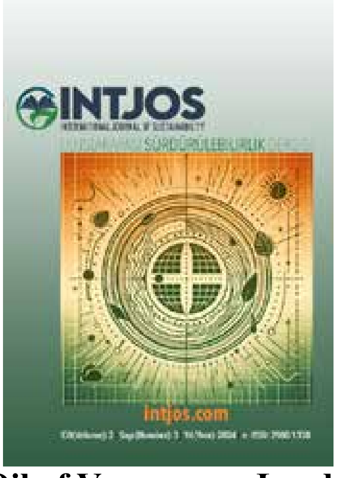

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Determination of Dissolved Gas Limits in Insulating Oil of Vacuum on-Load Tap Changer In Power Transformers

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ABSTRACT

In power transformers, which are widely used in the electricity transmission system, voltage adjustment is performed by means of on-load tap changers (OLTC). One of the commonly used types of on-load tap changers is vacuum type on-load tap changers. In vacuum type on-load tap changers, while tap-changing under load, flammable gases occur in the insulating oil inside the tap changer chamber due to malfunction of vacuum tubes, mechanical breakdowns or fixed and movable bypass contact switches in the oil. Failure detection can be made with limit values and analysis methods determined by looking at the types and amounts of these flammable gases. In this study, vacuum, resistance and separate compartment (VRS) type, on-load tap changers used in power transformers of Turkish Electricity Transmission Corporation (TEİAŞ) are discussed. The warning limits of gases dissolved in mineral oil in these VRSs are determined by using the outlier analysis method in IEEE C57.139 standard. In addition, the N1 region within the X1 region for these OLTCs in the duval triangle2 is determined as the normal operating region.

Keywords: *On-load tap changer, dissolved gas, duval triangle, outlier.*

ÖZET

Elektrik iletim sisteminde yaygın olarak kullanılan güç transformatörlerinde gerilim ayarı, transformatörün dönüştürme oranının yük altında kademe değiştiriciler (YAKD) vasıtasıyla yapılmaktadır. Yükte kademe değiştiricilerin yaygın olarak kullanılan tiplerinden birisi de vakumlu tipte yükte kademe değiştiricilerdir. Vakumlu tip yükte kademe değiştiricilerde yük altında kademe değiştirirken, kademe değiştirici haznesinin içerisindeki yalıtım yağında vakum tüplerinin arızalanması, mekanik bozulmalar veya yağın içerisinde bulunan sabit ve hareketli baypas kontak anahtarlarından kaynaklı olarak yanıcı gazlar meydana gelmektedir. Bu yanıcı gazların türlerine ve miktarlarına bakılarak belirlenen limit değerler ve analiz yöntemleri ile arıza tespiti yapılabilmektedir. Bu çalışmada, Türkiye Elektrik İletim Anonim Şirketi (TEİAŞ)'a ait güç trafolarında kullanılan vakumlu, dirençli ve ayrı bölmeli (VRS) tip, yükte kademe değiştiriciler ele alınmıştır. Bu YAKD' ler içerisindeki mineral yağda çözünmüş gazların uyarı limitleri, IEEE C57.139 standardındaki aykırı değer analiz yöntemi kullanılarak tespit edilmiştir. Ayrıca duval üçgen2' de bu YAKD'ler için X1 bölgesi içerisindeki N1 bölgesi, normal çalışma bölgesi olarak belirlenmiştir.

Anahtar kelimeler: *Yük altında kademe değiştirici, çözünmüş gazlar, duval üçgen, aykırı değer*

INTRODUCTION

Power transformers are vital components in electricity transmission networks. For voltage adjustment in power transformers, it is necessary to change the number of turns of the windings. Tap changers are used in power transformers to adjust the winding ratio of the windings to keep the voltage on one side at a desired level. This can be done either on-load using an on-load tap changer or off-load using a de-energized tap changer *(Al-Ameri et al., 2021).* On-load tap changers are broadly classified as arc-switched (A) and vacuum tube (V). According to the transition elements, on-load tap changers are also divided into resistor type (R) and reactor type (X). Under load tap changers are available in two different configurations: Diverter switch and tap selector in different oil compartments (Separate) (S), diverter switch and tap selector in the same oil compartment (Combined) (C) *(CIGRE, 2010).*

It is observed that 31% of power transformer failures are caused by tap changer failures *(Tenbohlen, 2017).* Insulation in electrical equipment is mostly composed of liquid or solid insulation materials. It is important to know the deterioration conditions of these insulation materials to prevent failures. Since there is no cellulosic material inside the tap changer, monitoring the deterioration of the oil and gas analysis contributes to prevent failure. To minimize oil degradation in tap changers, vacuum type tap changers with innovative switching mechanisms are used *(Hohlein, Atanasova and Frotscher, 2010).*

The vacuum on-load tap changer represents the development direction of the OLTC due to its excellent insulation performance, high insulation recovery rate, long service life and no carbonization of the insulating oil *(Pan et al., 2020).* Shen Dazhong suggested that the addition of vacuum technique to the tap switch under a load would allow 300.000 operations to be performed without manual maintenance, while saving the volume and weight of the device. The advantages of the OLTC with vacuum interrupter are low maintenance costs, fast recovery of insulation power and the elimination of oil contamination caused by the arc under oil *(Shen, Axel, and Dieter, 2011).*

Insulating oils are a mixture of hundreds of hydrocarbon molecules of different structures and types. Some chemical groups such as CH, CH_2, CH_3 are attached to carbon atoms and oil molecules are formed. If sufficient electrical or thermal energy is released during electrical or thermal faults and events, some of the bonds between the C - C and C - H atoms in the oil molecules are broken and small formations such as H, CH_2, CH_3 and C are formed. These events take place through a rapid and complex series of reactions. Depending on the amount of energy released, new molecules with different structures are then formed from these small groups. Carbon monoxide *(CO)* and carbon dioxide (CO_2) gases are also formed during oil oxidation *(Sezer, 2014).*

In vacuum type OLTCs, flammable such as methane (CH_4) ethane (C_2H_6), ethylene (C_2H_4) and acetylene (C_2H_2) gases can be generated due to failure of vacuum tubes, mechanical breakdowns or problems with fixed and movable bypass contact switches and reversing switches in the oil. The amounts of flammable gases depend on the design of the OLTC, the number of switchings and the environmental conditions. Overload operation of transformers and increasing the number of switching can increase the amount of flammable gases. Particularly acetylene is formed in very small amounts in vacuum type OLTCs. In cases where acetylene and other flammable gases are low, gas ratios may not be useful to identify faults. The outlier analysis method specified in the IEEE C57.139 standard can be used to determine the warning limits of flammable gases in vacuum type OLTCs *(IEEE C.57.139, 2015).*

In addition, one of the most widely used methods to determine the type of failure in tap changers is duval triangle2 *(IEEE C.57.139, 2015; CIGRE, 2019).* Duval triangle1 is used to detect faults from dissolved gases in transformer oils, duval triangle3 is used to detect faults in transformers filled with non-mineral oil, and duval triangles4 and 5 are used to detect low temperature faults in transformers *(Duval, 2008).* The normal gas limits in vacuum OLTCs usually show the combustible gas ratios corresponding to the N3 region in duval triangle2. When the amounts of combustible gases are very low, they may not correspond to the N3 region *(CIGRE, 2019).* Depending on the type of the vacuum OLTC, the user can set new normal operating *zones (IEEE C.57.139, 2015).* Hydrogen, acetylene and ethylene gases are used for evaluation in vacuum OLTCs. Even several hundred ppm of hydrogen gas can be released each year. At acetylene values lower than 5 ppm, no evaluation is performed according to gas ratios *(ABB Power Technologies, 2004).*

In their study, Naderian et al. indicate the operating condition of the tap changer by determining the combustible gas factor (CGF) for the combustible gas generated in vacuum OLTCs and state that if the CGF is less than 1.2, the condition of the tap changer is good. Naderian et al. determined dissolved gas analysis (DGA) factor limits to determine whether the DGAs are working properly by giving weight factors to the gases according to the gas analysis values of 3 different types of DGAs *(Naderian, 2008).*

In modern vacuum type OLTCs, the amount of sparking gas is usually in the single digits. If there is excessive sparking, this indicates erratic behavior of the contact system or potential fluctuations at the electrodes. CO and CO_2 gases are used to indicate the beginning of thermal oil aging. Since CO and CO_2 gases are formed at very low temperatures, they are due to transition resistances and provide sensitive criteria for the assessment of thermal effects in the OLTC oil. The CO_2 / CO ratio can be used to detect overheating resistors or to identify contacts that are starting to overheat *(CIGRE, 2019; Frotscher, 2017).* The CO_2 / CO ratio is between 4 and 15 in vacuum type OLTCs (Shen, Axel, and Dieter, 2011). When the vacuum tube is exploded in a vacuum type OLTC, an excessive amount of pressure is generated. In this case, a large amount of arc gases are produced and the fault can be easily determined from these gases *(Frotscher, 2017).*

In the study specified in the IEEE C57.139-2015 standard, in dissolved gas samples taken from the oil of a vacuum type OLTC with type VXAB in the United States, they set warning limits for only two combustible gases because the limits of combustible gas amounts were low. According to these limits, excessive increases in flammable gases were detected in the vacuum type OLTC monitoring. When they opened the vacuum type OLTC, it was found that the B phase contacts were burnt. After repair, an excessive decrease in flammable gases was observed *(IEEE C.57.139, 2015)*. In the study conducted by CIGRE groups, the duval triangle was used to determine whether there was a malfunction in the VRC vacuum type OLTC according to the rate of increase in flammable gases and it was determined that there may be a malfunction. In order to detect the fault, the OLTC was disassembled and it was determined that the fault was caused by the lack of grounding of a shielding ring *(CIGRE, 2019)*.

In Frotcher's study, gas limits were determined from 315 gas data in VRS vacuum type OLTC. The warning limit (U2) was calculated as 171 ppm for hydrogen gas, 9,6 ppm for acetylene, 51 ppm for methane, 11 ppm for ethane, 16 ppm for ethylene and 528 ppm for CO . It was also stated that additional regions in the duval triangle2 can be used to interpret combustible gases in vacuum OLTCs and for VRS and VRC vacuum type OLTC, the N3 region in the duval triangle2 can be used *(Frotscher, 2018*). In another study conducted by Frotcher, it was determined that the acetylene gas value in MR brand vacuum type OLTCs can vary according to the OLTC type in 1000 operations and is below 4 ppm. In addition, based on field experiences, it is recommended to examine the OLTC after the acetylene gas level exceeds 50 ppm *(Frotscher, 2016)*.

In this study, it is aimed to determine the normal operating limits of VRS vacuum type under load tap changers used in power transformers according to the values of flammable gas dissolved in oil during operation, using the outlier analysis method, and the normal region using the duval triangle2.

MATERIAL AND METHOD

The on-load tap changer, from which the oil-dissolved gas analysis data are taken, is vacuum, resistance and separate chamber type. In this study Gas analysis results of 290 OLTCs taken from different substations of VRS vacuum type under load tap changers used in TEİAŞ power transformers were used as data. Gas limits were tried to be determined according to IEEE C57.139 standard. This method uses statistical outlier calculation to determine gas limits *(IEEE C.57.139,2015)*. The data obtained are sorted from the smallest value to the highest value. The data is divided into quarters. The first quartile is called Q_1, the second quartile is called Q_2 (median) and the third quartile is called Q_3 (Figure 1).

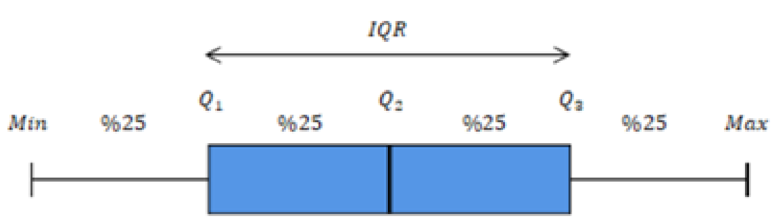

Figure 1. Box Plot of Normal Distribution

$$Q_1 = x_k + d(x_{k+1} - x_k) \quad (1)$$

Where,

- *d* is the fractional part of the number calculated as 0.25(N+1),
- N is the number of data points in the set,
- χ_k is the value of the kth data point, counting up from the smallest value,
- χ_{k+1} is the value of the k+1th data point, counting up from the smallest value.

Similarly,

- The second quartile, Q_2 also known as the median, is calculated from 0.5(N+1),
- The third quartile, Q_3, also known as the 75th percentile, is calculated from 0.75(N+1).

The interquartile range IQR is defined as shown in Equation 2 (IEEE C.57.139, 2015)

$$IQR=Q_3-Q_1 \quad (2)$$

$$U_1=Q_3+3\ IQR/2 \quad (3)$$

$$U_2=Q_3+3IQR \quad (4)$$

U_1 is recommended as the limit between normal and abnormal values and U_2 as the warning *(Frotscher,2017)*.

When gas analysis results are evaluated, firstly the gas amounts are compared with the determined limits. Then, if at least one gas is above the limits or there is a significant increase compared to the previous analysis, gas ratios (Equation 5.6.7.) are calculated. Then, if a fault is found or suspected, interpretation methods are used to determine the type of fault. One of the fault interpretation methods is the duval triangle *(Sezer,2014)*. The duval triangle method was introduced by Michel Duval in 1974 *(Duval, 1974)*. The duval triangle 2 is formed by using methane, ethylene and acetylene measurement values in Equation 5.6.7.

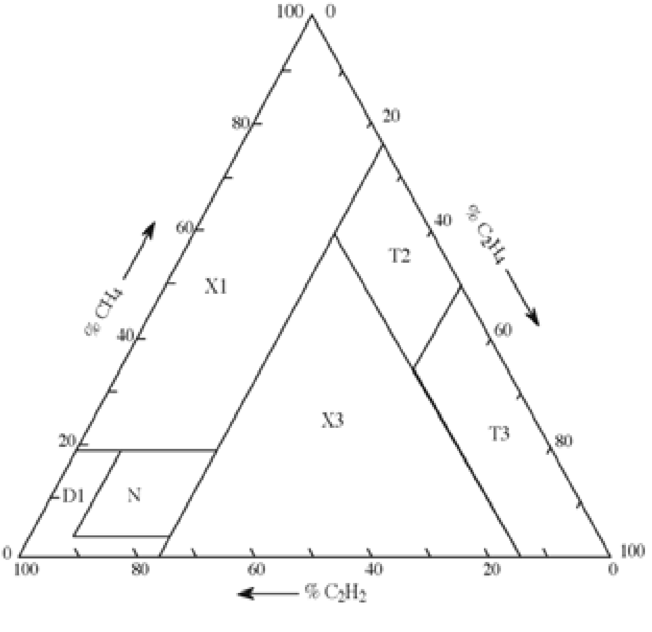

Figure 2. Duval Triangle2 Regions

$$\%CH_4 = \frac{CH_4}{CH_4 + C_2H_4 + C_2H_2} \quad (5)$$

$$\%C_2H_4 = \frac{C_2H_4}{CH_4 + C_2H_4 + C_2H_2} \quad (6)$$

$$\%C_2H_2 = \frac{C_2H_2}{CH_4 + C_2H_4 + C_2H_2} \quad (7)$$

RESULTS

For this study, 290 oil samples were taken from the oils of VRS vacuum type under load tap changers used in TEİAŞ power transformers, which were manufactured between 2013 and 2021. The gas values in the oil samples were obtained by gas chromatography using the “C” method of ASTM D3612 standard *(ASTM D 3612-02, 2009)*. Analyses were performed using Statistical Package for Social Sciences-SPSS. Gas analysis results of the oil samples are shown in Figure 3.

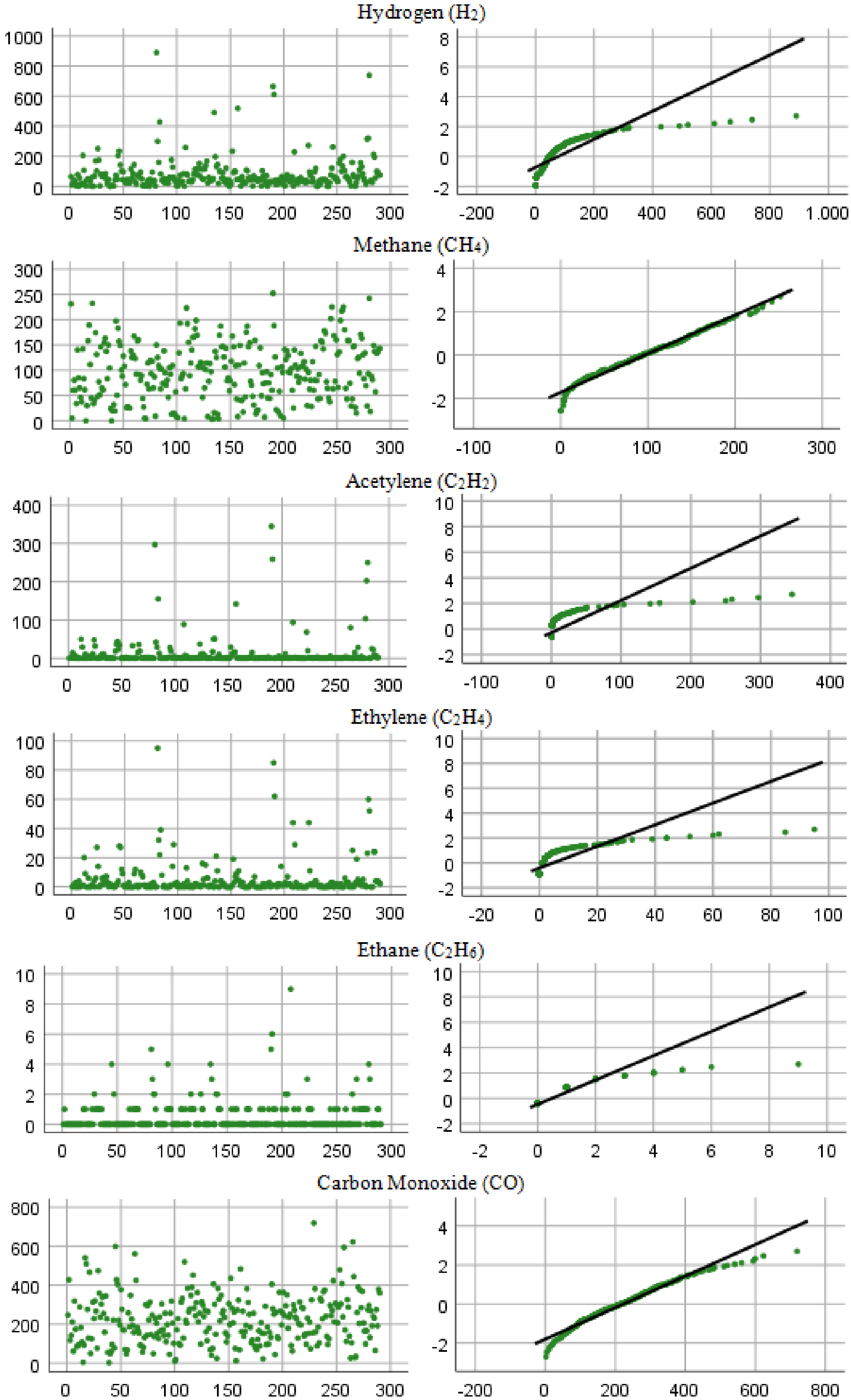

Figure 3. Data on Gases and Q-Q Plots

As a result of the normality test, it was seen that the *p* value of methane gas was greater than 0,05. Therefore, it can be said that methane gas has a normal distribution. It is seen that other gas observation results do not meet the assumption of normal distribution. This is due to the presence of outlier(s) in the gas observation values. It is seen in Figures 3 and 4 that hydrogen, acetylene, ethylene, ethane and carbon monoxide gases, which do not have a normal distribution, contain outliers.

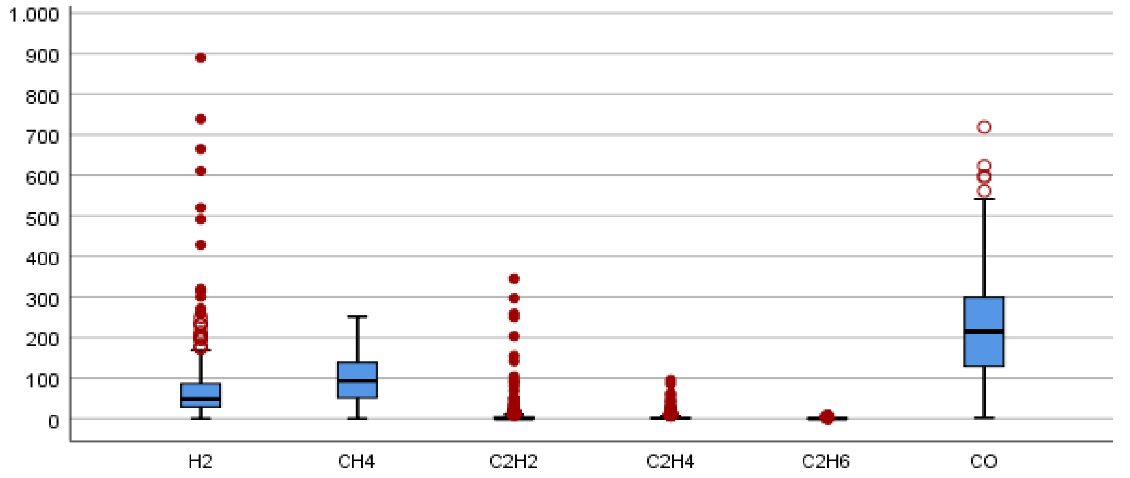

Figure 4. Box Plots for Gases

Outlier calculations of dissolved gas analysis values of oils were performed according to IEEE C57.139-2015 standard. Each gas was evaluated within itself and limits were determined. The analysis results of the gas data are shown in Table 1.

Table 1. VRS vacuum type OLTC values (ppm)

	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO
Min	0	0	0	0	0	2
Q_1	28,5	50,75	0	0	0	129
Q_2	48	93,5	0	1	0	215
Q_3	86,75	138,5	4	3	1	299
Max	890	252	345	95	9	719
IQR	58,25	87,75	4	3	1	170
U_1	174,125	270,125	10	7,5	2,5	554
U_2	261,5	401,75	16	12	4	809

According to the results obtained from the gas data, gas results up to U_1 can be considered normal. Warning limits U_2 261,5 ppm for hydrogen, 401,75 ppm for methane, 16 ppm for acetylene, 4 ppm for ethane and 809 ppm for carbon monoxide are acceptable. For vacuum type OLTC above these values, detailed tests and investigations should be carried out.

The ratios of methane, ethylene and acetylene from 227 VRS vacuum type OLTC oil-dissolved gas data below U_1 of 290 VRS vacuum type OLTC oil-dissolved gas data according to Equation 5.6.7. placed in duval triangle 2 are shown in Figure 5. Each point in Figure 5 shows the combustible gas ratios of one vacuum type OLTC. Only 1 of the points in Figure 5 is in the T2 region. This may be due to the fact that the gas values (CH_4, 5 ppm, C_2H_4, 2 ppm, C_2H_2, 1 ppm) are very low and the acetylene value may not be evaluated because it is below 5 ppm *(CIGRE, 2019).* The other 226 gas analysis ratios are in the X1 region of the duval triangle 2.

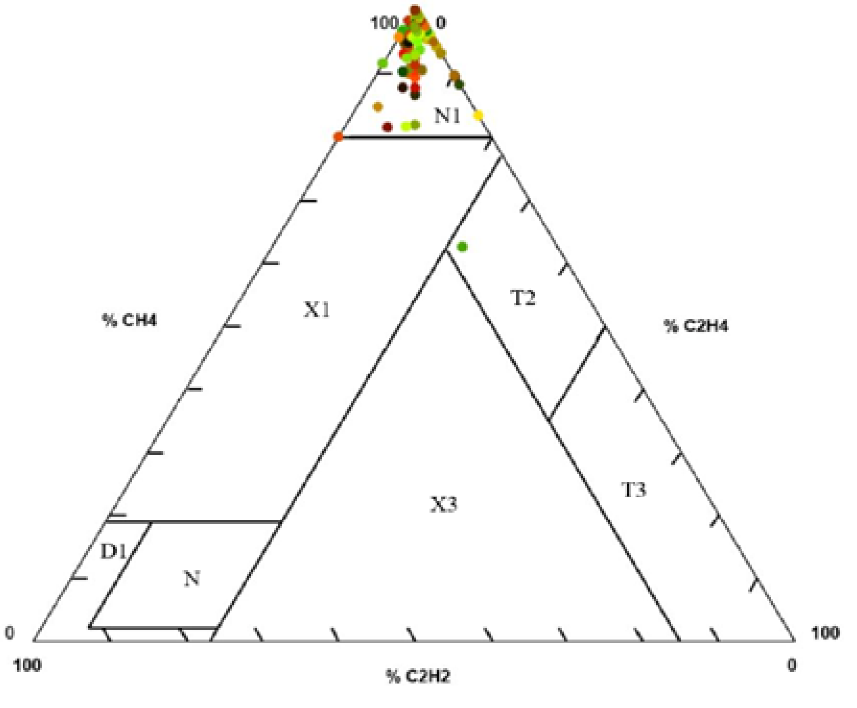

Figure 5. Placement of methane, acetylene and ethylene gas percentages in the duval triangle2

The IEEE C57.139-2015 standard states that for OLTCs of different manufacturers, different regions in the duval triangle can be assigned as the normal operating region (Shen, Axel, and Dieter, 2011). Therefore, according to the data placed in the duval triangle2 in Figure 5, the N1 region of density can be used as the new normal region for the VRS vacuum type OLTC. By placing the gas values above the limits in the the duval triangle2, if the gas ratios are found outside the N1 region in the duval triangle2, it should be evaluated that there may be a malfunction in the OLTC and a detailed examination should be performed in the OLTC.

CONCLUSION

Vacuum on-load tap changers are widely used in power transformers with the development of technology. Gas analysis provides a good diagnostic opportunity to detect the faults of vacuum type OLTC. Therefore, it is important to determine whether the combustible gases in the insulating oil are normal or not. In this study, it is tried to determine the warning limits of VRS vacuum type OLTC according to the dissolved gas values in the oil. It is shown that the N1 region in the duval triangle2 can be used as the normal region while investigating the fault finding in the VRS vacuum type OLTC. It is intended to contribute by determining the normal operating limits of vacuum type OLTCs, which are widely used in power transformers, by gas analysis. In particular, gas values will be monitored periodically and will contribute to the determination of the presence of malfunctions in VRS vacuum type OLTCs above the specified limits according to flammable gas values.

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