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Electrochemical Gas Sensors Can Make DGA a Portable Screening Procedure

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ABSTRACT

Dissolved Gas Analysis (DGA) in its classical chromatography-based laboratory approach has become a routine procedure for testing and assessment of power transformer condition. New measurement practice employing novel gas sensing devices can yet help in making DGA simpler and migrating it into the field.

INTRODUCTION

As a word of introduction it seems valuable to make the Reader acquainted with the Author's home institution: *Wroclaw University of Technology* (WUT) and its organisational structure segment: *Institute of Electrical Engineering Fundamentals*, where he currently works as a junior scientist and academic teacher. WUT, named Politechnika Wroclawska in Polish, is one of the leading research and education centres in Poland. With an enrolment of over 32000, mainly full-time, students it is the second largest among eleven higher education institutions in Wroclaw.

The University's nearly 2000 academic teachers and researchers work at 27 Institutes making 12 faculties. Because a good teaching at the university level requires a strong research, WUT is thus very research-oriented: an extensive research in various fields of engineering and fundamental sciences is carried out here in development, application and implementation areas. As examples of multidisciplinary activities one can mention:

- *Centre of Advanced Materials and Nanotechnology* – a body within WUT structure that is a self-organised network of research groups distributed throughout the university departments aiming at integration and support of research activities on complex systems with controlled structures and functions at nanometre scale.
- *Wroclaw Centre of Technology Transfer* with the mission of improving industrial effectiveness and competitiveness through enterprise staff training, consulting, implementation of quality and production management, support in innovations and technology transfer.

Much more detailed and comprehensive information can be found at WUT's website *http://www.pwr.wroc.pl.*

Institute of Electrical Engineering Fundamentals is located within WUT's *Faculty of Electrical Engineering*. The Institute is composed of three Sections: *Theoretical Electrotechnics*, *High Voltage Engineering* and *Electrotechnology*. Students keen on studying here can specialise in the following key-areas: Measurement and Instrumentation Systems, Technology and Diagnostics in Electrical Engineering, and Theoretical Electrotechnics. The Author's workplace - Section of Electrotechnology – is a multidisciplinary formation, which scope of scientific activities covers in general:

- investigation of various types of electrical properties: polarisation, conductivity, transient phenomena, space charge distribution, electrostatic and piezoelectric properties of solid/liquid dielectrics;
- magnetic properties of solid materials;
- superconducting ceramics and its acoustic emission phenomena;
- electron/ion beam treatment of polymeric and inorganic materials;
- plasma deposition of polymers and sol-gel techniques for inorganic layers;
- solid state sensors and actuators;
- metrology and instrumentation aspects related to the mentioned science sectors.

A close co-operation with two other Institute's Sections and other scientific institutions (e.g. Electrotechnical Institute Division of Technology and Materials Science in Wroclaw) makes it possible to support our scientific activities with expertise in theoretical and high voltage problems. Moreover, problems, which are dealt with by our associates, also provoke us to carry on research and to develop and introduce new measuring equipment and procedures. An approach to apply gas sensors in classical Dissolved Gas Analysis (DGA) procedure and to unconventionally exploit benefits offered by those devices is a good example of that mutual stimulation process.

DISSOLVED GAS ANALYSIS

DGA procedure has become a world-wide-accepted standard test for assessing power transformer insulation condition. The method relies on proven dependence between electrical and thermal processes deteriorating transformer insulation and kind of gaseous products generated during those fault events[1]. A classical DGA test consists of four main stages: oil sampling from a transformer, gas-from-oil extraction, laboratory identification of key gases dissolved in the oil by gas chromatography (GC) and a final interpretation of qualitative and quantitative gas data, performed by a highly qualified and experienced personnel.

However, attention should be paid to the fact that a classical DGA, as an indirect method, is not a universal remedy for all types of ailments suffered by power transformers. It is only applicable in case of slowly, comparing to the frequency of periodical tests, developing faults. And therefore, from the point of its effectiveness view, it is worthy to increase the frequency of oil testing. This approach is yet impractical in laboratory, chromatography-based DGA form, when economic and logistic criteria are taken into account. Thus cheaper and more mobile DGA systems and methods are still necessary - it stimulates research aiming at making classical DGA procedure simpler and automated as well as lowering its total costs. New, non-standard ways of oil sampling and degassing (e.g. *ShakeTest* syringes by *Morgan Schaffer Systems Inc.*) and automated *headspace sampling* chromatographic units are being introduced.

True minute field tests are yet possible only when portable or on-line automated gas analysis systems are introduced. These have usually embedded miniaturised gas chromatographs (e.g. *TFGA-P200* by *Morgan Schaffer Systems Inc.* or *TrueGas* system by *Micromonitors Inc.*) or, less commonly, various designs of gas sensors (e.g. system *Hydran* by *Syprotec Inc.*). It is yet important to observe that in all classical or new DGA method variation designs a "decoding-encoding" scheme is used. A primary goal is first to obtain precise qualitative and quantitative information regarding key gases present in the sampled transformer oil. Then, in the last stage of DGA procedure, those values are once more subjected to more or less complicated mathematical processing in order to produce some kind of "generalised" codes (e.g. IEC, Rogers, Schliesing, Duval triangle). The codes are particularly useful for human interpretation, since pure concentration values are strongly dependent on various factors like kind, history and operational parameters of transformers. Such advanced methods as artificial neural networks, genetic algorithms and fuzzy sets are employed to process classical chromatographic and novel gas sensor data.

Yet it seems that in case of introductory screening DGA tests to be done rapidly in the field by means of portable gas analysers, fitted with non-selective gas sensors, much simpler solutions may be applicable in order to recognise basic transformer faults. Desirable gas sensor cross-sensitivities, being usually a drawback, may be in this case almost directly employed to "generalise" measurement results to give final evaluation of the transformer state not in gas content but fault sense. But when we decide to use such approach we must accept, that result of "sensor" and classical GC-DGA measurement is incomparable. In such approach using non-selective gas sensors we do not measure a particular gas content. Instead, we register complicated time-domain sensor signals, which accommodate generalised (encoded) information on more than one gas. When we have e.g. 2 different sensors, the amount of information is doubled and, as it will be shown, it is already sufficient for a correct interpretation of very basic transformer faults.

A practical observation shows that a complete, GC-like, analysis of gaseous constituents present in the oil sampled from a transformer is not always indispensable. A more functional and demanded by power transformer end-users is a clear statement on its state given directly in the field. It lets to consider as true that mobile DGA systems do not have to provide the same set of determinants as classical chromatographic analysis, providing that diagnosis based on those novel methods is correct in terms of transformer fault identification.

Application of various gas sensors in DGA is not a novel idea[2] – certain market products are already available which exploit this concept. But they all aim at maximal selectivity of gas sensors and thus mimic classical GC-DGA method, which is not an easy task, since GC is one of the most selective gas sensing techniques.

The research undertaken by the author led to the development of 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 – already mentioned lack of their selectivity – was taken as the advantage to expand the spectrum of gases being recognised and analysed. Further enhancement of the measurement accuracy (and therefore recognition of transformer insulation faults) was achieved by adopting additional descriptors of time-domain sensor signals. Such unconventional data processing of the gas sensor measurement results allows for a correct correlation with typical faults observed for transformers in-service.

The main goal was to design the prototype gas-in-oil analysis device as portable and autonomous, easy to operate by unqualified operator. Two electrochemical gas sensors compose the system's heart. The sensors are highly sensitive towards hydrogen and carbon monoxide respectively but they also demonstrate several more or less significant cross-sensitivities. The analyser operates on filtered atmospheric air as a carrier gas to provide closed-loop degassing of oil sample. For a more detailed description of the analyser and its performance the reader should consult[3,4].

The analyser response was successfully verified against a laboratory GC unit using gas-in-oil standards. Over 200 tests were also done with laboratory-aged oil samples with gas content representative for common faults observed in in-service transformers. These simulated insulation defects included: partial discharges (PD) in oil, breakdown in oil and its thermal decomposition. Oils with various water contents were used in every type of simulation also in order to assess correlation between amount of gas and water dissolved in oil.

The novelty of the discussed approach lies in a fact that each analysed oil sample is characterised not directly by gas contents but by a set of three parameters, relative to gases present in oil. The first one is a quota k_1 of two values calculated when the gas sensor responses arrive at their plateau, corresponding to the generalised concentration of gases in the oil. The following measures are two response time parameters k_2 and k_3. All those three values are easily calculated from gas sensor response curves recorded during oil analysis run.

The next step in the approach to perform a rapid DGA test is to locate the point, corresponding to the determined k_1, k_2 and k_3 values, on a 3D fault map. The map, which is shown in Fig. 1, was constructed on the basis of statistical analysis of results obtained for tests done on laboratory aged oil samples. When projection of the (k_1, k_2, k_3) point onto walls of the plot locates itself in areas characteristic for any of the basic faults it should be treated as an alerting signal. Interpretation of a real measurement (illustrated in Fig. 1), performed for oil sampled from an in-service transformer, suggests that it may suffered from thermal oil decomposition of moderate characteristic temperature (region A on the 3D map).

When more advanced data mining is accomplished it is possible to differentiate between faults in which higher water-in-oil concentration is also observed[5]. Such peculiarities as hydrogen appearing in the transformer oil insulation due to electrochemical reactions (e.g. corrosion) is another example of effects detectable by the discussed method.

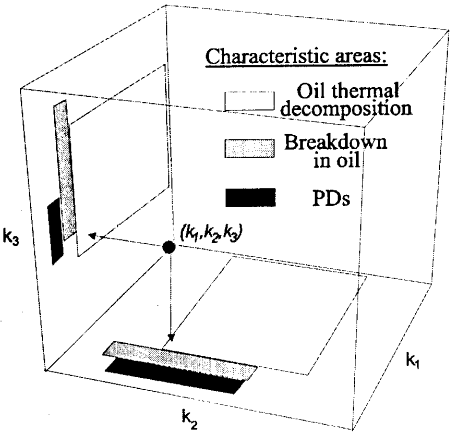

Figure 1. 3D map for fault interpretation. Characteristic areas are given in approximated form

The analyser may be also used directly in monitoring of heavily loaded transformer performance as well as in indirect monitoring of chemical nature of processes progressing in its insulation. In order to prove its usefulness in such situation, the tester was thus examined 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 unit was overloaded by 110, 120, 130, 140 and 150 % of its I_n for every 3 days whereas oil sampling was performed everyday. Fig. 2 shows the variation of k_1 over the test period. As it can be seen, on the 8th day of the test a dramatic change in k_1 occurred. This change may be attributed to a new insulation decay chemical reaction, activated when the temperature of some internal transformer parts started to be high enough.

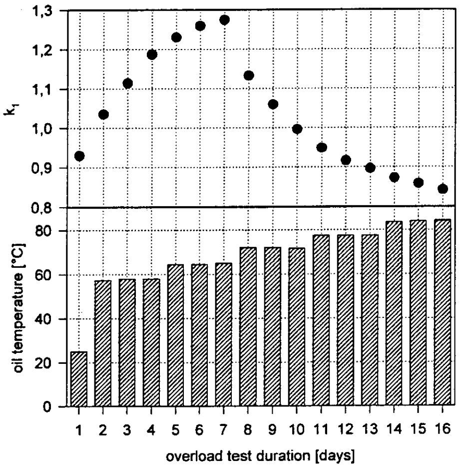

Figure 2. Variations of k_1 parameter and oil mean temperature over transformer overload test period

The above statement is supported by an *Arrhenius* plot (i.e. rate of gaseous products generation versus 1000/T, where T is the temperature in K) when constructed for data gathered in this experiment. Despite that the mean temperature (which cannot be treated as characteristic for the reaction) of oil in the transformer tub is used as characteristic for the plot, one obtains two straight lines with different slopes. The lines correspond to a pair of chemical decomposition reactions. They intersect at the point matching with transformer load reaching 130% of I_n. It is thus evident that the reaction having an higher activation energy starts when the load exceeds 120%, exactly where k_1 starts to fall. Therefore, we may state that abrupt changes of k_1 values, so easily detected by means of the analyser, may be attributed to inception of new mechanisms of the oil breakdown, having different activation energy.

CONCLUSION

A simplified analysis of oil samples cannot contest with precision and sensitivity of a classical GC DGA but it can supplement it. As it was illustrated, unconventional tional treatment of measurement data, collected from electrochemical gas sensors, is adequate for a correct identification of basic transformer fault types. Almost instantaneous availability of, although very limited-in-scope, predictions is an advantage of such an approach.

The use of electrochemical gas sensors in transformer monitoring may not be only limited to every-day practice. They may have also more advanced research applications like identification of thermally stimulated oil cracking paths or phenomena related to a role played by water in transformer oil decomposition with gaseous products.

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