Research Journal of Applied Sciences 6 (6): 354-360, 2011
ISSN: 1815-932X

Effect of Electric Arc on Dielectric Characteristic and Dissolved Gases of Mineral Oil

Suwarno and Santosh
School of Electrical Engineering and Informatics,
Institut Teknologi Bandung, Jl. Ganesha 10, 40132 Bandung, Indonesia

Abstract: Arcing is one of the most dangerous faults in a power transformer because it release large amount of energy. Arcing result in scission in chemical bonds of liquid insulation and afterward the recombination of those broken bonds create solid contaminants such as carbon oxides and gases. The appearance of these substances enhances the degradation of the liquid insulation. In long term it may cause failure. This study reports the experimental results on the effects of electric arc on dielectric characteristics such as breakdown voltage, resistivity, dissipation factor and dissolved gases in mineral transformer oil. The electric arc was generated using multi needles-plane electrode system under AC applied voltage with frequency of 50 Hz. The arc magnitude was adjusted using different gap between electrodes. The amount of arc energy was also adjusted by using different arcing period from 0-30 min. The experimental results indicated that breakdown voltage significantly reduced by applying electric arc. Similar behavior was observed for oil resistivity. The arc application enhanced the dielectric losses factor (tan δ). Very small change was observed on dielectric constant.

Key words: Arcing, dielectric characteristic, partial discharge, dissolved gas, chemical bond, Indonesia

INTRODUCTION

Transformer is a important component in power system. Transformer very often experience failure, a massive factor which cause the failure in insulation system. Since, many years ago transformer use liquid insulation as insulation material. The most used liquid insulation is mineral oil made out of crude oil. Mineral oil is a mixture of hydrocarbon molecule consist of paraffin (40-60%), naphthenic (30-50%) and aromatic (5-20%) (Abeysundara *et al*., 2001). The advantages of using mineral oil are have good ability in heat dissipation, its price relatively cheap and easily get.

In using period, liquid insulation can experience degradations which are electrically and thermally (Ilyas and Rubadi, 2008). Arcing is the most dangerous disturbance in transformer because it release large amount of energy. Arcing results by overvoltage which commonly causes by lightning, switching and fault in phase line. Arcing especially occurs in sharp edged parts in transformer. The arc may excite the atom and during recombination released the energy in the form of photon (Palmer *et al*., 2000). The arc with associated energy may degrade the transformer oil and reduce the performance (Carraz *et al*., 1995; Masala and Lesaint, 2001). Arcing causes decreasing in liquid insulation quality and raise the posibility of failure. Arcing results in chemical bond breaking and then afterward recombine create contaminants such as solid particel and gas. The appearance of these contaminants causes degradation in insulation consequently disturbs transfoermer performance even results in failure.

Insulation condition can be known by knowing dielectric characteristic, partial discharge, dissolved gas and hemical bond of that insulation. Arcing change dielectric characteristic namely breakdown voltage, dielectric loss factor, capacitance and relative permitivity and resistivity. Besides, arcing also change partial discharge characteristic namely charge, inception voltage, pulse number and PD pattern. In addition to those arcing also cause change in chemical bond composition and fomation of dissolved gases. Dissolved gases fomed are combustible gas. These gases are very dangerous because flammable. These gases have certain pressure. If this pressure high can cause leak in transformer. This leak can cause fire in transfomer as those gas react with oxygen under thermal or electrical energy.

MATERIALS AND METHODS

Oil samples: Oil samples used were mineral type transformer oils widely used in 150 kV transformers in Indonesian Electric Power company i.e., PT. PLN Persero.

Arcing treatment: Test circuit consists of a step-up traformer used to increase grid input voltage 220 V.

Corresponding Author: Suwarno and Santosh, School of Electrical Engineering and Informatics, Institut Teknologi Bandung, Jl. Ganesha 10, 40132 Bandung, Indonesia

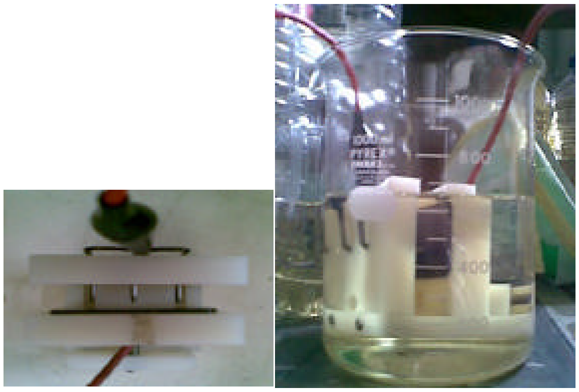

Fig. 1: Needle plane electrode arrangement

Fig. 2: Physical appearance of oil samples

Resistance R for reducing current which flow when breakdown occured and test cell. It is well known that needle-plane electrode system is a suitable arrangement to generate discharges (Suwarno, 2009). Test cell consisted of a glass and neddle-plane electrode. The configuration has three steel needles and a plane electrodes. Electrode spacing was controled by using screw and bolt to got varying arcing voltage. The bigger electrode spacing the bigger arcing voltage can be obtained. The electrode arrangement is shown in Fig. 1.

Voltage value was controlled from control desk and voltage value at secondary side of transformer can be read in voltmeter on control desk. Arc voltage given on oil namely 15, 20 and 25 kV, respectively with arc duration of 10, 20 and 30 min.

The voltage of 15, 20 and 25 kV corelated with electrode spacing of 2, 4 and 6 mm. So, that produced 9 sample and with new mineral oil make 10 sample in total as shown in Table 1. The physical appearances of the samples are shown in Fig. 2. Those treatments could have given information about the effects of arc voltage and duration on dielectric characteristic and dissolved gas in mineral oil.

Breakdown Voltage (V_{BD}) experiment: Device used to determine the breakdown voltage was Liquid dielectric test, LD 60 from Phenix technologies. This device uses grid input of 220 V, 50 Hz with output voltage up to 60 kV. This device is completed with test cell which has bi-spherical electrodes as shown in Fig. 3. The voltage increase rate of 2000 V sec^{-1} eas used in accordance with breakdown voltage test standard of IEC 156 (1995).

Fig. 3: Bi spherical electrode for breakdown voltage measurement

Table 1: Sample and given treatment

Sample name	Voltage (kV)	Duration (min)
ARC0	0	0
ARC1	15	10
ARC2	15	20
ARC3	15	30
ARC4	20	10
ARC5	20	20
ARC6	20	30
ARC7	25	10
ARC8	25	20
ARC9	25	30

Relative permitivity (ε_r) and dielectric losses factor ($\tan \delta$) experiment: Equipments used was a two-terminal test cell Tettex instrument, a reference capacitor, tan δ meters and oscilloscope null indicator. This equipments use grid input 220 V, 50 Hz. Tests conducted by Schering bridge principle. Test standard is IEC 247 (2004). Tests were performed on each sample 5 times and then taken the average. Testing was conducted at room temperature.

Resistivity experiment (ρ): The equipment used was high resistance meter production of Hewlett Packard. This equipment uses grid input 220 V, 50 Hz. Tests used the plates electrode. The test standard are standard IEC 247 (2004). Tests were carried out on each sample 5 times and then taken the averaged. Testing was conducted at room temperature.

Dissolved Gas Analysis (DGA) experiment: This experiment was conducted using a gas chromatograph HP 6890 which is integrated with Automatic Liquid Sampler

Fig. 4: Gas chromatiograph for dissolved gas analysis

HP 7649 and a set of computer (PC) as shown in Fig. 4. Tests conducted on 10 samples based on ASTM standard D3612 (ASTM D3612-02, 2009).

RESULTS AND DISCUSSION

Breakdown voltage: Figure 5 shows values of voltage breakdown as a function of arc duration for three different arc voltage of 15, 20 and 25 kV.

From Fig. 5, it is clearly seen that breakdown voltage decreased when the arc duration and arc voltage increased. The lowest value of breakdown voltage occured when the mineral oil was subjected to arc voltage of 25 kV for 30 min that was sample ARC 9.

Provision of electric arc causes chemical bonds in the mineral oil broken off and then recombine to form carbon in the form of solid particles and gas bubbles. In addition, high electric field can also cause the electrons released from chemical bonds.

Carbon because of its high permitivity will be directed toward high electric field area between two electrodes so that at some point will bridge the two electrodes and then breakdown occurs. Gas bubble because of its low permitivity will withstand high electric field so that at some point will be broken to form bubbles which are smaller and numerous. At some point this bubble will be linked to form a bridge between the two electrodes and breakdown occur. Free electrons due to the high field will be accelerated, strike other molecules, release other electrons so that resulted in an avalanche and breakdown occur. The reduction of breakdown voltage may be due to the appearance of contaminants released by the arc exposed to the samples. The contaminants created by the arc would help in initiating the streamer especially when conductive particles existing in the liquids.

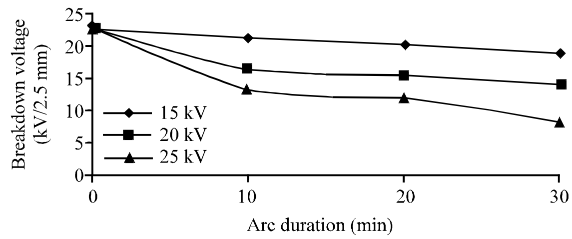

Fig. 5: Breakdown voltage as a function of arc duration at different arc voltages

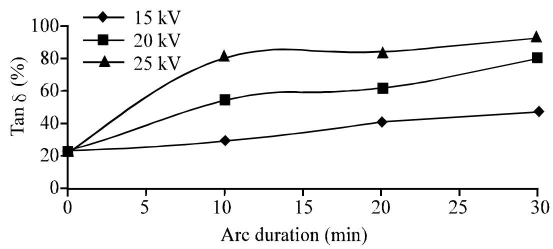

Fig. 6: Tan δ (%) as a function of arc duration at different arc voltages

Dielectric loss factor (tan δ): Figure 6 shows typical values of tan δ (%) as a function of arc duration for three different arc voltage of 15, 20 and 25 kV.

From Fig. 6, it is clear that the value of tan δ decreased when the arc duration and arc voltage increased. The lowest value of tan δ occurred when the mineral oil was subjected to arc voltage of 25 kV for 30 min that was sample ARC 9.

In general, dielectric loss is caused by free electrons or conductive particles in a dielectric material that causes the flow of conduction currents in the material. The following equation shows the relationship between tan δ with conductivity.

$$\tan\delta = \frac{\sigma}{2\Pi f\varepsilon} \quad (1)$$

Where:

σ = Conductivity of oil
ε = Permittivity of oil
f = Frequency

Provision of electric arc causes the formation of a conductive carbon and free electrons that cause oil conductivity increases and the increase of dielectric loss.

Capacitance (C) and relative permitivity (ε_r): Figure 7 and 8 shows values of capacitance and relative permitivity as a function of arc duration for three different arc voltage of 15, 20 and 25 kV. The Fig. 7 and 8 shows that the capacitance and relative permitivity slightly decreased with the arc duration and arc voltage. The lowest value of capacitance and relative permitivity occurred when the mineral oil was subjected to arc voltage of 25 kV for 30 min

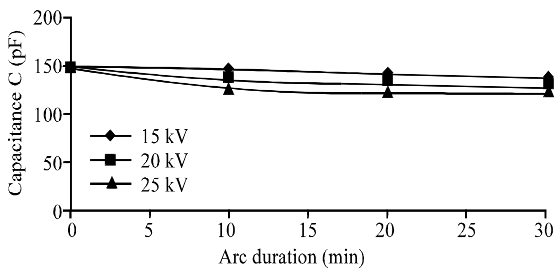

Fig. 7: Capacitance as a function of arc duration at different arc voltages

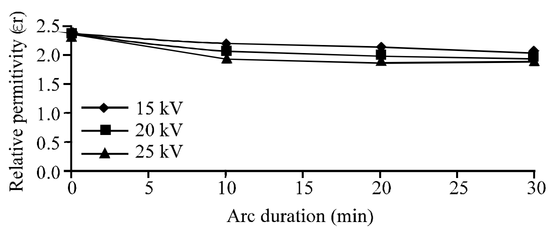

Fig. 8: Relative permittivity as a function of arc duration at different arc voltages

that was sample ARC 9. Capacitance expressed ability to store electrical energy (Palmer *et al*., 2000). While the value of the relative permittivity is proportional to the capacitance. Application of electric arc caused the formation of a conductive carbon and free electrons resulted in increase in dielectric loss, this because of increase in conduction current which means reducing the ability of materials to store energy. As a result the value of Capacitance (C) and relative permittivity (εr) declined. Increase in arc duration and voltage will increase the concentration of carbon and free electrons which are formed as a result the value of capacitance and relative permitivity decreased.

Resistivity (ρ): Figure 9 shows the resitivity (In logarithmic) as a function of arc duration for three different arc voltage of 15, 20 and 25 kV. The Fig. 9 shows that mineral oil resistivity decreased with the arc duration and arc voltage. The application of alectric arc strongly affected the resistivity. The lowest value of resistivity occured when the mineral oil was subjected to arc voltage of 25 kV for 30 min that was sample ARC 9. Provision of electric arc increased charge carrier concentration that enhances the flow of conduction or increase conductivity resulted in lower resistivity. Increase in arc duration and voltage will increase the concentration of carbon and free electrons which are formed as a result the value of resistivity decreased.

Dissolved Gas Analysis (DGA)

Effect of arc voltage on formation of combustible gases: Figure 10 shows the concentration of combustible gases

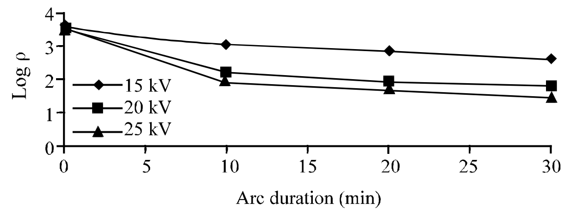

Fig. 9: Resistivity as a function of arc duration at different arc voltages

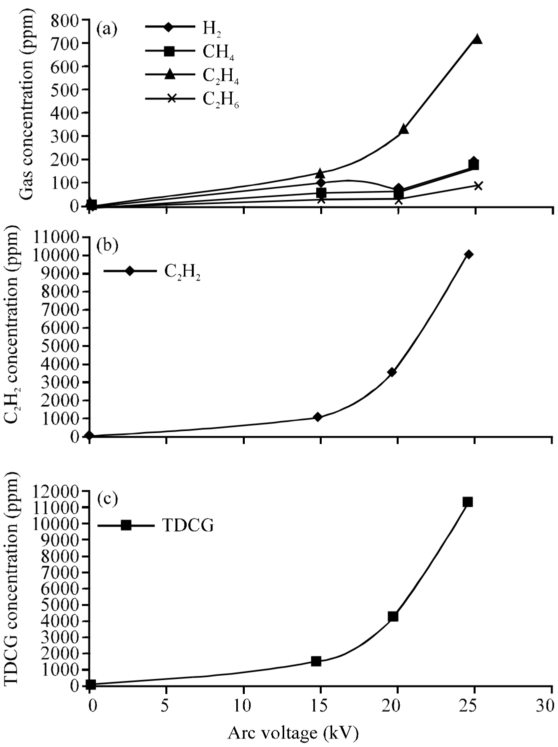

Fig. 10: Gas concentration as a function of arc voltage at arc duration of 20 min (a) H_2, CH_4, C_2H_4 and C_2H_6, (b) C_2H_2 and (c) TDCG

that released such as H_2, CH_4, C_2H_4, C_2H_6 and C_2H_2 for three different arc voltage of 15, 20 and 25 kV at arc duration of 20 min. Figure 10a shows the gas concentration for H_2, CH_4, C_2H_4, C_2H_6 and Fig. 10b for C_2H_2 (Acetylene). It can be seen that concentration of those combustible gases increased if arc voltage increased. The C_2H_2 (Acetylene) gas has much higher concentration compared to those other gases. Based on Fig. 10, the combustible gases can be sorted by the rate of increase in concentration as follows:

$$C_2H_6 \rightarrow CH_4 \rightarrow H_2 \rightarrow C_2H_4 \rightarrow C_2H_2$$

C_2H_6 gas has the lowest rate of increase in concentration followed by CH_4, H_2, C_2H_4, up to C_2H_2 with the highest rate of increase of gas concentration. This phenomenon occurs due to electrical arc events generate high energy and C_2H_2 gas will also be formed with the availability of high energy. The greater the electric arc voltage, the greater electric arc energy.

Figure 10c shows the concentration of Total Dissolved Combustible Gas (TDCG). For all those three graph in Fig. 11 concentration of each combustible gas and TDCG rose by almost at exponential trend.

Effect of arc duration of the formation of combustible gases: Figure 11 shows the concentration of combustible gases that is formed such as H_2, CH_4, C_2H_4, C_2H_6 and C_2H_2 for three different arc duration of 10, 20 and 30 min at arc voltage of 15 kV.

It can be seen that concentration of those combustible gases increased if duration voltage increased. Based on Fig. 11, the combustible gases can be sorted by the rate of increase in concentration as follows:

$$C_2H_6 \rightarrow CH_4 \rightarrow H_2 \rightarrow C_2H_4 \rightarrow C_2H_2$$

Where is the highest gas concentration increases experienced by the acetylene (C_2H_2). This phenomenon occurs due to electrical arc events generate high energy and C_2H_2 gas will also be formed with the availability of high energy as explain before. The greater the electric duration voltage, the greater electric arc energy.

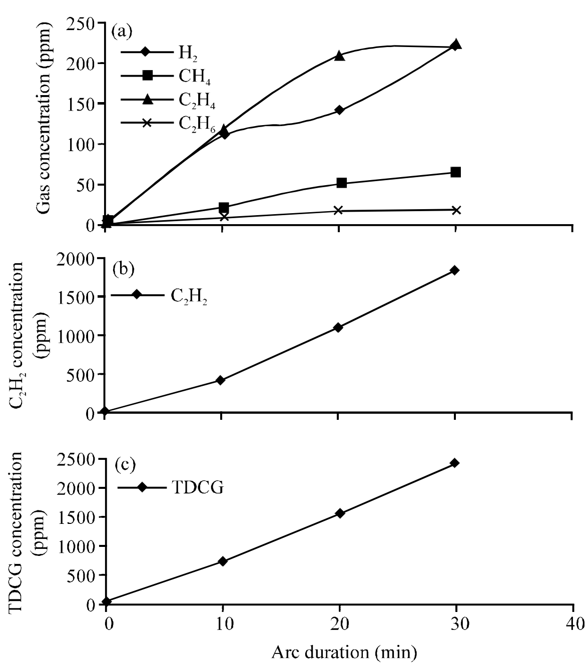

Fig. 11: Gas concentration as a function of arc duration at arc voltage of 15 kV (a) H_2, CH_4, C_2H_4 and C_2H_6, (b) C_2H_2 and (c) TDCG

Figure 11 also shows the concentration of Total Dissolved Combustible Gas (TDCG) which is the sum of all combustible gases. For all those three graph in Fig. 11 concentration of each combustible gas and TDCG rose by almost at linear trend.

Data interpretation using Total Dissolved Combustible Gas (TDCG) method: Table 2 shows data interpretation based on DGA data using TDCG Method. This method is based on IEEE standard C57.104 (Rogers, 1978).

Table 2 shows changes in the level of sample condition from condition 1-4 which indicates the level of oil decomposition. This show that provision of electric arc cause decomposition of oil. This because of formation of combustible gas showed by DGA data. The greater arc voltage and duration thus the higher concentration of combustible gas formed. It can be said decomposition is more severe.

Data interpretation using key gas method: Figure 12 shows the percentage of concentration of ech combustible gas for each sample. From Fig. 12 looks sample ARC 1 up to sample ARC 9 have the same dominant gas namely acetylene (C_2H_2). This gas is the key gas for sample ARC 0 up to sample ARC 9 because this gas has higher concentration than the others gases in each sample.

Table 2: Interpretation using TDCG method

Sample	Condition/Level
ARC 0	1
ARC 1	1
ARC 2	2
ARC 3	3
ARC 4	3
ARC 5	3
ARC 6	4
ARC 7	4
ARC 8	4
ARC 9	4

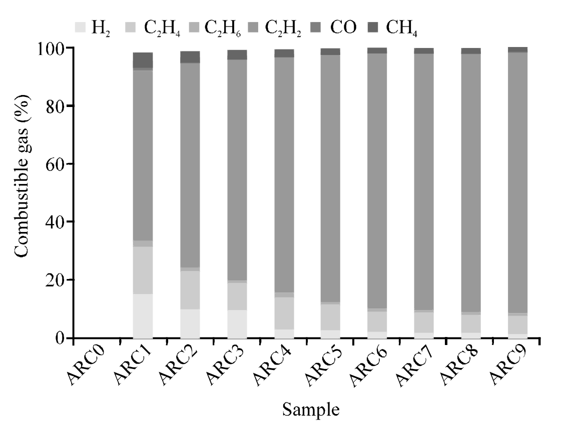

Fig. 12: Concentration of combustible gas in each oil samples

Table 3: Interpretation using key gas method

Samples	Key gas	Diagnosis
ARC 0	-	Normal
ARC 1	C_2H_2	Arcing
ARC 2	C_2H_2	Arcing
ARC 3	C_2H_2	Arcing
ARC 4	C_2H_2	Arcing
ARC 5	C_2H_2	Arcing
ARC 6	C_2H_2	Arcing
ARC 7	C_2H_2	Arcing
ARC 8	C_2H_2	Arcing
ARC 9	C_2H_2	Arcing

Table 4: Interpretation using Roger's Ratio method

	Roger Ratio				
Samples	CH_4/H_2	C_2H_6/CH_4	C_2H_4/C_2H_6	C_2H_2/C_2H_4	Diagnosis
ARC 0	-	-	-	-	-
ARC 1	0	0	1	1	Arc with power follow-through-or persistent sparking
ARC 2	0	0	1	1	Arc with power follow-through-or persistent sparking
ARC 3	0	0	1	1	Arc with power follow-through-or persistent sparking
ARC 4	0	0	1	1	Arc with power follow-through-or persistent sparking
ARC 5	0	0	1	1	Arc with power follow-through-or persistent sparking
ARC 6	0	0	1	1	Arc with power follow-through-or persistent sparking
ARC 7	0	0	1	1	Arc with power follow-through-or persistent sparking
ARC 8	0	0	1	1	Arc with power follow-through-or persistent sparking
ARC 9	0	0	1	1	Arc with power follow-through-or persistent sparking

Table 5: Interpretation using Duval triangle method

Samples	Area	Diagnosis
ARC 0	-	Normal
ARC 1	D1	Discharge low energy level
ARC 2	D1	Discharge low energy level
ARC 3	D1	Discharge low energy level
ARC 4	D1	Discharge low energy level
ARC 5	D1	Discharge low energy level
ARC 6	D1	Discharge low energy level
ARC 7	D1	Discharge low energy level
ARC 8	D1	Discharge low energy level
ARC 9	D1	Discharge low energy level

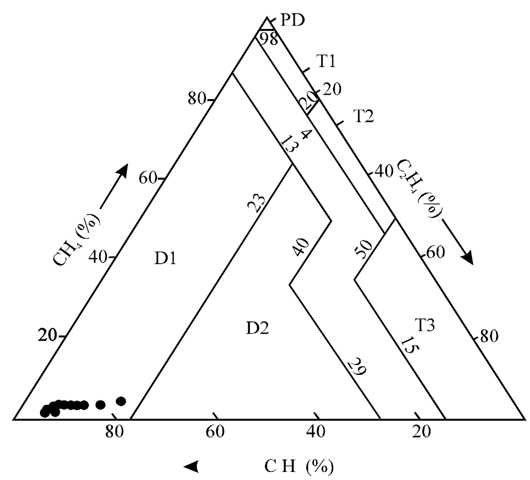

Fig. 13: Duval Triangle plot

Key Gas method produced interpretation as it is shown in Table 3. This method is based on IEEE standard C57.104. In sample ARC 0 combustible gases is completely not formed. From diagnostic result sample ARC 1 up to ARC 9 experienced the same condition namely arcing. Because in those sample formed C_2H_2 gas with high concentration and dominant from the other gases. So that gas use to diagnose in this method. High concentration of C_2H_2 shows that that given electric arc produced high energy and temperature.

Data interpretation using Roger's Ratio method: Table 4 shows data interpretation with Roger's ratio method based on (IEEE Standards C57.104, 1991). Interpretation using this method shows the same result as shown using Key gas method. Where sample ARC 0 shows normal condition and sample ARC 0 up to ARC 9 show the sam econdition namely arc with power follow through or persistent sparking. This is because of decomposition of oil result in excessive amount of combustible gas so categorized as arcing or persistent sparking.

Data interpretation using Duval Triangle method: Duval Triangle method use only three gas namely CH_4, C_2H_4 and C_2H_2 to yield a diagnosis.

Each of those gases is calculated its percentage of all those three gases. Then, ploted into a triangle which has faults areas and coordinates to plot percentage of those three gases (Duval, 1989). The results are shown in Fig. 13 (Table 5).

Interpretation result almost the same as two previous method where sample ARC 0 which is no given electric arc stated in normal condition while sample ARC 1 up to ARC 9 show the same result namely Discharge low energy level.

CONCLUSION

From the experimental results, it is concluded that arcing caused change in dielectric characteristic of mineral oil such as:

- Decrease in breakdown voltage
- Increase in dielectric loss factor
- Slight decrease in relative permitivity
- Decrease in resistivity

Arcing caused fomation of combustible gas such as H_2 (Hydrogen), CH_4 (Methane), C_2H_4 (Ethylen), C_2H_6 (Ethane) and C_2H_2 (Acetylen). Largest gas concentratin is C_2H_2 (Acetylen). Combustible gas concentration increase exponentially toward increase of arc voltage and increase linearly toward increase of arc duration. DGA interpretation for samples that were given arcing produced:

- TDCG method interpreted decomposition occur at level 2, 3 and 4
- Key Gas method interpreted arcing
- Roger's Ratio method interpreted arc with power follow through or persistent sparking
- While Duval Triangle method interpreted discharge low energy level

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