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Rapid Dissolved Gas Analysis by means of Electrochemical Gas Sensors

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Abstract: **Rapid, introductory analysis of gases dissolved in insulating oil (DGA) carried out in the field can help in effective screening of faulty transformers as well as minimising number of classical laboratory chromatographic DGA tests. It is also crucial for shortening a time gap between oil sampling and its analysis.**
A novel approach to DGA is presented in this paper. A rapid analysis of oil samples is carried out by means of a portable analyser fitted with electrochemical gas sensors. Extraction of gases from the oil matrix is achieved by means of a dynamic, closed-loop stripping process. The analyser, which was built, is controlled by a microprocessor and may be operated in the field as an autonomous device. The system incorporates only two gas sensors and due to an extended set of their output signal wave descriptors used for the analysis it allows for a reliable identification of fault gases present in an oil sample. The identification of basic transformer fault types is illustrated on the basis of analytical results obtained for artificial oil samples prepared in a laboratory as well as those taken from transformers in-operation.

INTRODUCTION

Several years of industrial practice has proved that analysis of gases dissolved in insulating oil (DGA) is a very effective and reliable method for predictive maintenance of transformers. But classical DGA procedures incorporating IEC standard gas extraction techniques [1] are expensive, especially when the test equipment is not used at its full analysis capacity. Reduction of those costs is possible when novel extraction methods, such as *Headspace* or *Shake Test*®, are introduced [2]. There are also still some limitations related to the method of chromatographic analysis of gases – it is to be run in the laboratory by highly qualified personnel and therefore its costs are high too. A time gap between oil sampling and its laboratory analysis is also of some importance - it may lead to deterioration of gas content in poorly secured oil samples making analysis results profitless. Present DGA procedures involve oil sampling at intervals of 6 to 12 months for transformers not supposed to be defective. But some incipient faults are thus likely to occur undetected during such long intervals between subsequent DGA tests. Making intervals shorter is not economically reasonable taking into account the present cost of a complete laboratory DGA analysis.

Therefore cheaper and more mobile DGA systems and methods are necessary. A complete analysis of gaseous constituents present in the oil sampled from a transformer is also not always necessary, especially when the total gas content value is typical. It implies that mobile DGA systems do not have to render the same set of determinants as classical chromatographic analysis, providing that diagnosis based on novel method is correct.
This paper describes a portable gas analyser that is able to rapidly determine features of gas content of a small oil sample taken directly from a transformer on-site. A novelty of this approach lies in application of electrochemical gas sensors probing gases directly from a stream prepared by a closed-loop gas-from-oil stripping extraction assembly. The main drawback of gas sensors – namely lack of their selectivity, which is disadvantageous in most of applications – was taken as the advantage to expand the spectrum of gases being recognised. Further enhancement of the measurement accuracy (and therefore recognition of transformer insulation faults) was achieved by adopting additional descriptors of time-domain sensor signals. Unconventional data processing of the measurement results also allows for correlation with typical faults observed for transformers in-service. On-site, urgent analyses are possible thanks to a robustness and autonomous operation of the developed DGA analyser.

DESCRIPTION OF THE ANALYSER

Two electrochemical gas sensors are installed into the system; one of them designed for hydrogen, the other for carbon monoxide monitoring. Both are fitted with current-to-voltage converters producing voltage signals proportional directly to a concentration of active gases in sampled air stream. A similar, but limited to monitoring of hydrogen only, approach has been proposed by Inue [3].
A small sample of oil is introduced into the system chamber and a stream of filtered atmospheric air, which is used as a carrier gas, is passed through it. The carrier gas collected over the surface of the oil is then fed to both gas sensors. A small and chemically inert circulating gas pump feeds the carrier gas back to the oil sample chamber. Bubbling greatly extends a

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surface of gas exchange between the liquid and the carrier gas making stripping of gasses dissolved in the oil fast and effective. A more comprehensive and detailed description of the analyser can be found elsewhere [4].

A single analysis run takes 15 minutes on average, including baseline initial check, flushing of oil sample to a drain container and final ventilation of the sample chamber and the sensors.

The device is supplied from 12 V DC power source, consuming approx. 6 W during operation. The analysis process is fully controlled by a micro-controller supervised by an external PC via serial data link. An application controlling operation of the analyser and processing of measurement data was prepared in HP Vee software package (*Agillent*). Figure 1 gives an actual photography of the assembled analyser (*DGAnalyser*).

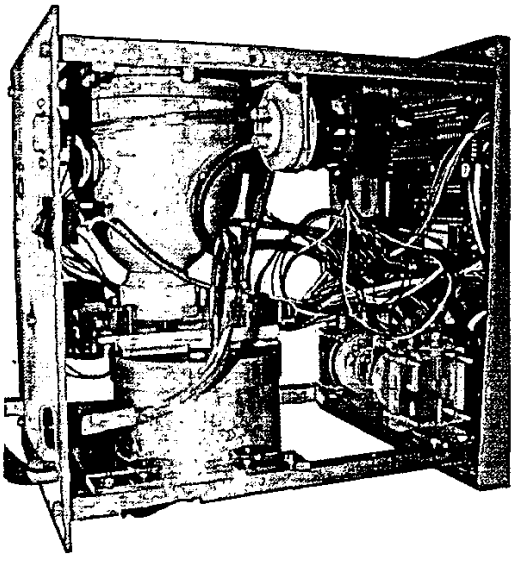

Figure 1. Photograph of the *DGAnalyser* ready for its operation.

Figure 2 presents a typical, time-domain signals generated by gas sensors and recorded in a single analysis run. The software calculates two parameters for each sensor output wave – a value at the *plateau* of the signal and rise time, characterising rate of its increase before terminal stabilisation. Schematic results of this procedure are shown in Figure 2.

Each analysed oil sample is characterised thus by a set of four parameters: two voltage values (U_{H2} and U_{CO} – subscripts H2 and CO relate to the appropriate gas sensors) calculated at the *plateau*, corresponding to the concentration of gases in the oil and two response time constants. Relative values of these parameters are used for further analysis: a quotient of the two terminal voltage values (depicted as $k_{CO/H2}$) and response time values (denoted as RT_{rH2} and RT_{rCO}), normalised by those obtained for characteristic pure gases (H_2 and CO) for each sensor. Application of relative values makes the measurement values independent on a particular batch of sensors used and facilitates comparisons between separate oil samples. Consequently we obtain five values representing an oil sample: U_{H2} and U_{CO}, proportional to gas concentration values and dimensionless $k_{CO/H2}$, RT_{rH2} and RT_{rCO}.

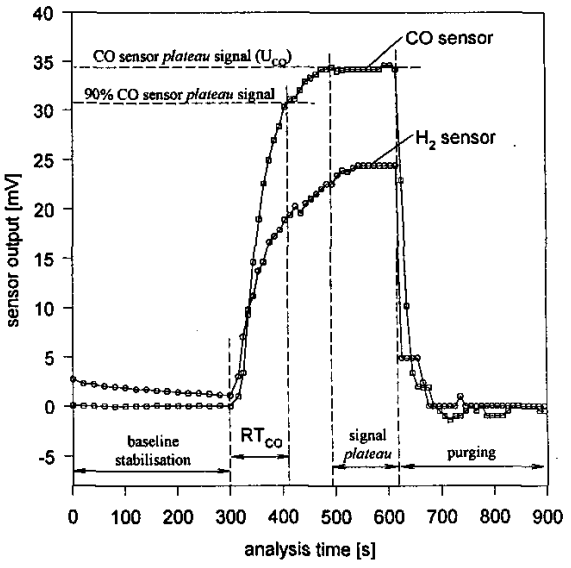

Figure 2. Gas sensor output waves recorded during analysis run.

RESULTS and DISCUSSION

The analyser was initially scaled using gas-in-oil standards. Test runs done for known standards allowed for calculation of the analyser sensitivities for most of the typical gases produced during insulation faults in a transformer. The gas sensors were meant by the manufacturer to be applicable only in H_2 and CO monitoring but they turned to have a few cross-sensitivities, advantageous particularly from DGA point of view. They turned to be increasingly sensitive to alkenes and alkynes with variable but very characteristic RT_r values. Any considerable overlapping of sensitivities between both sensors was not observed.

It is important to point out high sensitivity of the system, being able to recognise variations in concentration of acetylene, carbon monoxide and hydrogen at levels of 40, 10 and 30 ppm respectively and much lover of ethylene (2.5 ppm) as well as propylene and butylene (8 ppm).

To prove usefulness of the analyser in rapid diagnosing of transformer insulation conditions and to insure, that a correct identification of transformer faults is possible by a simplified DGA procedure based on use of electrochemical gas sensors, fitted in the *DGAnalyser*, typical faults, observed frequently in these devices, were simulated. The following processes, considered by many authors as typical [5] faults:

- partial discharges in oil,
- breakdown of oil,
- overheating of oil,

have been chosen and simulated in laboratory set-ups. PDs were generated in a plane-point electrode arrangement (electrode distance 20-50 mm) for several tens of hours. The same arrangement was adopted for breakdowns of constant energy. All those experiments were done for AC industrial voltage. Thermal decomposition of oil was stimulated by a metal (copper-platted Kanthal®) heater, immersed directly in the oil bath

and electrically heated to 150°C. Oil sampling and analyses were performed at constant time intervals (in case of PD and overheating) or every 5 or 10 breakdowns.

Figure 3 illustrates rate, at which signals of gas sensors (their *plateau* values) increased over the simulation period for all chosen fault processes.

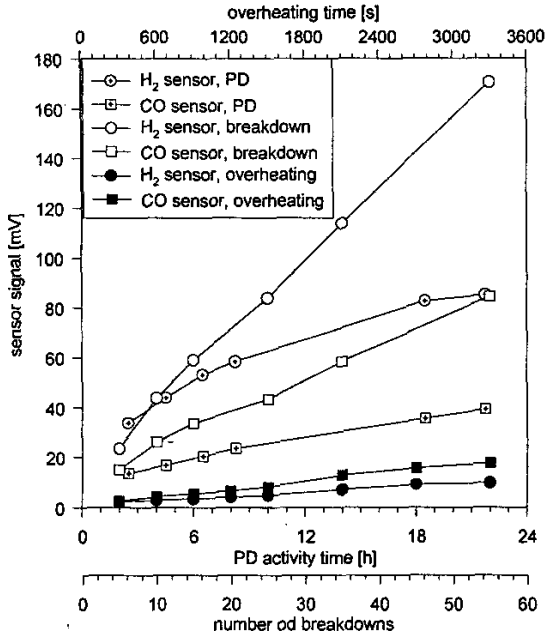

Figure 3. Rate of gas sensor output rise for simulated fault types.

Although number of breakdowns cannot be directly translated to time, the graph clearly shows the tendencies at which the gas content of oil, accompanying its electric and thermal breakdown, increases together with advancement of the simulated fault. It is also a prove that the system incorporating electrochemical gas sensor is capable of monitoring minute gas-in-oil changes therefore being applicable in monitoring of rate at which gases accumulate in transformer liquid insulation. Signals of both gas sensors, determined at their *plateau*, correspond to Total Gas Content (TGC) of oil.

Non-linearity of signal rise, observed in case of PD generation, should be rather attributed to physics of the simulated process and the dynamics of gas dissolution in the oil matrix and not to the sensors or the system operation. It is confirmed by linear responses obtained for breakdowns and thermal processes.

As it was mentioned before, values of gas sensor signals measured at the *plateau* of their output wave are not the only ratings available. A normalised rise time (response time) of each individual sensor to an oil sample as well as a ratio between sensor *plateau* responses also carry valuable information on gaseous constituents dissolved in the oil sample. Figure 4 clearly illustrates this statement. Points corresponding to pairs ($k_{CO/H2}$, RT_r) are arranged in separate regions characteristic for PDs, discharges in oil and its thermal decomposition. Therefore a clear and precise assessment of characteristic fault type is possible on the basis of a quick and not very labour-intensive test.

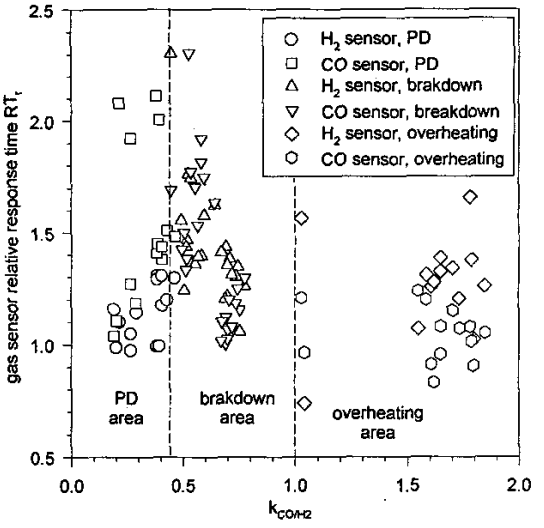

Figure 4. Identification of transformer fault type.

The electrochemical gas sensors are also suitable for monitoring faults of transformer insulation caused by thermal "hot spots". Figure 5 shows alternations of the parameters characterising signals of the gas sensors during simulated development of a "hot spot" in the oil. At the beginning of the test oil was heated in a previously described manner but 15 minutes from the test start the temperature of the heater was risen to over 300°C.

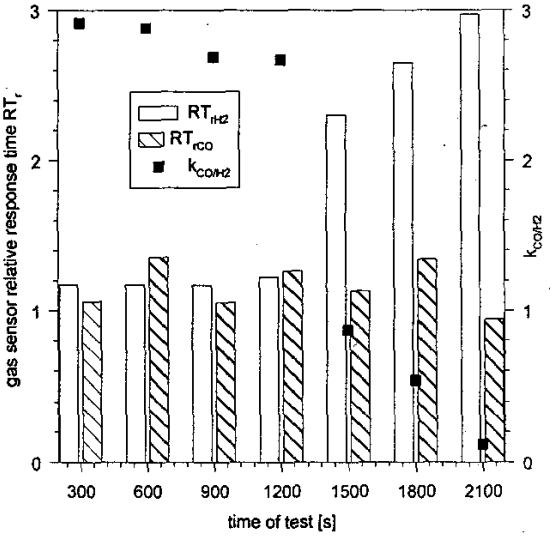

Figure 5. Variation of $k_{CO/H2}$ and RT_r for "hot spot" simulation.

A massive decrease of $k_{CO/H2}$ as well as almost step increase of RT_{rH2} was observed during the next sampling of oil and these tendencies continued along with elapsing time of "hot spot" activity. The volume of oil used for the test was somewhat

small (approx. 5 l) but the graph clearly illustrates the sensitivity of the analyser to minute changes of the gas-in-oil composition.

The developed system was also tested using oil samples taken from a real transformer (160 kVA, 10/0.4 kV, I_n=9.2 A) during its overload test. The transformer was overloaded by 110, 120, 130, 140 and 150 % of its I_n for every 3 days; oil sampling was performed everyday. Figure 6 shows variations of only $k_{CO/H2}$ value over the test period.

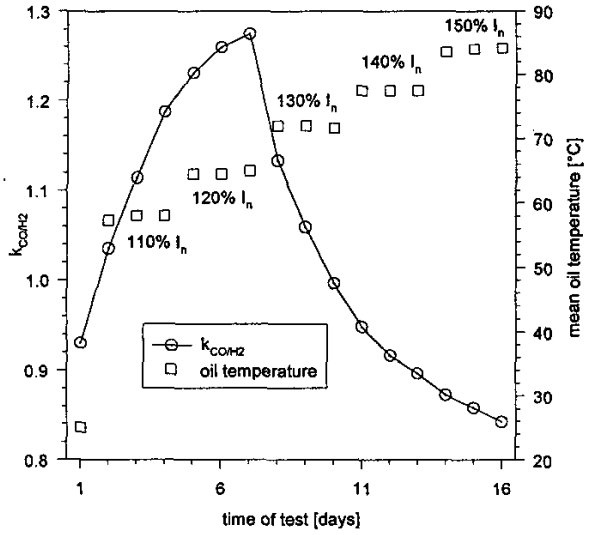

Figure 6. Rate of $k_{CO/H2}$ change during transformer overload test.

As one can see, the 8th day of the test brought a spectacular change of $k_{CO/H2}$ variation character. This change may be attributed to a new mechanism of thermal oil decomposition activated when the load reached 130% I_n and therefor temperature of some internal parts in the transformer started to be high enough for the new reaction. This statement is also evidently illustrated by Figure 7, containing an *Arhenius* plot, constructed for data gathered in this experiment.

Despite the mean temperature of oil in the transformer tub was used as characteristic for the plot, we observe two straight lines corresponding to both reactions taking place in the tested transformer. It is evident that the reaction having higher activation energy starts when the load exceeds 130% I_n. Therefore abrupt changes of $k_{CO/H2}$ values, so easily measured by means of the developed analyser, may be attributed to new mechanisms of the oil breakdown, having different activation energy.

It seems that a financial aspect of a simplified, introductory DGA analysis is also worth mentioning. The investment in *DGAnalyser* pays back already after approx. 100 analyses (taking into account costs published by IEC) or even 15, when common-practice prices for a single GC DGA analysis are used. Of course such a simplified analysis of oil samples cannot even contest with precision and sensitivity of a classical, chromatography-based DGA but it can supplement it saving much money invested in unnecessary analyses or replacement of faulty transformers, which were not diagnosed on-time.

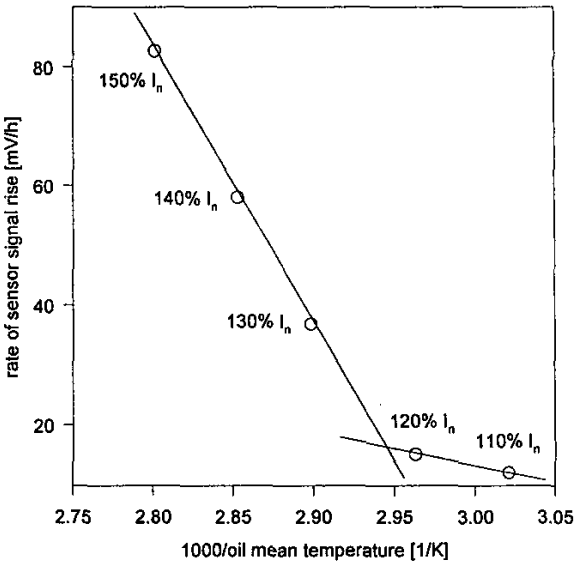

Figure 7. *Arhenius* plot for overload test data.

CONCLUSSIONS

As it was illustrated by the test results, a set of carefully selected parameters, calculated from measurement data collected from electrochemical gas sensors fitted in a described *DGA-nalyser* is sufficient for a correct identification of transformer fault type. Moreover, basing on those effortlessly calculated parameters, it is possible to monitor more advanced phenomena, like changes of the activation energy for thermally stimulated oil breakdown or development of "hot spots" in a transformer. Authors propose to include the discussed method of rapid, introductory analysis of gases dissolved in the insulating oil, performed by means of electrochemical gas sensor, to every-day transformer diagnostic practice. Almost instantaneous availability of a limited-in-scope diagnosis is an advantage of such an approach beyond any doubt.

ACKNOWLEDGMENT

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