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# Power Transformer Incipient Faults Diagnosis Based on Dissolved Gas Analysis

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***Abstract***

*Incipient fault diagnosis of a power transformer is greatly influenced by the condition assessment of its insulation system oil and/or paper insulation. Dissolved gas-in-oil analysis (DGA) is one of the most powerfull techniques for the detection of incipient fault condition within oil-immersed transformers. The transformer data has been analyzed using key gases, Doernenburg, Roger, IEC and Duval triangle techniques. This paper introduce a MATLAB program to help in unification DGA interpretation techniques to investigate the accuracy of these techniques in interpreting the transformer condition and to provide the best suggestion for the type of the fault within the transformer based on fault percentage. It proposes a proper maintenance action based on DGA results which is useful for planning an appropriate maintenance strategy to keep the power transformer in acceptable condition. The evaluation is carried out on DGA data obtained from 352 oil samples has been summarized into 46 samples that have been collected from a 38 different transformers of different rating and different life span.*

***Keywords:*** *dissolved gas analysis (DGA), fault diagnosis, power transformer, insulating oil, condition assessment*



## 1. Introduction

Power transformers are the most expensive and important equipment in electric power systems that serves to convert the power with different level of voltage. During its lifetime, transformer insulation is exposed to mainly electrical, mechanical and thermal stresses. Therefore, the life of a transformer depends mainly on the condition of the insulation and its ability to withstand the above stresses, during its normal operation. The main reason behind the stresses can be due to aging of insulation and the most critical reason is a short circuit event. As the health of the oil implies the health of the transformer, the oil should be sampled and tested regularly to evaluate the oil condition and to determine the possible fault problems [1, 2]. Therefore, incipient fault detection of transformers is necessary in order to avoid electrical power system fault as quickly as possible.

The transformer insulation can be classified into mineral oil and solid insulation [3, 4]. Any weakness of insulation may result in failure of the transformer [5]. Insulating oil in a transformer during operation is exposed to a combination of heat, oxygen and electrical discharge, which may lead to its degradation especially through the process of oxidation [6-8]. When an incipient fault occurs in power transformer, either electrical or thermal, causing decomposition of the transformer oil and a number of gases are generated and dissolved into the oil. Such these gases are mainly include Hydrogen (H2), methane (CH4), Ethane (C2H4), Ethylene (CH6), acetylene (C2H2), carbon monoxide (CO) and carbon dioxide (CO2) and the non-fault gases are nitrogen (N2), oxygen (O2). Transformer oil can decompose CO and CO2 as a result of its oxidation [8].

Dissolved gas analysis (DGA) is one of the most acceptable techniques used for detecting and evaluating gasses dissolved from mineral oil and also from solid insulation of internal incipient faults in the power transformer based on the oil samples [9, 10]. It is critically important to monitor the incipient of transformer fault depending on the type and the concentrations of these gases formation. DGA interpretation techniques such as Key gas technique, Doernenbug technique, Roger ratio technique, IEC ratios technique, and Duval

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triangle technique [8], [11-14] are different techniques for the detection of incipient transformer fault conditions.

In this paper, the dissolved gasses were interpreted using several techniques. Different techniques give different analysis result, and it is faced with so much diverse information. These techniques of interpretation of the fault gases are investigated. The study was done to evaluate the accuracy of each technique in predicting the fault based on a fault percentage using MATLAB program.

## 2. Samples of Evaluated Transformers

The evaluation is carried out on DGA data obtained from 352 oil samples has been summarized into 46 samples that have been collected from a 38 different transformers of different rating and different life spans as given in Table 1. It is difficult to determine whether a transformer is behaving normally if it has no previous dissolved gas history. For analyzing the aging degree of the transformer for normal state, we can classify the normal condition as a four status conditions such as: Normal Operation, Caution (investigate), Abnormal (more investigation), and Danger (nearing failure). The DGA guide to classify risks to transformers with no previous problems has been developed by the IEEE [5, 13]. It uses combinations of individual gases and total combustible gas concentration. This guide is not universally accepted and only one of the tools is used to evaluate transformers.

Table 1. Transformer details

| Transf. | No. of transformer | Year of Manufacture | Rating MVA | Voltages KV |
|---|---|---|---|---|
| A | 7 – transformer | 3- transformer (1981) | 75 | 220/66/11 |
| | | 3- transformer (2005) | 125 | |
| | | 1- transformer (2005) | 75 | |
| B | 2 – transformer | 2- transformer (1982) | 75 | 220/132 |
| C | 23 – transformer | 6- transformer (1990) | 25 | 66/11 |
| | | 2- transformer (1997) | | |
| | | 2- transformer (2000) | | |
| | | 4- transformer (2004) | | |
| | | 5- transformer (2005) | | |
| | | 2- transformer (2008) | | |
| | | 2- transformer (2011) | | |
| D | 3 – transformer | 1- transformer (1978) | 20 | 66/11 |
| | | 2- transformer (1980) | | |
| E | 3 – transformer | 1- transformer (1978) | 12.5 | 66/11 |
| | | 2- transformer (1983) | | |

Table 2 [5], [13] gives one set of guidelines based on good utility practice that is useful for determining the overall health of a power transformer based on the total concentration of combustible gases. The four conditions are defined below:

Table 2. Dissolved key concentration limits in (ppm )

| Gases in (PPM) | Gases Status | | | |
|---|---|---|---|---|
| | Normal | Caution | Abnormal | Danger |
| Hydrogen (PPM) | 100 | 101-700 | 701-1800 | > 1800 |
| Methane (PPM) | 120 | 121-400 | 401- 1000 | > 1000 |
| Acetylene (PPM) | 35 | 36-50 | 51-80 | > 80 |
| Ethylene (PPM) | 50 | 51-100 | 101-200 | > 200 |
| Ethane (PPM) | 65 | 66-100 | 101-150 | > 150 |
| Carbon Monoxide PPM) | 350 | 351-570 | 571-1400 | > 1400 |
| Carbon Dioxide (PPM)[a] | 2500 | 2501-4000 | 4001-0000 | >10000 |
| TDCG (PPM) | 720 | 721-1920 | 1921-4630 | >4630 |

[a]it is not a combustible gas

## 3. Proposed Accurate DGA Technique

It is worth to mention that in some cases, for each individual traditional interpretation techniques approach such as "key gas, roger's ratio, Doernenburg ratio, IEC ratio and Duval triangle" have been given different fault conditions for the same sample unit. To avoid this, the suggested technique gives the appropriate fault based on fault percentage which is given by all the above existing DGA interpretation techniques without any overlapping.

Firstly, check the limit value of the combustible and non combustible gases are applicable or not based on the quantity of each gas concentrations in ppm (parts per million) as an input data for each diagnostic technique as given in table 3quoted from [5, 13].

Table 3. Limit concentrations of dissolved gas

| Key gas | Concentrations L1 "ppm" |
|---|---|
| Hydrogen ($H_2$) | 100 |
| Methane ($CH_4$) | 120 |
| Carbon monoxide (CO) | 350 |
| Acetylene ($C_2H_2$) | 1 |
| Ethylene ($C_2H_4$) | 50 |
| Ethane ($C_2H_6$) | 65 |

Table 4. Suggested DGA fault types codes for accurate DGA technique

| Technique | F1 | F2 | F3 | F4 | F5 | F6 | F7 |
|---|---|---|---|---|---|---|---|
| Duval | Normal | Thermal Fault <300 ºC | Thermal Fault 300-700 ºC | Thermal Fault >700 ºC | Low energy discharge and High energy discharge | PD With mix thermal and electrical fault | Out of code fault |
| Doernenbug | Normal | Out of code fault | Thermal decomposition | | Arcing | Partial Discharges | Out of code fault |
| IEC | Normal | Thermal fault of low temp <150 ºC<br>Thermal fault of low temp between 150-300 ºC | Thermal fault of medium temp. between 300-700 ºC | Thermal fault of high temp >700 ºC | Discharge with low energy<br>Sparking<br>Discharge with high energy, Arcing | Partial discharge with low energy density | Out of code fault |
| Rogers | Normal | Thermal fault of low temperature range <150 ºC<br>Thermal fault of temperature range 150-200 ºC<br>Thermal fault of temperature range 200-300 ºC | Winding circulating current<br>Core/tank circulating current. | Insulated conductor overheat | Arc with power follows through.<br>Sparking.<br>Flashover. | Partial discharge<br>Partial discharge with tracking | Out of code fault |
| Key Gas | Normal | Out of code fault | Overheating of oil | Hot Spot | Arcing fault | Partial Discharge (Corona) | Out of code fault |
| Accurate Technique | Normal | Thermal Fault <300 ºC | Thermal Fault 300-700 ºC | Thermal Fault >700 ºC | Arcing fault | Partial discharge | Out of code fault |

Secondly, the same sampling oil unit is analyzed by each computerized individual technique to determine the possible fault types. As an example, for the same sample unit , Key Gas technique got diagnosis condition as "Acing in Oil", Rogers Ratio technique got diagnosis condition as "Arc with Power Follow Through", IEC Ratio technique got condition as "No Prediction", and Doernenburg Ratio technique got diagnosis condition as "Arcing" and Duval Triangle technique got diagnosis condition as "Discharge of High Energy". Therefore, for the fault identification with respect to each traditional technique, the faults are categorized into seven types of faults which is assigned with fault codes F1-F7 as suggested in Table 4. The next step is to compare all incipient fault types using each technique. Then, the conclusion is given for final fault type of the tested transformer oil same sample unit based on the percentage given by each techinque. Finally, using MATLAB software all diagnostic results of individual technique and Accurate DGA technique result are displayed.

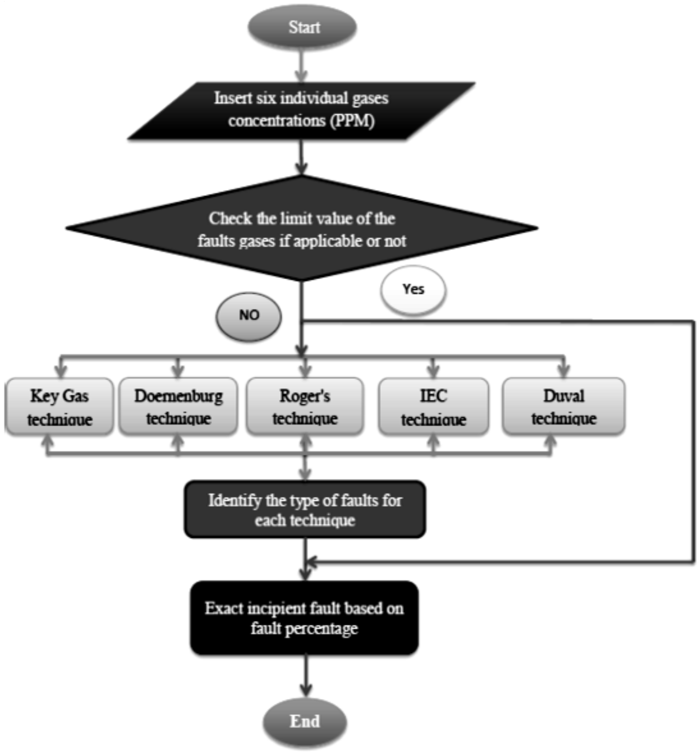


Figure 1. The flowchart of the procedure of Accurate DGA technique

The flowchart on a PC using MATLAB software given in Figure 1 is used in this paper to represent the results of all mentioned techniques. The Accurate DGA technique program will focus on the fault examination analysisidentification using fault percentage analysis to find the accurate fault result, in order to diagnose the incipient faults of the suspected transformers and suggest proper maintenance actions as soon as possible.

## 4. Results and Analysis

Table 5 shows the diagnosis results according to healthy conditions and accurate DGA technique. The developed accurate DGA technique (which is derived from individual traditional techniques) effectively conclude the appropriate fault of the traditional interpretation approach based on fault percentage without any overlapping as it is clear in Table 5. The suggested technique is based on the fault percentage that is mainlydetermined by using the existing DGA interpretation techniques which are listed in Table 4 without any overlapping, for that resion it is more accurate than any one of them and it is more helpful to detect the transformer faults compared with techniques suggested by Duval, M. [8], Key Gas, IEC ratio, Doernenburg ratioand R. R. Rogers [14].

Table 5. Result of fault types codes for individual and accurate DGA technique and transformer state

| no | Gases in (ppm) | | | | | | | Traditional Techniques | | | | | Accurate Technique | Transformer State |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $H_2$ | $CH_4$ | $C_2H_2$ | $C_2H_4$ | $C_2H_6$ | CO | CO2* | Key Gas | Doernenburg | Roger's | IEC | Duval | | |
| 1. | 41 Normal | 65 Normal | 0 Normal | 58 Normal | 22 Normal | 130 Normal | 1453 Normal | F7 | F1 | F3 | F3 | F3 | F3 | Thermal Fault 300-700 ºC |
| 2. | 17 Normal | 66 Normal | 0 Normal | 17 Normal | 9 Normal | 268 Normal | 1362 Normal | F7 | F1 | F7 | F3 | F1 | F1 | Normal |
| 3. | 20 Normal | 48 Normal | 0 Normal | 186 Normal | 36 Normal | 143 Normal | 533 Normal | F7 | F1 | F3 | F4 | F4 | F4 | Thermal Fault >700 ºC |
| 4. | 179 Caution | 306 Caution | 0 Normal | 579 Danger | 73 Caution | 496 Caution | 1050 Normal | F7 | F3,F4 | F3 | F4 | F4 | F4 | Thermal Fault >700 ºC |
| 5. | 73 Normal | 177 Caution | 0 Normal | 52 Caution | 37 Normal | 1767 Danger | 5398 Abnormal | F7 | F1 | F3 | F3 | F3 | F3 | Thermal Fault 300-700 ºC |
| 6. | 210 Caution | 43 Normal | 187 Danger | 102 Abnormal | 12 Normal | 167 Normal | 1070 Normal | F7 | F1 | F7 | F5 | F5 | F5 | Arcing fault |
| 7. | 39 Normal | 7 Normal | 0 Normal | 65 Caution | 12 Normal | 1469 Danger | 2692 Caution | F4 | F1 | F7 | F7 | F4 | F4 | Thermal Fault >700 ºC |
| 8. | 37 Normal | 96 Normal | 0 Normal | 57 Caution | 19 Normal | 132 Normal | 926 Normal | F7 | F1 | F3 | F3 | F3 | F3 | Thermal Fault 300-700 ºC |
| 9. | 46 Normal | 147 Caution | 0 Normal | 150 Abnormal | 27 Normal | 184 Normal | 2678 Caution | F7 | F1 | F7 | F4 | F4 | F4 | Thermal Fault >700 ºC |
| 10. | 18 Normal | 63 Normal | 0 Normal | 51 Caution | 20 Normal | 390 Caution | 2633 Caution | F7 | F1 | F7 | F3 | F3 | F3 | Thermal Fault 300-700 ºC |
| 11. | 200 Caution | 30 Normal | 98 Danger | 60 Caution | 9 Normal | 138 Normal | 308 Normal | F7 | F1 | F7 | F5 | F5 | F5 | Arcing fault |
| 12. | 28 Normal | 62 Normal | 0 Normal | 76 Caution | 16 Normal | 538 Caution | 1206 Normal | F7 | F1 | F3 | F4 | F4 | F4 | Thermal Fault >700 ºC |
| 13. | 68 Normal | 78 Normal | 0 Normal | 136 Abnormal | 103 Abnormal | 550 Caution | 1720 Normal | F7 | F3,F4 | F7 | F3 | F4 | F4 | Thermal Fault >700 ºC |
| 14. | 54 Normal | 143 Caution | 0 Normal | 101 Abnormal | 23 Normal | 1358 Abnormal | 4497 Abnormal | F7 | F3,F4 | F3 | F4 | F3 | F3 | Thermal Fault 300-700 ºC |
| 15. | 19 Normal | 47 Normal | 0 Normal | 62 Caution | 27 Normal | 229 Normal | 1114 Normal | F7 | F1 | F3 | F3 | F4 | F3 | Thermal Fault 300-700 ºC |
| 16. | 678 Caution | 70 Normal | 237 Danger | 89 Caution | 31 Normal | 768 Abnormal | 1909 Normal | F7 | F5 | F7 | F5 | F5 | F5 | Arcing fault |
| 17. | 86 Normal | 277 Caution | 0 Normal | 338 Danger | 63 Normal | 323 Normal | 2574 Caution | F7 | F1 | F7 | F4 | F4 | F4 | Thermal Fault >700 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | °C |
| 18. | 20 Normal | 19 Normal | 0 Normal | 77 Caution | 45 Normal | 571 Abnormal | 1854 Normal | F4 | F1 | F7 | F2 | F4 | F4 | Thermal Fault >700 °C |
| 19. | 25 Normal | 49 Normal | 0 Normal | 58 Caution | 42 Normal | 424 Caution | 1814 Normal | F7 | F1 | F3 | F3 | F4 | F3 | Thermal Fault 300-700 °C |
| 20. | 53 Normal | 150 Caution | 0 Normal | 379 Danger | 64 Normal | 312 Normal | 987 Normal | F7 | F1 | F3 | F4 | F4 | F4 | Thermal Fault >700 °C |
| 21. | 114 Caution | 241 Caution | 0 Normal | 574 Danger | 80 Caution | 1309 Abnormal | 5675 Abnormal | F7 | F3,F4 | F3 | F4 | F4 | F4 | Thermal Fault >700 °C |
| 22. | 99 Normal | 288 Caution | 0 Normal | 386 Danger | 73 Caution | 304 Normal | 1625 Normal | F7 | F3,F4 | F3 | F4 | F4 | F4 | Thermal Fault >700 °C |
| 23. | 1374 Abnormal | 2648 Danger | 298 Danger | 5376 Danger | 628 Danger | 783 Abnormal | 2819 Caution | F7 | F3,F4 | F3 | F4 | F4 | F4 | Thermal Fault >700 °C |
| 24. | 34 Normal | 83 Normal | 0 Normal | 136 Abnormal | 100 Caution | 645 Abnormal | 3197 Caution | F7 | F3,F4 | F7 | F3 | F4 | F4 | Thermal Fault >700 °C |
| 25. | 20 Normal | 132 Caution | 0 Normal | 17 Normal | 61 Normal | 712 Abnormal | 2576 Caution | F7 | F1 | F2 | F2 | F3 | F2 | Thermal Fault <300 °C |
| 26. | 13 Normal | 138 Caution | 0 Normal | 16 Normal | 83 Caution | 1046 Abnormal | 5197 Abnormal | F7 | F1 | F2 | F2 | F3 | F2 | Thermal Fault <300 °C |
| 27. | 762 Abnormal | 93 Normal | 126 Danger | 54 Caution | 38 Normal | 459 Caution | 5346 Abnormal | F7 | F5 | F7 | F5 | F5 | F5 | Arcing fault |
| 28. | 43 Normal | 116 Normal | 0 Normal | 139 Abnormal | 65 Caution | 718 Abnormal | 2326 Normal | F7 | F3,F4 | F3 | F3 | F4 | F3 | Thermal Fault 300-700 °C |
| 29. | 179 Caution | 306 Caution | 0 Normal | 579 Danger | 73 Caution | 496 Caution | 1050 Normal | F7 | F3,F4 | F3 | F4 | F4 | F4 | Thermal Fault >700 °C |
| 30. | 57 Normal | 141 Caution | 0 Normal | 51 Caution | 38 Normal | 1405 Danger | 5484 Abnormal | F7 | F1 | F3 | F3 | F3 | F3 | Thermal Fault 300-700 °C |
| 31. | 40 Normal | 8 Normal | 0 Normal | 15 Normal | 34 Normal | 2723 Danger | 3929 Caution | F4 | F1 | F7 | F1 | F1 | F1 | Normal |
| 32. | 35 Normal | 283 Caution | 0 Normal | 222 Danger | 121 Abnormal | 1475 Danger | 11034 Danger | F7 | F3,F4 | F7 | F3 | F3 | F3 | Thermal Fault 300-700 °C |
| 33. | 15 Normal | 159 Caution | 0 Normal | 87 Caution | 29 Normal | 1769 Danger | 11263 Danger | F7 | F1 | F7 | F3 | F3 | F3 | Thermal Fault 300-700 °C |
| 34. | 55 Normal | 159 Caution | 0 Normal | 493 Danger | 114 Abnormal | 1309 Abnormal | 11298 Danger | F7 | F3,F4 | F3 | F4 | F4 | F4 | Thermal Fault >700 °C |
| 35. | 37 Normal | 123 Caution | 0 Normal | 52 Caution | 67 Caution | 869 Abnormal | 3896 Caution | F7 | F1 | F2 | F2 | F3 | F2 | Thermal Fault <300 °C |
| 36. | 723 | 191 | 288 | 293 | 110 | 459 | 5346 | F | F5 | F7 | F | F5 | F5 | Arcing |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Abnormal | Caution | Danger | Danger | Abnormal | Caution | Abnormal | 7 | | | 5 | | | fault |
| 37. | 7 Normal | 15 Normal | 0 Normal | 58 Caution | 78 Caution | 687 Abnormal | 4647 Abnormal | F7 | F1 | F2 | F2 | F4 | F2 | Thermal Fault <300 ºC |
| 38. | 30 Normal | 51 Normal | 0 Normal | 54 Caution | 12 Normal | 803 Abnormal | 3566 Caution | F7 | F1 | F3 | F4 | F4 | F4 | Thermal Fault >700 ºC |
| 39. | 31 Normal | 56 Normal | 0 Normal | 77 Caution | 33 Normal | 771 Abnormal | 5175 Abnormal | F7 | F1 | F3 | F3 | F4 | F3 | Thermal Fault 300-700 ºC |
| 40. | 109 Caution | 226 Caution | 0 Normal | 192 Abnormal | 68 Caution | 1150 Abnormal | 5240 Abnormal | F7 | F3,F4 | F3 | F3 | F3 | F3 | Thermal Fault 300-700 ºC |
| 41. | 137 Caution | 279 Caution | 0 Normal | 505 Danger | 66 Caution | 897 Abnormal | 3085 Caution | F7 | F3,F4 | F3 | F4 | F4 | F4 | Thermal Fault >700 ºC |
| 42. | 59 Normal | 119 Normal | 0 Normal | 70 Caution | 36 Normal | 735 Abnormal | 4738 Abnormal | F7 | F1 | F3 | F3 | F3 | F3 | Thermal Fault 300-700 ºC |
| 43. | 151 Caution | 242 Caution | 0 Normal | 232 Danger | 68 Caution | 1076 Abnormal | 5418 Abnormal | F7 | F3,F4 | F3 | F4 | F3 | F3 | Thermal Fault 300-700 ºC |
| 44. | 870 Abnormal | 77 Normal | 14 Abnormal | 54 Caution | 73 Caution | 459 Caution | 5346 Abnormal | F7 | F6 | F6 | F7 | F5 | F6 | Partial discharge |
| 45. | 376 Caution | 575 Abnormal | 0 Normal | 1092 Danger | 146 Abnormal | 674 Abnormal | 2160 Normal | F7 | F3,F4 | F3 | F4 | F4 | F4 | Thermal Fault >700 ºC |
| 46. | 17 Normal | 40 Normal | 0 Normal | 86 Caution | 11 Normal | 78 Normal | 823 Normal | F7 | F1 | F3 | F4 | F4 | F4 | Thermal Fault >700 ºC |

In some cases, Accurate DGA Technique may lead to more than one result (e.g. Accurate Technique in samples number 2, 6, 7, 9, 10, 11, 33, 44). To avoid this in the developed proposed technique, the output will be selected based on the worst case. Consequently, based on MATLAB Code the above analysis is summarized in table 5. The internal incipient faults diagnosis of power transformer is also accomplished by evaluation of transformer condition using individual and TDCG concentrations for determining the overall health of a power transformer based on four status conditions: Normal Operation, Caution, Abnormal, and Danger (nearing failure). So, the result of this work is useful for planning an appropriate maintenance strategy to keep the power transformer in acceptable conditions. Therefore, incipient fault detection of transformers is necessary in order to avoid electrical power system fault as quickly as possible.

## 5. Conclusion

This paper introduces an accurate DGA technique for identifying the internal incipient faults in the power transformer based on the fault percentage of dissolved gasses released from transformer oil and solid insulation using practical oil samples collected from different transformers. The techniques of interpretation of the fault gases are investigated and compared with each other based on the Accurate DGA technique which is derived from individual techniques to evaluate the accuracy of each technique in predicting the fault based on a MATLAB program as shown in Table 5. Furthermore, the deteriorated transformer by means of this analysis can be carefully focused for the appropriate maintenance as condition-based maintenance before severe damage occurs.

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