Software implementation of automatic fault identification based on the Duval Pentagon

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Abstract. Dissolved Gas Analysis (DGA) is one of the most widely used monitoring technology for oil immersed power transformers. The Duval Pentagon method is a graphic interpretation method of DGA. Besides the six typical faults usually interpreted by DGA, this method also can be used alone to bring auxiliary information about the internal faults of power transformers. Based on Duval Pentagon method, this paper presents a detailed software implementation process of automatic fault identification for power transformers. Moreover, this paper also offers clear threshold conditions which indicate the abnormality of DGA results before applying the Duval Pentagon method to improve the practical use of this DGA interpretation method. Thus, the program developed by this paper can provide a commercial system of DGA interpretation.

1. Introduction
In the power networks, live fault detection of power equipment has developed rapidly for recent years. Consequently, the cost caused by power equipment outage maintenance can be reduced without sacrifice of reliability [1]. The need for live fault detection in practical engineering applications has encouraged researchers to devote their work for development of such methods from different aspects. Among these technologies, Dissolved Gas Analysis (DGA) is one of the most widely used monitoring technology for oil immersed power transformers [2, 3]. Any abnormal electrical or thermal stress working on the insulation layer inside transformers could lead to production of new gases [4]. The principle of DGA is extracting the principal gases dissolved in the insulating oil to reveal the fault inside power transformers [5]. Specifically, the principal gases include hydrogen (H₂), methane (CH₄), acetylene (C₂H₂), ethylene (C₂H₄), ethane (C₂H₆), carbon monoxide (CO), carbon dioxide (CO₂), oxygen (O₂) and nitrogen (N₂). DGA becomes an economical tool for online monitoring and periodic monitoring condition of power transformers [6].

Many methods have been developed for the interpretation of DGA results [3-9]. Conventional methods recommended by IEEE, IEC, CIGRE and other electrical standards associations are the Dornenburg ratio method [3], Rogers ratio method [4], IEC 60599 code [7], and Duval Triangle method [9]. The basic concept of these methods is to utilize the gas proportion portfolio as eigenvalues to find the corresponding fault types of power transformers. Six types of typical faults can usually be identified by most DGA interpretation methods: (1) partial discharge (PD), (2) low-energy discharge (D1), (3) high-energy discharge (D2), (4) low-temperature thermal faults (T1, temperature less than 300°C), (5) moderate-temperature thermal faults (T2, temperature between 300°C ~ 700°C) and (6) high-
temperature thermal faults (T3, temperature is greater than 700°C). Extracting more auxiliary information about the internal faults of power transformers can help maintenance personnel reduce the scope of inspection, more accurately arrange the maintenance schedule, and develop solutions. To this end, Michel Duval proposed Duval Triangles 4 and 5 to obtain advanced subtypes of faults in 2008 [9]. The software implementation of Duval Triangle method is introduced in [10]. In 2014, Michel Duval proposed the Duval Pentagon method which represents five ratios of principal gases in a pentagon to bring complementary information for interpretation of DGA [11]. This method can be used alone for auxiliary information of thermal faults specially. However, the premise of applying the interpretation of DGA is to determine whether the analyzed sample has reached a concentration limit or abnormal growth rate.

This paper investigates a software implementation program based on the Duval Pentagon method for automatic fault identification for power transformers. The rest of the paper is organized as follows. The principle of the Duval Pentagon method is briefly explained in the second section. Then, the third section proposes the software implementation program based on Duval Pentagon. Moreover, the boundary conditions of applying the Duval Pentagon method are also considered for accurate interpretation results. The program developed by this paper improves the practical use of the Duval Pentagon method, and offers a commercial system of DGA interpretation.

2. Duval Pentagon method
The Duval Pentagon method uses the concentrations of five hydrocarbon gases (H₂, CH₄, C₂H₆, C₂H₄ and C₂H₂) to calculate their corresponsive percentage by Equation (1). Then the percentages are drawn in a pentagon, of which each summit represents a type of hydrocarbon gas as shown in Figure 1 [11]. The order of summits is arranged by the generation of each characteristic gas with increasing energy or temperature [6].

\[
\begin{align*}
\text{pH}_2 &= \frac{H_2}{H_2 + CH_4 + C_2H_6 + C_2H_4 + C_2H_2} \times 100 \\
\text{pCH}_4 &= \frac{CH_4}{H_2 + CH_4 + C_2H_6 + C_2H_4 + C_2H_2} \times 100 \\
\text{pC}_2H_6 &= \frac{C_2H_6}{H_2 + CH_4 + C_2H_6 + C_2H_4 + C_2H_2} \times 100 \\
\text{pC}_2H_4 &= \frac{C_2H_4}{H_2 + CH_4 + C_2H_6 + C_2H_4 + C_2H_2} \times 100 \\
\text{pC}_2H_2 &= \frac{C_2H_2}{H_2 + CH_4 + C_2H_6 + C_2H_4 + C_2H_2} \times 100 
\end{align*}
\]

(1)

![Figure 1. Coordinate of a pentagon where the percentage of 5 hydrocarbon gases can be drawn in.](image)
The six typical fault types mentioned in the introduction can be identified by Duval Pentagon 1, of which coordinate is shown in Figure 2. Moreover, Duval Pentagon 2 is used to obtain advanced subtypes of thermal faults as shown in Figure 3. The four fault subtypes including (7) stray gassing at temperatures < 200°C (S), (8) overheating < 250°C without carbonization of paper (O), (9) possible paper carbonization (C) and (10) thermal fault T3 in mineral oil only (T3-H) are described in detailed in [6] and [11].

![Figure 2. Fault types identified by Duval Pentagon 1 [6].](image1)

![Figure 3. Fault types identified by Duval Pentagon 2 [6].](image2)

### 3. Software implementation process of automatic fault identification

In order to automatically identify the internal faults of power transformers based on Duval Pentagon method, the implementation process is described step-by-step by the flowchart in Figure 4.

![Figure 4. The flowchart of the software implementation process for automatic fault identification of power transformers.](image3)

The flowchart contains three essential steps which are explained in detailed in the following subsections.

#### 3.1. Step 1: detection of the threshold conditions

Detection of any abnormal gas generation in the oil is the first step of the interpretation of DGA. High gas concentration or increasing gassing rate indicates the abnormality inside the power transformer, so it is important to detect the limitation of threshold conditions. The threshold conditions according to the guidelines in [12] and [13] are summarized in Table 1.
Table 1. Threshold conditions of gas concentration and gassing rate.

| No. | Threshold conditions                                      |
|-----|----------------------------------------------------------|
| Con1| total hydrocarbon (TCG) concentration ≥150μL/L          |
| Con2| TCG<150μL/L, and rate, rate =10%/month, and C_2H_2>0.1μL/L |
| Con3| If it is the first time of getting DGA data since the transformer began on operation, C_2H_2≥0.1μL/L |
| Con4| C_3H_2≥Warning value (voltage level of power transformer≥330kV, Warning value =1μL/L; voltage level of power transformer <330kV, Warning value =5μL/L) |
| Con5| (voltage level of power transformer≥330kV, Warning value =1μL/L; voltage level of power transformer <330kV, Warning value =5μL/L) |
| Con6| H_2≥150μL/L |

In Table 1, rate R_TCG and rate a_C2H2 are defined by Equations (2) and (3) respectively:

\[
\text{rate}_R_{TCG} = \frac{C_{TCG,t_n} - C_{TCG,t_{n-1}}}{t_n - t_{n-1}} \times \frac{1}{\text{t_n} - \text{t}_{n-1}} \times 100\% \text{ (/month)}
\]  
\[
\text{rate}_a_{C2H2} = \frac{C_{C2H2,t_n} - C_{C2H2,t_{n-1}}}{t_n - t_{n-1}} \times \frac{m}{\rho} \text{ (mL/day)}
\]

where, C_{TCG,t_n} and C_{C2H2,t_n} present the total hydrocarbon concentration and C_2H_2 concentration of the latest DGA sample, t_n denotes the latest sampling date, t_{n-1} denotes the last sampling date which meets the calculating condition, and respectively C_{TCG,t_{n-1}} and C_{C2H2,t_{n-1}} present the total hydrocarbon concentration and C_2H_2 concentration with sampling time t_{n-1}. This equation only works when the sampling time interval is no less than 30 days [13]. Moreover, m indicates the oil weight and \( \rho \) denotes the oil density.

If the test sample doesn’t meet all the threshold conditions illustrated in Table 1, the DGA results are considered acceptable. Otherwise, when any abnormality is detected, the Duval Pentagon method can be used to identify suspicious behavior inside the test object.

3.2. Step 2: convert the coordinate system

The second step is to convert the information of the DGA sample and the pentagons illustrated in Figure 2 and Figure 3 into the coordinate system. First, the five gas percentage values of the sample as in Equation (1) can be presented in Cartesian coordinate system by equation by Equation (4).

\[
\begin{align*}
    x_1 &= 0, \\
    x_2 &= \text{pC2H6} \times \cos(180° - 18°), \\
    x_3 &= \text{pCH4} \times \cos(180° + 54°), \\
    x_4 &= \text{pC2H4} \times \cos(-54°), \\
    x_5 &= \text{pC2H2} \times \cos(18°),
\end{align*}
\]

\[
\begin{align*}
    y_1 &= \text{pH2} \\
    y_2 &= \text{pC2H6} \times \cos(90° - 18°) \\
    y_3 &= \text{pCH4} \times \cos(90° + 54°) \\
    y_4 &= \text{pC2H4} \times \cos(90° + 54°) \\
    y_5 &= \text{pC2H2} \times \cos(90° - 18°)
\end{align*}
\]

These five points form an irregular polygon, and the centroid of this polygon can be calculated by Equation (5) [11].

\[
\begin{align*}
    Cx &= \frac{\sum_{i=1}^{4}(x_i + x_{i+1})(x_i y_{i+1} - x_{i+1} y_i)}{3 \sum_{i=1}^{4}(x_i y_{i+1} - x_{i+1} y_i)} \\
    Cy &= \frac{\sum_{i=1}^{4}(y_i + y_{i+1})(x_i y_{i+1} - x_{i+1} y_i)}{3 \sum_{i=1}^{4}(x_i y_{i+1} - x_{i+1} y_i)}
\end{align*}
\]

As shown in Figure 1, The Duval Pentagon method uses the location of the centroid in the pentagon to discover the fault type or subtype. Hence, it is necessary to draw the pentagon and the fault zones as shown in Figure 2 and Figure 3 in the Cartesian coordinate system. The fault zones can be expressed by the coordinates of their summits in the Cartesian coordinate system. Then ten fault zones corresponding
to ten fault types and subtypes can be presented in Table 2 based on the description of Duval Pentagon in [6].

Table 2. The coordinates of polygon summits corresponding to fault types and subtypes.

| No. | Fault type | coordinates of polygon summits |
|-----|------------|--------------------------------|
| 1   | PD         | (0, 33), (-1, 33), (-1, 24.5), (0, 24.5) |
| 2   | D1         | (0, 40), (38, 12), (32, -6.1), (4, 16), (0, 1.5) |
| 3   | D2         | (4, 16), (32, -6.1), (24.3, -30), (0, -3), (0, 1.5) |
| 4   | T3         | (0, -3), (24.3, -30), (23.5, -32.4), (1, -32.4); (-6, -4) |
| 5   | T2         | (-6, -4), (1, -32.4), (-22.5, -32.4); |
| 6   | T1         | (-6, -4), (-22.5, -32.4), (-23.5, -32.4), (-35, 3), (0, 1.5); (0, -3) |
| 7   | S          | (0, 1.5), (-35, 3.1), (-38, 12.4), (0, 40), (0, 33), (-1, 33), (-1, 24.5), (0, 24.5) |
| 8   | O          | (-3.5, -3), (-11, -8), (-21.5, -32.4), (-23.5, -32.4), (-35, 3.1), (0, 1.5), (0, -3) |
| 9   | C          | (-3.5, -3), (2.5, -32.4), (-21.5, -32.4), (-11, -8) |
| 10  | T3H        | (0, -3), (24.3, -30), (23.5, -32.4), (2.5, -32.4), (-3.5, -3) |

3.3. Step 3: identify the fault type or subtype

With the previous two steps, the graphic view based on the Duval Pentagon is achieved already. The next step is to make the machine understand which zone the test sample belongs to, so that automatic identification can be implemented by DGA software.

The principle of this step is to determine whether the calculated centroid point lies inside the zone for every polygon in Table 2. The number of summits of a polygon is marked as $n$, which means this polygon has $n$ edges. In the case, $(p_i x, p_i y)$ is used to present the coordinate of a summit. A way to solve this problem is to use a ray starting from the point and going in horizontal direction to intersect the edges of the polygon. Then, an equation is defined in (6):

$$k = \frac{(C y - p_i y) (p_{i+1} x - p_i x)}{(p_{i+1} y - p_i y)} + p_i x - C x, \quad i \in [1, n]$$

(6)

Specially, when $i = n$, $p_{i+1} = p_1$. Another equation is defined in (7):

$$m = (p_{i-1} y - C y) (p_{i+1} y - C y), \quad i \in [1, n]$$

(7)

Specially, when $i = 1$, $p_{i+1} = p_1$.

![Figure 5](image-url)
The scan of fault zones starts with the first polygon, and the procedure is explained by the flowchart in Figure 5. In the figure, the value $f$ indicates the number of fault zones as shown in Table 2, and the calculations of parameter $k$ and $m$ are mentioned in Equations (6) and (7), which are used to count the intersecting times. If the number of intersecting times is odd, the point is inside the polygon, and the program proceeds the next polygon in the same way. Finally, the output $f$ corresponding to the number listed in Table 2 indicates the identified fault type or subtype.

3.4. Program application
To validate the implementation, an oil sample is applied in the program developed based on the aforementioned process. The related DGA data in this case are: $H_2 = 35 \, \mu L/L$, $CH_4 = 188 \, \mu L/L$, $C_2H_6 = 130 \, \mu L/L$, $C_2H_4 = 46 \, \mu L/L$ and $C_2H_2 = 0 \, \mu L/L$. It can be found that the total hydrocarbon concentration of this oil sample is 364 $\mu L/L$ which goes over 150 $\mu L/L$. It meets the ‘Con1’ as illustrated in Table 1, which means an abnormal gas generation happens in this oil sample. As a consequence, DGA interpretation methods can used to identify the fault types. By using the method of IEC 60599 code, the analyzed result is low-temperature thermal faults (T1, temperature less than 300°C). By inputting the data of this oil sample into the developed program, the result analyzed by program is shown in Figure 6.

![Gas Concentration of Test Sample](image)

| Sample 1 | $H_2$ | $CH_4$ | $C_2H_6$ | $C_2H_4$ | $C_2H_2$ |
|----------|-------|--------|----------|----------|----------|
|          | 35    | 188    | 130      | 46       | 0        |

**DGA Results**

Sample 1:

- **T1**: low-temperature thermal faults ($t < 300^\circ C$)
- **O**: overheating ($t < 250^\circ C$) without carbonization of paper

**Figure 6.** DGA results of the case study.

The abnormality of the oil sample is detected automatically, and the DGA interpretation result according to the Duval Pentagon is displayed in the pentagon in Figure 6. Besides, the identified fault information is pulled as well. In this case, the fault information is ‘T1: low-temperature thermal faults (T1, temperature less than 300°C) and O: overheating<250°C without carbonization of paper’. It not only agrees with the analyzed result of IEC 60599 code, but also offers additional auxiliary information of this low-temperature thermal fault. In summary, this case study shows correct performance of the developed program. Therefore, this program can automatically analyze the inputting oil samples using the Duval Pentagon.

4. Conclusions and discussions
In conclusion, an implementation process for automatic fault identification of power transformers is investigated in this paper. In this program, the threshold conditions indicating the abnormality of DGA results are considered, and the Duval Pentagon method is applied for interpretation of DGA. The developed program offers a commercial system of DGA interpretation. This system can be used alone or with other DGA interpretation systems as a complementary tool.
The reliability of this DGA interpretation program highly depends on the accurate gas concentration measurements. Therefore, once the DGA results met the threshold conditions, it is highly recommended to analyze another oil sample and for confirmation.

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