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A Review of Dissolved Gas Analysis in Power Transformers

Huo-Ching Sun[a*], Yann-Chang Huang[a], Chao-Ming Huang[b]

[a]Department of Electrical Engineering, Cheng Shiu University, Kaohsiung, TAIWAN
[b]Department of Electrical Engineering, Kun San University, Tainan, TAIWAN

Abstract

Dissolved gas analysis (DGA) of transformers can provide insights into thermal and electrical stresses sustained by oil-immersed power transformers. Because it detects incipient transformer faults, DGA can help prevent further damage. Moreover, DGA is a sensitive and reliable technique for detecting incipient fault conditions in oil-immersed transformers. The many approaches developed for analyzing these gases and interpreting their significance include Key Gas, Dornenburg Ratio, Rogers Ratio, Nomograph, IEC Ratio, Duval Triangle, and CIGRE. This study compares the effectiveness of these methods for interpreting transformer conditions.

Keywords: Dissolved Gas Analysis; Power Transformers; Fault Diagnosis

1. Introduction

Large Power transformers are major power system equipment. Their reliability not only affects the electric energy availability of the supplied area, but also affects the economical operation of a utility. Failures of power transformers are problematic for four reasons, namely failure of a transformer can cause operational problems to the system, generally large power transformers are placed in large tanks containing flammable oil and are environmentally hazardous, the utilities do not have a spare one in case of maintenance or breakdown, and finally the various types of thermal and electric stresses often age the transformer and subject them to incipient faults. Thus the utilities need to keep a track of the health of the transformer and also develop a diagnosis system.

The insulation oil used in power transformers is a combination of liquid transformer oil and solid impregnated cellulose. Deteriorated insulation and ageing are the two major causes of incipient faults. The major causes of ageing and deterioration of insulation are thermal stresses, electrical stresses, mechanical stresses, and moisture. DGA approaches can evaluate the ageing process and the deteriorating cellulose material of the transformer oil, the degree of polymerization measurements, and Furan analysis.

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* Corresponding author. Tel.: +886-7-731-0606 ext. 3436; fax: +886-7-733-7390.
E-mail address: sunny@csu.edu.tw.

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Determining the degree of polymerization (DP) value of cellulose is a standard method of quantifying cellulose degradation. The DP value indicates the average polymer length of the cellulose molecules. When cellulose is aged by thermal stress, the molecular chains are broken. Advanced aging causes the paper to become brittle and to lose its mechanical stability. The method is effective for quantitatively measuring thermal aging. The main drawback is the need to take a paper sample from the transformer. This action is intrusive because it can only be performed by qualified service personnel, and the transformer must be removed from service. The sample cannot be taken from inside the winding and is normally taken from one of the high current leads in the upper part of the transformer.

In cellulose materials, aging caused by thermal stress generates furanic compounds as a degradation product. These compounds are a family of chemical substances that differ in stability and production rates. Because these compounds dissolve in oil, they can be detected and studied by standard analytical methods. The observed relationships between DP and various concentrations of furanic compounds enable indirect measurement of aging of the cellulose. However, measurements are complicated by the different furans produced by different papers, and the concentration depends on the mass ratio between oil and cellulose. Furthermore, the stability of the compounds is unclear at typical transformer temperatures and concentrations of dissolved oxygen. Therefore, further studies are needed to determine the full potential of furanic compound analysis. However, furanic compound analysis has already proven effective for predicting the lifetime of insulation material.

Of the existing methods of diagnosing incipient faults, DGA is the most widely used for transformer maintenance by utilities and for fault diagnosis by researchers. By sampling and examining the insulating oil of transformers, ratios of specific gas concentrations, their generation rates, and total combustible gases are often used as the attributes for classification by diverse DGA approaches. Temperature measurements are used and can even be incorporated into certain key gases.

The detection of certain gases generated and dissolved in power transformers in service is often the first available indication of a malfunction that, if uncorrected, can eventually cause a transformer failure. The gases generated in oil-filled transformers can be used for qualitatively determining fault types since the gases are typical or predominant at various temperatures. After incipient faults are detected, preventive maintenance can be performed, and conditions can be assessed by DGA. This study reviewed the various conventional and non-conventional DGA methods used by various agencies and utilities to monitor the condition of the cellulose contained in in-service transformers.

2. DGA Approaches

The DGA [1-8] is among the most common techniques used for on-line incipient fault diagnosis because the transformer need not be de-energized. The DGA requires routine oil sampling and modern technologies for on-line gas monitoring. The key step in using gas analysis for fault detecting is correctly diagnosing the fault that generated the gases. Abnormal electrical or thermal stresses cause insulation oil to break down and to release small quantities of gases. The composition of these gases depends on the fault type. The detection of certain level of gases generated in oil-filled transformer in service is often the first available indication of a malfunction that can cause a transformer failure if not corrected. Possible mechanisms of gas generation include arcing, corona discharge, low energy sparking, overheating of insulation due to severe overloading, and failure of forced cooling systems. Faults in oil-filled transformers can be identified according to the gases generated and the gases that are typical or predominant at various temperatures. These gases are hydrogen (H_2), methane (CH_4), ethylene (C_2H_4), ethane (C_2H_6), acetylene (C_2H_2), carbon monoxide (CO), and carbon dioxide (CO_2). Each fault type produces gases that are generally combustible. An increase in total combustible gases (TCG) that correlates with an increase in gas generating rates may indicate the existence of any one or a combination of thermal, electrical or corona faults.

Various DGA methods have been used by organizations and utilities to assess transformer conditions.

These DGA interpretation schemes are based on empirical assumptions and practical knowledge gathered by experts worldwide. Nevertheless, if these interpretation schemes are not applied cautiously, they may incorrectly identify faults because they only indicate possible faults. In some cases, DGA interpretation schemes may differ in terms of identified faults, which is clearly unacceptable for a reliable fault diagnosis system.

Interpretation schemes are generally based on defined principles such as gas concentrations, key gases, key gas ratios, and graphical representations. Common schemes mentioned in IEEE Standard C57.104-2008 include Key Gas Analysis, Dornenberg and Rogers Ratio Methods, Nomograph, IEC Ratio, Duval Triangle, and CIGRE Method. The DGA can distinguish faults such as partial discharge (corona), overheating, and arcing in many different power transformers. Like a blood test or scanner examination of the human body, DGA can provide the early diagnosis needed to increase the chance of finding an appropriate cure. This study investigated and compared seven current methods of using dissolved gas data to diagnosis fault type:

- Key Gas Method,
- Dornenburg Ratio Method,
- Rogers Ratio Method,
- Nomograph Method,
- IEC Ratio Method,
- Duval Triangle Method, and
- CIGRE Method.

2.1. Key Gas Method

The Key Gas method [1-2] measures the gases released from insulating oil after a fault, which then increases the temperature in the power transformer. The presence of the fault gases depends on the temperature or energy that disrupts the chemical structure of the insulating oil. This method detects faults by measuring individual gases rather than by calculating gas ratios. The significant and proportion of the gases are called “key gases”.

Because it provides the first indication of a problem, this test is the most important and the most frequently performed. Whatever the cause, the stresses cause chemical breakdowns in some of the oil or cellulose molecules. The main degradation products are gases, which entirely or partially dissolve in the oil under thermal and electrical stress conditions caused by faulty currents in the transformers. The hydrocarbon molecules of mineral oil decompose and form active hydrogen and hydrocarbon fragments, which then combine into gases such as H_2, CH_4, C_2H_2, C_2H_4, C_2H_6 etc. Gases that are produced in transformer oil can be grouped as (1) Hydrocarbon and hydrogen (CH_4, C_2H_2, C_2H_4, C_2H_6, H_2); (2) Carbon oxides (CO, CO_2); and (3) Non-fault gases (N_2, O_2).

This method identifies faults according to the presence and percentage of each key gas. It interprets DGA results based on a simple set of facts. For example, low intensity partial discharge (PD) or corona mainly produces H_2 with trace amounts of some hydrocarbon gases, so the key gas for PD or corona is H_2, and PD or corona is detectable in an oil sample that contains a high percentage of H_2.

The key gas method relates key gases to fault types and attempts to detect four fault types, including overheating of oil, overheating of cellulose, corona (partial discharge) and arcing. The fault types are identified by the concentrations of key gases (C_2H_4, CO, H_2, C_2H_2) expressed in ppm (part per million). The suggested relationships between key gases and fault types are summarized as follows: (1) O_2 and N_2: non-fault condition, (2) CH_4 and C_2H_6: low temperature overheating of oil, (3) C_2H_4: high temperature overheating of oil, (4) CO and CO_2: overheating of cellulose insulation, (5) H_2: corona, and (6) C_2H_2: arcing. Since the key gas method does not give numerical correlations between fault types and gas types extensive experience is required for accurate diagnosis.

2.2. Dornenburg Ratio Method

For convenient fault diagnosis, gas ratio methods use coding schemes that assign certain combinations of codes to specific fault types. The codes are generated by calculating ratios of gas concentrations and comparing the ratios with predefined values derived by experience and continually modified. A fault condition is detected when a gas combination fits the code for a particular fault.

The Dornenburg Ratio method [3] identifies faults by analyzing gas concentration ratios such as CH_4/H_2, C_2H_2/CH_4, C_2H_4/C_2H_6 and C_2H_2/C_2H_4, which can be used to identify thermal faults, corona discharge and arcing. This method is based on thermal degradation principles. In this method, the ratio procedure is considered valid if the gas concentrations (in ppm) for H_2, CH_4, C_2H_2, and C_2H_4 exceed twice the value of the fixed limit for each gas and if that for CO and C_2H_6 exceeds thrice the value of the fixed limit. To determine the validity of the four ratios, each successive ratio is then compared with certain values. Finally, if all four succeeding ratios for a specific fault type fall within the predetermined values, the diagnosis is confirmed. This method, which is specified in IEEE Standard C57.104-2008 [1], characterizes dissolved gases of transformer oil. However, the method may obtain numerous “no interpretation,” results due to incomplete ratio ranges.

2.3. Rogers Ratio Method

The most common gas ratio method is the Rogers ratio method [4], which distinguishes more thermal fault types compared to the Dornenberg ratio method [3]. The Rogers method analyzes four gas ratios: CH_4/H_2, C_2H_6/CH_4, C_2H_4/C_2H_6 and C_2H_2/C_2H_4. Faults are diagnosed *via* a simple coding scheme based on ranges of the ratios. The Rogers ratio is a simple scheme based on ranges of ratios used for diagnosing faults. The four detectable conditions of an oil-insulated transformer are normal ageing, partial discharge with or without tracking, and electrical and thermal faults of varying severity. This method, which is based on thermal degradation principles, is also included in IEEE Standard C57.104-2008 [1]. This method is effective because it correlates the results of numerous failure investigations with the gas analysis of each case. However, some ratio values are inconsistent with the diagnostic codes assigned to various faults in this method. Also, since the method does not consider dissolved gases below normal concentration values, a precise implementation of the method may still misinterpret data.

2.4. Nomograph Method

The Nomograph Method [5] improves the accuracy of fault diagnosis by combining fault gas ratios and the concept of Key Gas threshold. By graphically presenting fault gas data, it simplifies interpretation of fault gas data. A nomograph is a series of vertical logarithmic scales for representing the concentration of individual gases as straight lines drawn between adjacent scales. The lines connect points representing the values of individual gas concentrations. Straight lines are diagnostic criteria for determining fault type. Fault types are identified by visually comparing the slopes of line segments with the keys at the bottom of the nomograph. Fault severity is indicated by the position of lines related to the concentration scales. The threshold value of each vertical scale is indicated by an arrow. For the slope of a line to be considered significant, at least one of the two tie points should exceed the threshold value. The fault is not considered significant if the tie point lies above a threshold value.

2.5. IEC Ratio Method

The IEC Ratio Method [5] resembles the Rogers Ratio method but excludes the C_2H_6/CH_4 ratio, which only indicates a limited temperature range of decomposition. Here, the remaining three gas ratios have different ranges of code in comparison with the Rogers ratio method. The fault diagnosis scheme recommended by the International Electrotechnical Commission (IEC) originated from the Rogers method except that the C_2H_6/CH_4 ratio was dropped since it only indicated a limited temperature range of decomposition. The four detected conditions are normal ageing, partial discharge of low and high energy density, thermal faults and electrical faults of varying severity. However, it does not classify thermal and electrical faults into precise subtypes. The first version of the IEC method (IEC 60599-1978) is based on a simple coding scheme while the second version (IEC 60599-1999) uses revised ratio ranges directly. Dissolved gases must be assessed for 'normality' limits before interpretation by ratios. Another improvement in the second version of IEC method is the 3D graphical representation of ratio ranges. Faults that cannot be diagnosed are plotted onto the graph so that its nearest distance to a certain fault region can then be observed. Power transformer faults are typically classified as partial discharges, discharges of low and high energy, and thermal faults in which severity depends on fault temperature.

2.6. Duval Triangle Method

The Duval Triangle Method [6-7] uses values of only three gases CH_4, C_2H_4 and C_2H_2 and their location in a triangular map. To plot the triangle, gases are transformed into triangular co-ordinates. The three detectable fault types are partial discharges, electrical faults (high and low energy arcing), and thermal faults (hot spots of various temperature ranges). Although this method is easily performed, careless implementation can obtain false diagnoses since no region of the triangle is designated as an example of normal ageing. Hence, before using this method to analyze transformers that have been in service for the many years, the permissible amount of dissolved gases should be determined. An identified problem is diagnosed by calculating the total quantities of the three Duval Triangle gases (CH_4, C_2H_2, and C_2H_4) and dividing the quantity of each gas by the total to find the percentage of each gas of the total. The percentages of the total are then plotted on the triangle to obtain the diagnosis.

2.7. CIGRE Method

The CIGRE Method [8] of fault diagnosis analyzes key gas ratios and gas concentrations. The five key gas ratios considered in this method are C_2H_2/C_2H_6, H_2/CH_4, C_2H_4/C_2H_6, C_2H_2/H_2 and CO/CO_2. The key gas concentrations are C_2H_2, H_2, the sum of carbon hydrides, CO and CO_2. Suggested ratio ranges and concentration limits were published earlier in [8]. A transformer is considered healthy if separate applications of these methods obtain ratios and concentrations that are below limits. The advantage of this method is that two or more faults can be detected simultaneously.

Since 1999, CIGRE Task Force 15.01.01 has reconciled deviations and discrepancies among the different interpretation schemes. Hence, by gathering expert knowledge and incorporating some adjustments, the DGA interpretation method proposed by CIGRE modifies previous interpretation schemes to enhance the reliability of fault diagnostics. The two-step CIGRE interpretation scheme analyzes key ratios of gas concentrations and key gas concentrations and compares them to thresholds. These results are then combined to diagnose faults and to identify corrective actions.

Since most faults develop slowly, most are detectable by DGA monitoring. According to CIGRE [8], DGA identifies the fault location as the winding, cleats and leads, the tank, the selector switch, or the core. However, DGA may not reliably predict rapidly occurring instantaneous faults. Instantaneous failures that cannot be prevented by DGA are [8]: (1) flashover with power follow-through, and (2) serious failures that develop too rapidly for detection by DGA.

3. Conclusions

The key objective in fault gases analysis is correctly diagnosing the fault that generated the detected gases. This study analyzed and compared the seven most common methods of analyzing dissolved gas data to interpret fault type: Key Gas, Dornenburg Ratio, Rogers Ratio, Nomograph, IEC Ratio, Duval Triangle, and CIGRE. By comparing the consistency and accuracy of each method in predicting faults, this study gives a useful overview of DGA applications in power transformer fault diagnosis. The conclusions obtained in this study can be used for transformer fault diagnosis by researchers and field engineers.

Notably, using multiple DGA techniques, *e.g.,* the key gas method, the Rogers ratio method, the gas generating rate method and other industry standards, to analyze transformer faults may obtain different or conflicting fault interpretations. Therefore, optimizing the combination of various diagnostic techniques is an important issue. Moreover, the aforementioned DGA diagnosis techniques are computationally simple and effective for diagnosing severe faults and are commonly used as a general guideline by experts. However, much uncertainty exists in gas data due to the complexity of gas generating processes in oil, gas sampling processes and in chromatographic analysis in a laboratory. Therefore, varied patterns and amounts of gases are generated due to different intensities of energy dissipated by different faults, which are affected by many factors, including oil type, oil temperature, sampling method, insulation characteristics and environmental effects.

Moreover, most DGA diagnosis techniques rely on expert analyses, which could be insensitive to slowly developing and insignificant faults. Even under normal conditions, misjudgement may result from unscheduled operations such as oil-tank welding and the electric charge carried by the oil-flow. To handle the uncertainties in fault diagnosis, based on gas contents extracted from transformer oil samples, various techniques have been attempted by many researchers, including expert systems, fuzzy logic inference, and artificial neural networks. Firstly, fault types are classified based on on-site experience according to the combined criteria of total combustible gases, gas generation rates, the key gas method and on-site inspections. Various artificial intelligence methods are then used to reveal the relationships between fault symptoms and malfunction types founded on gas-fault mapping schemes.

Different transformer test approaches, *e.g.,* DGA, thermal analysis, frequency response analysis, and partial discharge analysis, also have different advantages and limitations, which complicates the selection of diagnosis methods. Thus, a more intuitive approach is combining the results derived from all major test approaches and integrating their data in an overall evaluation. As test results are may be imprecise and even incomplete, a suitable information integration method is needed to process DGA data to account for such uncertainties.

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