Abstract: Transformers are one of the most important and cost-intensive components of electrical energy supply networks, thus it is of special interest to prolong their life duration while reducing their maintenance expenditures. In order to reach these aims it is indispensable to gather detailed information about the operation conditions of transformers, which is usually done by various kinds of oil analyses like the standard oil test, the DGA (Dissolved Gas Analysis) and the Furan analysis.

Usually electrical abnormalities are shown by a DGA, which allows a detection of two different kind of failures: electrical and thermal faults, whereby each type of failure can be subdivided in three different categories according to the international standard IEC 60599 [1], thus the DGA became a well known and approved technique in the last decades, although different techniques of dissolved gas analysis and its interpretation exist.

In this contribution different DGA methods are introduced and compared in order to explain the problems of DGA and its evaluation and to give recommendations concerning the questions how to analyze an oil sample and how to evaluate the results of the analysis with a focus on different equipment.

Key words: Transformer, DGA, Degassing, Fault Analysis, Interpretation Rules

INTRODUCTION

For power transformers the combination of an insulating liquid and a solid insulation impregnated therewith is almost the only kind of utilized insulation. Only with such a combination transformer components can be insulated and the thermal losses can be dissipated simultaneously. As a first step for an evaluation of the actual condition of this insulating system usually a dissolved gas analysis is used, because failures inside the transformer lead to a degradation of the liquid insulation in such a way that different so called failure gases are produced, thus the compound of the gases, which is characteristic for different failure types, enables an identification of the failure cause.

Therefore from the gases that are dissolved in the insulating liquid, which usually consists of a mineral based insulating oil, an assessment of the strains that have been provoked insulation degradation, is possible. By such an analysis both thermal and electrical overstressing becomes evident, thus allowing an early beginning of countermeasures that prolong insulation reliability and lifetime.

However, for this appraisal at first the total extraction of the dissolved gases is necessary, thus the so called key gases

- Oxygen O\(_2\)
- Nitrogen N\(_2\)
- Carbon Monoxide CO
- Carbon Dioxide CO\(_2\)
- Hydrogen H\(_2\)
- Methane CH\(_4\)
- Ethane C\(_2\)H\(_6\)
- Ethylene C\(_2\)H\(_4\)
- Acetylene C\(_2\)H\(_2\)

and sometimes

- Propane C\(_3\)H\(_8\)
- Propene C\(_3\)H\(_6\)

are extracted by a degassing technique, for which often a so called Toepler-pump-system is used, which is shown exemplarily in Figure 1.
Using a Toepler-pump vacuum is applied to the insulation liquid in order to remove the key gases from the oil. Although long time experience has shown, that this extraction is efficient and gives good results for a subsequent analysis this vacuum pump contains usually high amounts of mercury, thus being a risk for the operating personnel and the environment. Alternative procedures like the so called headspace extraction, where the amount of dissolved gases is identified from a dissolution of the gases in the liquid into a defined gas in the headspace of a phiole lead to somewhat different results and is as explained in the standard IEC 60567 [2] more unprecise.

In this contribution therefore another system for DGA usable even at the transformer operating site is introduced. This system consists of a mercury free gas extraction device combined with a portable gas chromatograph (GC), which identifies the type and amount of gases after the extraction from the oil sample. The GC device contains a capillary column, in which the different gases are separated in a carrier gas flow, fow which in most cases Argon Ar is used. After passing the ripping-up column the gases are injected in a Thermal Conductivity Detector (TCD) or a Flame Ionization Detector (FID), each one sensitive for a special fraction of the detectable gases.

NEW DGA SYSTEM

With the new DGA system the analysis is done in 2 steps with high selectivity and accuracy fully compliable with laboratory procedure.

1. Degassing of the taken oil sample through vacuum extraction (according to IEC 60567 [2])

2. Dissolved gas analysis by gas chromatography with TCD (thermal conductivity detector), FID (Flame Ionization detector) and Methanizer

Both steps, which are explained in more details in the following, are synchronized by a micro-controller, which guarantees a fast and reliable measurement routine.

Vacuum Degassing

A new invented vacuum degassing method (Patent pending DE 102 52 652 4) degases the oil sample in multiple periods. After the extraction by a 4 step vacuum pump the gases are enclosed in a vacuum chamber where they are separated. The gases are evacuated from the vacuum chamber with a vacuum pump, therefore a very high sensitivity can be reached. The extraction principle is schematically shown in Figure 2 an a photo of the device is given in Figure 3.

In- and outlet of the oil sample as well as the switching valve are microprocessor controlled and a linear pressure sensor measures online the total gas content (TGC), which is an important parameter concerning bubbling problems.

Figure 2: Schematic view of the gas extraction unit

Figure 3: Photo of the gas extraction unit

The injection of the gas samples into the gas chromatograph is made via a fixed mounted and heated transfer pipe but also an additional port for a withdrawal of gas samples is installed.

Mobile GC

The analysis of the dissolved gases is done after the automatic or manual injection in an automatic sample loop (6 port valve) of the gas chromatograph. The gas sample is separated in an inert gas stream into 11 components. This guarantees a high selectivity with no interference of other gas signals.

A capillary column (type Carboxen 1010, length 30m x
ID 0.32 mm) is used for the separation of the different compounds, whereas the detection is carried out with a TCD (Thermal Conductivity Detector) and FID (Flame Ionization Detector). The compounds CO and CO$_2$ are converted with a methanizer for detection in the FID. This procedure guarantees a very high sensitivity and the determination of all mentioned key gases including Propane and Propene. All results are finally displayed in ppm and the sensitivity is as low as 0.1 ppm for certain hydrocarbons. Therefore, also new transformer oils and transformers after their periodic maintenance can be analyzed, as shown in Figure 4, in which some measurement examples are depicted.

Due to the small size of the GC, which is shown in Figure 5, the device is easy portable and therefore also suitable for analyses on-site e.g. from free gas in the Buchholz-relay. This is often very important in cases in which the Buchholz-relay respond after an failure thus the transformer is protected against expanded failures. In this cases the free gas accumulated in the relay can be analyzed on the spot, thus a first statement on the severity of the fault becomes possible. Therefore a 2 injection port is installed, thus it is also possible to monitor the Buchholz gases automatically. As soon as the relay releases, the measurement routine is interrupted and the relay gases are analyzed accordingly.

**Figure 5**: Mobile GC

**Online DGA System**

The introduced systems can be used as an online DGA system as shown in Figure 6, which is then controlled by a microprocessor. A serial interface (RS 232) allows transferring the data to a remote computer. The intervals of the analysis cycle can be freely defined by the operator (number of analyses per day or hour). The system has 8 additional analog inputs (0-1 V) for the measurement of other transformer parameters, like oil temperature, winding temperature, ambient conditions etc. The connection of these external sensors is realized via relay contacts, which can be specified by the customer as NC (normally closed) or NO (normally opened).

**Figure 6**: Online DGA system

Beside the display of the results in ppm all other operating conditions are registered online and stored in a database together with all other parameters. The graphical display of the results is in real time on the monitor, in a table or/and a test report in a print file. The data can also be transmitted to a remote computer or a control center. All relevant data are stored in a measurement file. The results are stored with other measurement parameters in the history (log file). The history starts with the day of the commissioning. The trend is shown in a diagram (hour / day / week / month / year) and the
interval can be adjusted by the operator. The integrated expert system will analyze even smallest deviations in the gas parameters. A plausibility test ensures the accuracy and reproducibility of the test results. Furthermore different alarm settings are possible, thus the following incidents lead to an alarm:

- Monitoring of all gas parameters (11 gases), excess of one parameter will activate an alarm and data will be send to a remote control system
- Trend analysis for predictive maintenance for each gas compound if the rise exceeds beyond predefined threshold levels (considering the temperature of the transformer)
- Interruption of power supply
- Status report of the system with automatic self diagnostic function
- Export of all data and alert to a remote control system

All threshold values can be individually selected for each gas component. The trend analysis starts with the day of installation and is stored as an unbroken chain of evidence. The trend will show any irregularity above 0.5 ppm or for organic components 0.1 ppm on the FID channel. The degree of degradation of the insulation of the transformer can be displayed with a comparison of the different parameters versus the time, which is an important criterion for prophylactic control of possible defects in the transformer.

COMPARISON MEASUREMENTS

The measured values of the new system have been compared with the results of a laboratory measurement. The results of this comparison are summarized in Table 1.

Table 1: Comparison of the measurement results

<table>
<thead>
<tr>
<th>Component</th>
<th>Toepler-pump</th>
<th>Vacuum degassing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lab GC</td>
<td>Mobile GC</td>
</tr>
<tr>
<td>H₂</td>
<td>234</td>
<td>235</td>
</tr>
<tr>
<td></td>
<td>225</td>
<td>239</td>
</tr>
<tr>
<td>CO</td>
<td>230</td>
<td>231</td>
</tr>
<tr>
<td></td>
<td>220</td>
<td>225</td>
</tr>
<tr>
<td>CO₂</td>
<td>1320</td>
<td>1297</td>
</tr>
<tr>
<td></td>
<td>1243</td>
<td>1341</td>
</tr>
<tr>
<td>Methane</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>25</td>
</tr>
<tr>
<td>Ethan</td>
<td>162</td>
<td>165</td>
</tr>
<tr>
<td></td>
<td>115</td>
<td>149</td>
</tr>
<tr>
<td>Ethylene</td>
<td>10,1</td>
<td>10,0</td>
</tr>
<tr>
<td></td>
<td>7,4</td>
<td>10,9</td>
</tr>
<tr>
<td>Acetylene</td>
<td>0,8</td>
<td>1,0</td>
</tr>
<tr>
<td></td>
<td>0,4</td>
<td>0,76</td>
</tr>
</tbody>
</table>

From the results in Table 1 it is obvious, that there are no significant differences neither between the different degassing techniques nor between the different used GCs, that means in this case the mobile GC and a high precision laboratory GC.

In Table 2 and the results of four measurements performed on an identical sample are shown. The measurements have been performed subsequently to demonstrate the error due to deviations in reproducibility of the measuring device.

Table 2: Reproducibility of different measurements using the same oil sample

<table>
<thead>
<tr>
<th>Component</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>1274</td>
<td>1089</td>
<td>1105</td>
<td>1075</td>
</tr>
<tr>
<td>CO</td>
<td>212</td>
<td>229</td>
<td>223</td>
<td>198</td>
</tr>
<tr>
<td>CO₂</td>
<td>7571</td>
<td>7198</td>
<td>7222</td>
<td>7275</td>
</tr>
<tr>
<td>Methane</td>
<td>234</td>
<td>231</td>
<td>243</td>
<td>235</td>
</tr>
<tr>
<td>Ethane</td>
<td>32,6</td>
<td>24,8</td>
<td>28,5</td>
<td>26,8</td>
</tr>
<tr>
<td>Ethylene</td>
<td>27,5</td>
<td>26,7</td>
<td>24,9</td>
<td>19,8</td>
</tr>
<tr>
<td>Acetylene</td>
<td>100,1</td>
<td>91,1</td>
<td>98,7</td>
<td>88,5</td>
</tr>
</tbody>
</table>

From Table 2 it becomes obvious that the method enables a high reproducibility, thus the differences, as shown in Figure 7 are rather small, thus an average deviation of approximately ±5 % could be seen.

The deviation between the results is of similar order judged against the comparison of the two measurement systems presented in Table 1. Out of these results it can be concluded, that independent from the method of extraction or analysis the values of the two measuring systems are comparable. This behavior has been verified by numerous measurements and shows that both procedures are adequate for an evaluation of the transformer condition.
EVALUATION OF FAILURE GASES

After the different components of the dissolved gases have been determined an evaluation of the conclusions, that can be drawn thereof, has to be made. For this evaluation different criteria as defined in the IEC 60599 [1] can be used or the MSS-criteria according to Müller, Schliesing and Soldner [3], the Rogers [4] or the Duval [5] criteria, which are the most often used ones. Furthermore large utilities or manufactures like ABB have also their own evaluation techniques, that are based on the before mentioned standard techniques but are improved based on their knowledge and experience. However, all the criteria have in common, that they draw their conclusions out of different quotients of the detected gases. The reason therefore is that through the division of the gas amount the total gas concentration has no impact on the results, as the gas generation may be different for every transformer, thus this approach avoids misinterpretations.

Finally, DGA analysis is often done by experienced people, due to the partly different interpretation rules and their experience, which is necessary in order to avoid misinterpretations. However, in the following a simplified interpretation rule is introduced, which uses instead of all fault gas concentrations mainly hydrogen and methane in order to reach a rough estimation of the failure cause. This procedure can divided into the following three steps:

**Step 1:**
At first it is necessary to decide if the fault gas concentrations should be evaluated, because this is only required in such cases, in which variations of the gas concentration indicate a failure. As a simplified rule, which is based on recommendation in the IEC 60599, it can be assumed that an increase of 10 % per month indicate an active failure, although the oil amount has to be taken into consideration, thus based on a fixed increase in per cent per month it can be stated that the more oil is in the transformer the more serious is the failure.

**Step 2:**
If the fault gas concentrations indicate an active failure according to step 1, it should be checked if the hydrogen content is higher than the acetylene concentration. If it is vice versa, thus the acetylene concentration is higher than the hydrogen content, it seems that there is a contamination from the OLTC-chamber (On Load Tap Changer). In this case the evaluation has to be performed by an expert, especially if various failure gases increase in comparison to the last sample.

**Step 3:**
If there is obviously no contamination from the OLTC according to step 2 the relation between the methane and hydrogen concentration has to be calculated. If the quotient is smaller than 1 an electrical failure, like partial discharges (PD) could be the cause, for the generation of the fault gases [6]. If the quotient is on the other hand larger than 1 the DGA indicates a thermal problem. Furthermore it can be said that the higher the quotient in both ranges, that means below or above 1, the higher is the energy converted at the failure spot or finally the more serious is the failure. That means PDs, which are usually very low energy discharges, have a quotient in a range below 0.1, whereas discharges of high energy often are characterized by a quotient close to 1. The same is valid for thermal faults, because the higher the temperature the more hydrogen is produced, thus e.g. for local overheating below 300°C hydrogen is not the mostly produced gas but the hydrogen concentration increases rapidly with increasing temperature, thus the higher the quotient the bigger the thermal problem.

**Example:**
If the gas concentration in Table 1 should be evaluated according to step 3, the methane to hydrogen ratio is about 0.1, thus an electrical failure could be assumed. Furthermore the ratio is rather small, thus the energy of the failure should be rather small, thus in case the DGA indicate partial discharges based on the above explained interpretation rules. The same result is obtained using other interpretation rules like IEC 60599, thus in most cases an estimation about the failure type and its seriousness is possible using this simple rule.

**CONCLUSIONS**
A system for DGA was introduced containing a new degassing technique and a mobile GC, thus these devices can be combined to an online DGA transformer monitoring system, which could enhance the reliability of transformers significantly. Uncertainties related to oil sampling can be avoided, when this system is installed online, thus the condition and gassing history of the transformer could be continuously monitored. Comparison tests with a Toepler-pump system and a high precision laboratory GC have shown a high preciseness and good reproducibility of the system.

Finally a simple failure gas interpretation rule was introduced, which allows also for non experts a rough evaluation of the failure gases.

**REFERENCES**