Application of Duval Pentagon in State Diagnosis of On Load Tap Changer

Yunkai YUE1a*, Dingqian YANG1b, Dandan HAN1c

1State Grid Xinjiang Company Limited Electric Power Research Institute, xinjiang, wulumuqi, 830010
a*yueyunkaitianyanan@163.com, b1292045278@qq.com, c2768059015@qq.com

Abstract-A comparative analysis on the effect of two DGA methods, Duval Pentagon and Duval triangle, in identifying abnormal OLTC was carried out. The corresponding area of Duval Pentagon corresponding to the normal state of OLTC was determined, and Duval Pentagon was used to judge the OLTC of UHV converter transformer. The results show that the Duval Pentagon can identify the normal and abnormal states of on load tap changers. More than 95.5% of the on load tap changers are in the low energy discharge area numbered D1. The identification results of 245 on load tap changer states show that the accuracy of normal state of Duval Pentagon is higher than that of Duval triangle, which can be used as an auxiliary criterion for on load tap changer state diagnosis.

1. Introduction
With the rapid development of my country's national economy, the demand for electricity has gradually increased, and the construction of UHV AC and DC projects has also been continuously strengthened, providing a strong national energy development strategy of "West-to-East Power Transmission, North-South Interconnection, and National Interconnection"[1]. As the most critical equipment in the UHV DC converter station, the converter transformer is responsible for the power interconnection of the AC and DC high voltage electrical equipment at the node of the converter station. The start and stop of the converter transformer plays a decisive role in the continuity of energy delivery and the reliability of regional energy security, therefore, the detection, evaluation and diagnosis of its status, timely detection of problems in operation and timely elimination of defects, are of great significance to the safe and stable operation of the regional power grid and the entire power system[2].

In order to ensure that the converter valve group is maintained in a state of low thermal power consumption, UHV DC transmission usually adopts fixed-angle phase-shift modulation, and the voltage regulation mode is on-load voltage regulation. Therefore, the converter transformer is equipped with an on-load tap switch device (On-Load-Tap-Changer, OLTC) [3]. The abnormal cases of UHV converter transformers in recent years show that compared with other electrical components, the failure rate of the on-load tap-changer is higher [4], because compared with other stationary components, the mechanical parts of the on-load tap-changer usually in operation, the electrical parts of the on-load tap-changer are usually in an arcing state, and the insulating medium of the on-load tap-changer is usually seriously polluted [5]. At the same time, the failure of the on-load tap changer may cause damage to the entire transformer, causing economic losses that are several times the value of the
tap changer. Therefore, carrying out condition monitoring for on-load tap-changers is of positive significance for improving the reliability of UHV converter transformers.

The detection and monitoring methods of the on-load tap-changer include dynamic resistance test, dissolved gas analysis in oil, mechanical vibration detection and motor current detection [6]. Among them, the dynamic resistance test can find serious and critical faults, and has the function of state evaluation, but it must be tested for power failure; mechanical vibration detection and motor current detection can only detect the state of the mechanical switching process, and the monitoring interval is not comprehensive [7]. In contrast, the dissolved gas analysis in oil covers all stages of on-load tap-changer status monitoring and has a fault warning function.

Dissolved gas analysis (DGA) is a widely used technology for diagnosing the insulation status of oil-filled equipment [8]. The insulating oil in OLTC is cracked due to operation, electrical and overheating failures [9]. The gases produced by the cracking of mineral oil include hydrogen (H₂), methane (CH₄), ethane (C₂H₆), ethylene (C₂H₄) and acetylene (C₂H₂), etc. The solid insulation damage produces carbon monoxide (CO) and carbon dioxide (CO₂). These gases dissolved in the insulating oil of the tap changer. The DGA judgment method is used to analyze the concentration of the above-mentioned cracked gas, and comprehensively judge the fault type according to the actual size, proportional relationship, and change trend of the gas concentration.

At present, the methods for diagnosis of transformer, casing and OLTC status based on DGA are mainly based on IEEE/IEC standard [10], Duval triangle method [11], improved three ratio method [12], Rogers ratio method, etc. [13]. In addition, BP neural network [14], support vector machine [15], extreme learning machine [16] and other classification algorithm fault diagnosis methods have appeared, which provide a reference for OLTC fault diagnosis to a certain extent. However, due to the frequent actions of on-load decomposition switches and the frequent occurrence of abnormalities such as arcs, therefore, the analysis of dissolved gases in oil is more complicated than that of power transformers. Although traditional methods can identify abnormal defects to a certain extent, but in field applications, since the number of fault samples is relatively small compared to the normal state samples, the use of classification methods such as BP neural network and support vector machine for fault diagnosis will lead to misdiagnosis. In the end, methods such as the Duval triangle method are still needed for further verification, or visual inspection of the equipment disassembly.

To this end, this paper proposes to use the Duval pentagon method for OLTC fault diagnosis. This method is based on the traditional Duval triangle method and fully considers the percentage content of five common gas components, and is summarized through the diagnosis results of a large number of power transformer OLCT. This article will use this method to diagnose the OLCT status of the converter transformer, aiming to provide a technical reference for the diagnosis of UHV converter transformer OLTC.

2. DGA judgment method
DGA judgment methods are divided into characteristic gas limit and ratio method, Duval triangle method and Duval pentagon method. Among them, characteristic gas limit and ratio are the prerequisites for starting DGA analysis [9-11]. The on-load tap-changer will also produce characteristic gas during normal operation, the content and ratio of characteristic gas can be compared horizontally to delineate suspected components. The characteristic gas ratio method used for on-load tap-changers has a high accuracy rate in identifying normal and faulty components, which can greatly reduce the scope of the analysis object; however, the ratio method cannot determine the type of fault and the faulty component. The Duval triangle method is based on the gas ratio method and increases the relationship between the gas content and the fault type; the Duval pentagon method adds hydrogen and ethane on the basis of the Duval triangle method, which has a high degree of confidence in identifying the fault type.
2.1 Characteristic gas limit and ratio method

Compared with transformers, OLTC are often in operation to meet the needs of voltage regulation. Mechanical vibrations and even arcs will occur during the contact between moving and static contacts, while transformers are almost "stationary" except for slight vibrations caused by electromagnetic forces. Therefore, the insulating oil inside the OLTC is more susceptible to cracking and degradation \[12\]. Compared with transformers, more ethylene and acetylene are dissolved in the insulating oil of the on-load tap-changer.

Applicable to OLTC characteristic gas limit method, using ethylene gas as an over-limit warning gas, the gas ratio method uses the gas ratio of \( \text{C}_2\text{H}_4/\text{C}_2\text{H}_2 \) as the state criterion \[13\]. Comprehensive gas content and gas ratio determine whether the on-load tap changer enters the attention state or even the alarm state. Table 1 shows the four gas data collected by an OLTC from 2003 to 2006. It can be seen that as the operating time increases, the \( \text{C}_2\text{H}_4 \) content increases significantly, and the ratio of \( \text{C}_2\text{H}_4 \) to \( \text{C}_2\text{H}_2 \) also increases rapidly. Finally, after core lifting treatment, it was found that the moving contact of the OLTC had severe ablation.

| Time          | \( \text{C}_2\text{H}_4 \) μL/L | \( \text{C}_2\text{H}_4/\text{C}_2\text{H}_2 \) |
|---------------|-------------------------------|----------------------------------|
| 2003-04-22    | 38                            | 0.26                             |
| 2004-11-09    | 53                            | 0.33                             |
| 2006-04-25    | 1390                          | 18.05                            |
| 2006-06-20    | 776                           | 11.76                            |

Note: In July 2006, the hanging core inspection found that the moving contact was severely ablated.

2.2 Duval Triangle Method

The Duval triangle method has been widely used in the diagnosis of insulating oil DGA. The method uses \( \text{C}_2\text{H}_2 \), \( \text{C}_2\text{H}_4 \), and \( \text{CH}_4 \) three hydrocarbon gases. First use the volume percentage of each gas divided by the sum of the three gas volume percentages to calculate the proportion of each gas, and then draw the Duval triangle, and use the proportions of the three gases as the coordinates to draw the ratio points in the Duval triangle \[14-16\].

![Fig. 1. The Duval triangle for the DGA of OLTC](image)

Figure 1 shows the Duval triangle for the development of the on-load tap changer DGA. The triangle is divided into 6 areas according to the type of failure. The area boundaries are shown in Table 2. The area where the ratio point falls indicates the type of failure in the equipment. According to the fault type corresponding to each area of the Duval triangle method listed in Table 2, the fault can be judged intuitively.
Tab.2 Identification of fault zone and boundaries using Duval triangle

| Area | geographic range | Fault type |
|------|------------------|------------|
| N    | CH₄ ∈ [2,19]    | No trouble |
|      | C₂H₄ ∈ [6,23]   |            |
| T3   | C₂H₄ ∈ [50,100] | Medium and high temperature overheating |
|      | C₂H₂ ∈ [0,15]   |            |
| T2   | C₂H₂ ∈ [23,85] | High-energy discharge |
|      | C₂H₄ ∈ [15,77] |            |
|      | C₂H₂ ∈ [0,2]    |            |
| D1   | C₂H₄ ∈ [0,23]  | Low energy discharge |
|      | C₂H₂ ∈ [23,50] |            |
|      | C₂H₂ ∈ [0,15]  |            |
| X1   | CH₄ ∈ [2,19]   | Low temperature overheating |
|      | C₂H₄ ∈ [6,23]  |            |

2.3 Duval pentagon method

In order to solve the problem that the Duval triangle method cannot determine the abnormal hydrogen growth equipment, two gases H₂ and C₂H₆ are added on the basis of the Duval triangle method to improve the recognition sensitivity of natural deterioration of insulating oil, partial discharge, and low temperature overheating[17]. The Duval pentagon method uses the relative percentages of five hydrocarbon gases H₂, CH₄, C₂H₆, C₂H₄, and C₂H₂ as the five-digit coordinates to draw a pentagon, and then finds the center point of the pentagon through mathematical calculations, and the center point falls into The area is the corresponding fault type, as shown in Figure 2.

![Duval pentagon for DGA of OLTC](image)

The calculation process of the pentagon is as follows [15]:

1) Calculate the relative content (percentage) of the five gases: %H₂, %CH₄, %C₂H₂, %C₂H₄ and %C₂H₆;

2) Calculate the vertex coordinates of the pentagon with the relative content of five gases as the vertex according to formula (1) and formula (2);

3) According to formula (3), calculate the area of the pentagon with the relative content of the five gases as the vertex;

4) According to formula (4), calculate the center coordinates of the pentagon with the relative contents of the five gases as the vertices;

5) Draw the center of the pentagon on the pentagon plane according to the center coordinates.
In the pentagon shown in Figure 2, there are a total of 6 areas, among which low-energy discharge and normal state share one area, and the fault types represented by each area are shown in Table 3.

### Tab.3 fault zone signed in Duval pentagon

| Area number | Fault type                  |
|-------------|-----------------------------|
| S           | No trouble                  |
| D1(N)       | Low energy discharge        |
|             | Normal area                 |
| D2          | High-energy discharge       |
| T3          | High temperature overheating|
| T2          | Moderate temperature overheating|
| T1          | Low temperature overheating |

3. **Comparison of Duval triangle and Duval pentagon**

In order to compare and analyze the effectiveness of the Duval triangle method and the Duval pentagon method for OLTC status diagnosis, 700 sets of dissolved gas data in the insulating oil of the on-load tap-changer in the operating state are selected as the analysis object, and they are drawn on the triangle and the pentagon respectively. In the shape, the results are shown in Figure 3 and Figure 4. The 700 samples are divided into two clusters in the triangle, one is located in the normal area numbered N, the other is located in the abnormal area labeled T3; the 700 groups of samples are also divided into two clusters in the pentagon, one cluster is located in the area numbered D1, another cluster is located in the area numbered T3. The result shows that the pentagon, like the triangle, can separate and identify the dissolved gas samples.
The above 700 sets of data are screened according to the level of dissolved gas content, and the screening methods are divided into total screening and incremental screening. Total screening refers to selecting the actual measured value of the dissolved gas volume percentage as the data object, and the screening result is also the actual measured value; Incremental filtering refers to selecting the difference between the measured values of two nearby dissolved gases as the data object. The screening result is also the difference (increment). The measured value of dissolved gas is relatively large and has a small impact on the gas ratio, so it is less affected by low-content gas, but the sensitivity is very low in reflecting the initial minor faults. The increment of dissolved gas is small and has a greater impact on the gas ratio, so it is more affected by low-content gas, but incremental analysis greatly reduces the impact of historical values, and has high sensitivity in reflecting initial minor faults. Since the denominator of the gas ratio in the triangular and pentagonal methods is the sum of part or all of the combustible gas, it is less affected by low-content gas, and the change in dissolved gas can be used to identify defects more accurately. In this paper, incremental screening is selected.

3.1 Analysis of incremental data samples
Select 245 groups of data objects whose dissolved gas increase is greater than the minimum reliable value (10μL/L) and ethylene and acetylene have increased (>1μL/L). Among them, 20 groups of data objects are confirmed to be faulty after inspection, and this group of data is selected as Typical sample.

Calculate the C2H4/C2H2 value of each group of samples. A total of 20 groups with C2H4/C2H2≥1.0 are all on-load tap-changers that have been checked and confirmed to have faults, and they are...
classified as abnormal groups. The remaining 225 groups of data subjects C<sub>2</sub>H<sub>4</sub>/C<sub>2</sub>H<sub>2</sub>&lt;0.5, are summarized as the normal group. Finally, calculate the triangle coordinates and the pentagonal coordinates of the normal group and the abnormal group respectively, and draw them in the triangle and the pentagon, as shown in Figure 5.

In the triangle, the number of normal group objects entering the normal area numbered N is 138 groups; In the abnormal group, half (10 cases) of the subjects entered the T3 high temperature and overheating area, and nearly half (8 cases) of the subjects entered the X3 high-energy discharge area. The reason for the remaining 2 cases entering the N zone is that the three-phase adjustment time is quite different, and there is no ablation of the contacts or damage to the transition resistance. This result shows that when the DGA analysis data is incremental data, the triangle method can realize the identification of the on-load tap changer fault and normal state.

In the pentagon, the distribution of objects in the normal group is relatively concentrated, with 212 objects falling into the low-energy discharge (normal) area numbering D1, and 11 objects falling into the high-energy discharge area numbering D2; Objects in the abnormal group have a wide range of distribution, 4 cases of objects fall in the low-energy discharge (normal) area numbered D1, 5 cases of objects fall into the high-energy discharge area numbered D2, and 9 cases of objects fall in the number T3 high temperature and overheated area. This result shows that when the DGA analysis data is incremental data, the pentagon can realize the identification of the fault and normal state of the on-load tap changer. See Table 4 and Table 5 for the accuracy of Duval triangle and Duval pentagon method when using incremental data.

| Fault type | Critical result | The actual amount | Correct rate(%) |
|------------|-----------------|-------------------|----------------|
| N          | 138             | 225               | 61.3           |
| T3         | 10              | 12                | 83.3           |
| X3         | 8               | 8                 | 100            |
| T2         | 0               | 0                 | -              |
| D1         | 152             | 0                 | -              |
| X1         | 17              | 0                 | -              |

| Fault type | Critical result | The actual amount | Correct rate(%) |
|------------|-----------------|-------------------|----------------|
| S          | 2               | 0                 | -              |
| D1         | 215             | 225               | 95.5           |
| D2         | 17              | 8                 | -              |
| T3         | 9               | 12                | 75.0           |
| T2         | 0               | 0                 | -              |
| T1         | 2               | 0                 | -              |

In the analysis using incremental data, the pentagonal D1 area is selected as the normal area, and the correct rate of the pentagon to determine the normal state of the component is 95.5%. In contrast, the correct rate of the triangle to determine the normal state of the component is 61.3%. The correct rate of the polygonal shape to judge high temperature overheating is 75%, and the correct rate of the triangle to judge high temperature overheating is 83.3%.

3.2 Analysis of total data samples
Select the total amount data corresponding to 225 groups of normal objects and 20 groups of abnormal objects, calculate the triangle coordinates and pentagon coordinates of the two groups of objects, and draw them in the triangle and the pentagon. The results are shown in Figure 6.
According to the statistical results in Table 6 and Table 7, the total number of normal objects falls into the two regions of the triangle N and D1, of which 174 are in the N region and 47 are in the D1 region. The correct rate of triangle identification in the normal state is 77.3%. Except for the two abnormal objects, the rest of the abnormal objects fell in the X3 and T3 areas, and the accuracy of the triangle to identify the abnormal state was 90%. In the pentagon, the normal object falls in the D1 area of the pentagon. The number of recognition is 227, and the actual number is 225. The correct rate of identifying the normal state is close to 100%. The abnormal object falls into the D2 and T3 areas, and there are two cases of frequently operating the tap switch to enter D1. The correct rate of identifying the abnormal state is 85%. This shows that using the pentagon method to analyze the total data, the accuracy of correctly identifying the load tap status is better than the triangle method.

The above comparison results show that the pentagon can also realize the analysis and judgment of the dissolved gas in the insulating oil of the on-load tap changer. The characteristic point of the normal tap changer is located in the low-energy discharge area numbered D1, and the D1 area is marked as the normal area. In the analysis using total data, the correct rate of the pentagon to judge the normal state of the component is close to 100%, the correct rate of the triangle to judge the normal state of the component is 77.3%, and the correct rate of the pentagon to judge the high temperature and overheat is 100%. The correct rate of discharge is 62.5%. The accuracy rate of the triangle for judging high temperature and overheating is 83.3%, and the accuracy rate for judging high-energy discharge is 100%.

4. Application of Duval Pentagon Method in OLTC Diagnosis of Converter Transformer
In order to further verify the effectiveness of the Duval pentagon method in diagnosing OLTC status, a DGA analysis was carried out on the on-load tap changer of the converter transformer of an UHV converter station to determine whether the tap changer is abnormal. Table 8 shows. The 12 on-load tap-changers have been in operation for just one year, so the total amount of dissolved gas in the oil is
equal to the increment. The characteristic points of each on-load tap-changer are drawn in a triangle and a pentagon respectively, and the results are shown in Figure 7. Shown.

Fig.7 Fault interpretation results of Test value Using Duval Pentagon and Duval Triangle

5. Application of Duval Pentagon Method in OLTC Diagnosis of Converter Transformer

In order to further verify the effectiveness of the Duval pentagon method in diagnosing OLTC status, a DGA analysis was carried out on the on-load tap changer of the converter transformer of an UHV converter station to determine whether the tap changer is abnormal, Table 8 shows. The 12 on-load tap-changers have been in operation for just one year, so the total amount of dissolved gas in the oil is equal to the increment. The characteristic points of each on-load tap-changer are drawn in a triangle and a pentagon respectively, and the results are shown in Figure 7. Shown.

The data of dissolved gas in oil and the corresponding ratio of the selected 12 tap-changers are shown in Table 8. The C2H4/C2H2 values of 4 abnormal tap-changers are all greater than 1.8. After endoscopic inspection, there were severe ablation of the internal moving contacts of 3 tap changers, and there was slight creepage at the metal screw of the tap changer switching core, the manufacturer replaced these tap-changers, and no abnormality was found in the remaining one. The result of the Duval pentagon method is tested by the characteristic gas ratio method, but it is different from the Duval triangle method. The actual inspection proves that the Duval pentagon method is superior to the Duval triangle analysis method in the diagnosis of the on-load tap changer status. According to the zoning results of the pentagon method, 7 of all 12 on-load tap-changers are in the low-energy discharge zone numbered D1, and the remaining 5 are in the zone numbered S.

| Number | H2 (µL/L) | C2H2 (µL/L) | C2H4 (µL/L) | CH4 (µL/L) | C2H6 (µL/L) | C2H4/C2H2 |
|--------|----------|-------------|-------------|-----------|-------------|-----------|
| 1      | 100.29   | 15.45       | 20.64       | 33.96     | 3.15        | 1.34      |
| 2      | 86.62    | 10.38       | 14.06       | 31.05     | 3.02        | 1.35      |
| 3      | 36.31    | 5.73        | 8.24        | 13.23     | 1.10        | 1.44      |
| 4      | 50.98    | 6.62        | 9.54        | 16.61     | 1.31        | 1.44      |
| 5      | 41.15    | 6.80        | 9.98        | 15.10     | 1.34        | 1.47      |
| 6      | 128.04   | 9.92        | 15.39       | 30.14     | 2.41        | 1.55      |
| 7      | 69.41    | 8.87        | 14.20       | 20.79     | 2.84        | 1.60      |
| 8      | 122.98   | 7.97        | 13.24       | 27.79     | 1.90        | 1.66      |
| 9      | 68.69    | 3.63        | 6.67        | 21.84     | 1.29        | 1.84      |
| 10     | 94.19    | 4.39        | 8.30        | 26.01     | 1.93        | 1.89      |
| 11     | 20.29    | 0.97        | 2.12        | 6.26      | 0.18        | 2.18      |
| 12     | 29.62    | 0.11        | 0.58        | 6.52      | 0.16        | 5.17      |
6. Conclusion

This paper uses the Duval pentagonal analysis method to analyze the dissolved gas samples in the insulating oil of the on-load tap changer, and compares the judgment effect with the Duval triangle analysis method. The Duval pentagonal analysis method is applied to the UHV converter transformer to diagnose the state of the on-load tap changer. The specific conclusions are as follows:

1) The analysis of 700 sets of operating data shows that the Duval pentagon method can cluster the on-load tap-changers by using the dissolved gas in the oil, and D1 in the pentagon can be regarded as the normal area of the OLTC state.

2) The analysis of 245 sets of typical sample data shows that under the total data or incremental data, the Duval pentagon method can effectively distinguish the normal and abnormal state of OLTC, and it has a higher accuracy rate than the Duval triangle method.

3) The practical application of 12 UHV converter transformer on-load tap-changers shows that the Duval pentagon method is accurate and effective in the diagnosis of the OLTC state.

References

[1] NIE Dedxin, DENG Jiangang, ZHANG Lianxing, et al. Developing processes of direct current partial discharge of defects on ultra high voltage converter transformer oil-paper insulation[J]. High Voltage Engineering, 2012, 28(12): 3249-3260.

[2] Rong Jingguo. Research on optimal operation and control method of AC / DC hybrid system for energy Internet [D]. North China Electric Power University (Beijing), 2019

[3] TU Renchuan, WANG Sheng, GUAN Hongbing, et al. Research of the Reactive Power Control Strategy in Nuozhadu UHVDC Project[J]. Southern Power System Technology, 2013, 7(06): 31-36.

[4] Lu Ming Ming. Research on fault rate model and fault diagnosis of oil immersed transformer [D]. Zhejiang University, 2014.

[5] SONG Yu-mei, SU Zhen-xi, QI Jiong, et al. Measurement and Analysis of Oil Properties of UHV AC Transformer with OLTC[J]. Transformer, 2016, 53(10): 56-59.

[6] WANG Fenghua, XIE Fangxin, WANG Weiguo, et al. Effect of Insulation Oil on Vibration Signals of On-load Tap-changer of Power Transformer[J]. High Voltage Engineering, 2019, 45(10): 3273-3279.

[7] Duan Ruochen, Wang Fenghua, Zhou Lidan, et al. Mechanical Condition Detection of On-Load Tap-Changer in Converter Transformer Based on Narrowband Noise Assisted Multivariate Empirical Mode Decomposition Algorithm[J]. Transactions of China Electrotechnical Society, 2017, 32(10): 182-189.

[8] Hazlee Azil Illias, Kai Choon Chan, Hazlie Mokhlis. Hybrid feature selection–artificial intelligence–gravitational search algorithm technique for automated transformer fault determination based on dissolved gas analysis[J]. IET Generation, Transmission & Distribution, 2020, 14(8): 1575-1582.

[9] R. Nagarajan, S. D. Vyas. Modern trend in Dissolved gas analysis in transformer and OLTC[J]. Water and Energy International, 2019, 61r (12).

[10] Ivanka Hohlein-atanasova, Rainer Frotscher. Relevance and Importance of the Carbon Oxide Gases and their Ratio for the Interpretation of Dissolved Gas Analysis In Transformers and Tap Changers[J]. Water and Energy International, 2012, 69(3).

[11] LI Wei, LIANG Nai-feng, ZHANG Yong, et al. Discussion on Comparison and Validation of National Standard and Industry Standard in Fault Diagnosis of Dissolved Gasses in Transformer Oil[J]. Transformer, 2014, 51(09): 15-19.

[12] LIU Xueli, LI Jinzhong, GAO Fei, et al. Key technology research for vacuum type on-load tap-changer of ±800 kV direct current convertor transformers[J]. Proceedings of the CSEE, 2016, 36(19): 5350-5356+5417.

[13] QIN Yu, HUANG Huihong, FANG Jian, et al. Fault Diagnosis of Transformer Based on FCM and Improved PCA[J]. High Voltage Apparatus, 2018, 54(12): 262-267.
[14] Mohd Shahril Ahmad Khiar, Yasmin Hanum Md Thayooob, Young Zaidey Yang Ghazali, et al. Diagnosis of OLTC via Duval Triangle Method and Dynamic Current Measurement[J]. Procedia Engineering, 2013, 68.
[15] Abdelaziz Lakehal, Fouad Tachi. Bayesian Duval Triangle Method for Fault Prediction and Assessment of Oil Immersed Transformers[J]. Measurement and Control, 2017, 50(4).
[16] Jeeng Min Ling, Ming Jong Lin, Chao Tang Yu. Transformer Fault Diagnosis with the Duval Triangle and Heuristic Techniques[J]. Applied Mechanics and Materials, 2014, 3044.
[17] Luiz Cheim, Michel Duval, Saad Haider. Combined Duval Pentagons: A Simplified Approach[J]. Energies, 2020, 13(11).