \) temperature,

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5.2 Results and interpretation

5.2.1 Henry constants

The experiments carried out clearly show that various gases behave differently with increasing temperature. The solubility of the investigated hydrocarbons (C\(_2\)H\(_2\), C\(_2\)H\(_4\), C\(_2\)H\(_6\), and CH\(_4\)) increases with rising temperature, whereas the solubility of hydrogen (H\(_2\)) decreases with increasing temperature (Fig. 10). This behaviour is also consistent with the available results [19, 27–30]. It should be noted that the Ostwald coefficients have an opposite behaviour since the Ostwald coefficients roughly correspond to the reciprocal of the respective Henry’s constants [21].

**Table 2** Comparison of own measurements with values from literature at 25°C

|                | Measurements | Calculations [4] | Calculations [11] |
|----------------|--------------|------------------|------------------|
| H\(_2\)         | 2.746 (± 0.089) | 0.079 (± 0.003) | 0.056 | 0.043 |
| C\(_2\)H\(_2\)  | 0.437 (± 0.065) | 2.563 (± 0.351) | 0.429 | 0.337 |
| C\(_2\)H\(_4\)  | 0.155 (± 0.021) | 7.244 (± 0.898) | 1.240 | 0.937 |
| C\(_2\)H\(_6\)  | 0.135 (± 0.036) | 7.781 (± 2.092) | 1.840 | 1.350 |
| CH\(_4\)        | 0.112 (± 0.009) | 9.944 (± 0.817) | 2.820 | 1.990 |
planned and timely maintenance measures, financial resources can be saved and the overall system reliability can be increased.

Current research is focused on the phase interface between the mineral oil and the gas phase in the conservator tank, where an exchange of gas molecules occurs. This exchange means that key gases dissolved in the oil dissipate into the ambient air and, vice versa, gases from the ambient air are dissolved in the mineral oil. The basis of interpretation of the DGA is consequently affected. This can lead to a wrong assessment of a fault criticality and to a fault being classified incorrectly. The exchange of gas molecules can be described using various theories of mass transfer. All these theories have in common that the basis is formed by the diffusion coefficients as well as the Henry constants. Currently, a model based on these theories is being developed.

The Henry constants can only be determined exactly by empirical means and they are strongly dependent on the temperature. A comparison of the determined values and the values from the literature shows that large differences sometimes occur between all values. This is primarily due to how the results are determined and the strong dependence on the density of the oil used. It can be seen that the Henry constants of hydrocarbons increase with temperature, whereas those of pure substances decrease. Furthermore, the absolute values of different gases differ greatly. The diffusion coefficients were calculated in this work and it can be seen that significant differences are dependent on both the equation used and the temperature. The literature also shows a very large range of error over several powers of ten. It would therefore appear appropriate in the view of the authors that an experimental procedure for the determination of the diffusion coefficients should be applied in further work.

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Fig. 11 Temperature dependent diffusion coefficients of hydrogen, determined with the help of different calculation methods
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