

Effect of acids formation on the breakdown voltage properties of transformer insulating oil

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Abstract. Studies show that acids influence the electrical insulation strength of transformer insulating oil. Thus, this study was conducted to verify the influence of Low Molecular Acid (LMA) and High Molecular Acid (HMA) on the breakdown voltage of transformer insulating oil. Different weight of LMA and HMA were added into transformer insulating oil samples and then mixed using hotplate magnetic stirrer at 50°C and 750 rpm for 3 hours. Prior to the mixing process, mineral insulating oil samples were filtered, dried and its moisture content were determined according to ASTM D1533 standard test condition. After the mixing process, total acid number (TAN) and AC breakdown voltage (BdV) of the oil mixtures were measured according to standard test conditions of ASTM D974 and ASTM D1816 respectively.. The obtained results verified that LMA significantly reduced the breakdown voltage of mineral insulating oil compared to HMA for acidity lower than 1 mg KOH/g.

1. Introduction

Generally, there are three (3) main functions of insulating fluid used in oil-immersed power transformer (Saha & Purkait, 2017); (1) providing electrical insulation among active parts (*i.e.* between high voltage (HV) coils and low voltage (LV) coils as well as between core and transformer's tank); (2) enhancing heat dissipation process because as transformer's core and coils heated up during transformer operation, insulating fluid will carries the generated heat by conduction and transfer it to surrounding areas, thus ensuring low and controlled temperature in a transformer; and (3) providing indicator to monitor the condition of a transformer (*i.e.* furanic compounds dissolved in oil are indicators specifically used to monitor the cellulosed-based material (Heywood, Xiao, Ali, & Emsley, 2000)). Generally, transformer's condition monitoring can be divided into three (3) tiers (Ghazali, Talib, & Rosli, 2009). Tier 1: Oil analysis (*i.e.* dissolved gas analysis, breakdown voltage, moisture content, acidity, power factor, furanic compounds), Tier 2: Basic electrical tests (*i.e.* turns-ratio, winding resistance, dielectric dissipation factor/tan delta, excitation current, insulation resistance and polarization index), and Tier 3: Advanced electrical tests (*i.e.* frequency response analysis and partial discharge). Noted that the oil acidity is a part of Tier 1: Oil analysis. Acidity is being monitored because few studies (Lars E. Lundgaard, Hansen, Linhjell, & Painter, 2004), (Yunguang et al., 2013) show that acids in transformer oil will affect cellulosed-based material thus at the same time the performance of a transformer as well. Therefore, this



paper is describing the formation of acids in mineral insulating oil as well as reporting the effect of acids on breakdown voltage of mineral insulating oil. The rest of this paper is organized as follows. The formation of acids in mineral insulating oil is described in the following section, followed by a brief description on the methodology adopted in this study. The findings of this study are then discussed with emphasis on two (2) different types of acids, and lastly, this paper provides verification on the effect of acids to breakdown voltage of mineral insulating oil.

2. Formation of acids in insulating oil

Figure 1 shows the molecule structure of acids that can be found in aged mineral insulating oil. The acids are categorized into two (2) types: (1) Low Molecular Acid (LMA) (*i.e.* formic, acetic and laevulinic acids) and (2) High Molecular Acid (HMA) (*i.e.* naphthenic and stearic acids). These acids are by-products formed due to ageing of transformer insulating materials (mineral insulating oil and cellulose) during a transformer's services. The ageing mechanisms for these insulating materials are described in the following section.

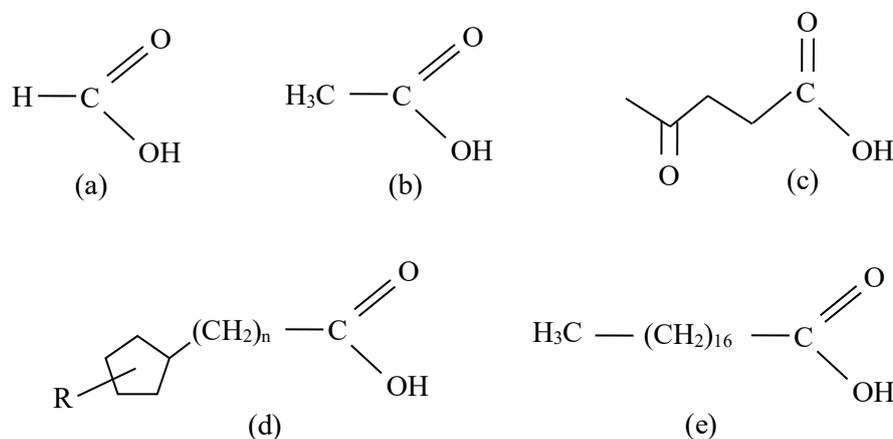


Figure 1: Molecular structure of carboxylic acids: (a) formic, (b) acetic, (c) laevulinic, (d) naphthenic and (e) stearic acids (L. E. Lundgaard, Hansen, & Ingebrigtsen, 2008)

3. Ageing mechanism of cellulose-based materials

Ageing mechanism of cellulose-based materials are due to (1) heat, (2) presence of oxygen, (3) moisture and acids. As cellulose being heated without any influences either from oxygen or moisture, to a maximum of 200°C, the cellulose's glycosidic bonds tend to break and in due course open the glucose rings. Thus, free glucose molecules, moisture, carbon oxides and organic acids are produced out of this reaction. In the presence of oxygen, cellulose's hydroxyl groups are oxidized to carbonyl (aldehydic) and carboxyl (acidic) groups. While existence of water and acids will cleave the cellulose glycosidic bonds yielding free glucose. (Unsworth & Mitchell, 1990).

4. Ageing mechanism of mineral-based insulating oil

Ageing mechanism of mineral insulating oil is normally associated with oxidation process; with high temperature and presence of moisture act as catalysts. Oxidation of oil resulting in formation of by-products such as acids, sludge and other polar compounds. In general, oxygen attack hydrocarbon molecule of mineral insulating oil, which generates hydro-peroxides. These hydro-peroxides can be further decompose to form ketones and water. Ketones can either be oxidized to form carboxylic acids or cleaved to make aldehydes. The carboxylic acids that are produced will either dissolve in the oil or volatilize into the headspace (Sanghi, 2003), (Meshkatoddini, 2008).

5. Methodology

The methodology adopted in this study is summarized in a flow chart, as shown in Figure 2.

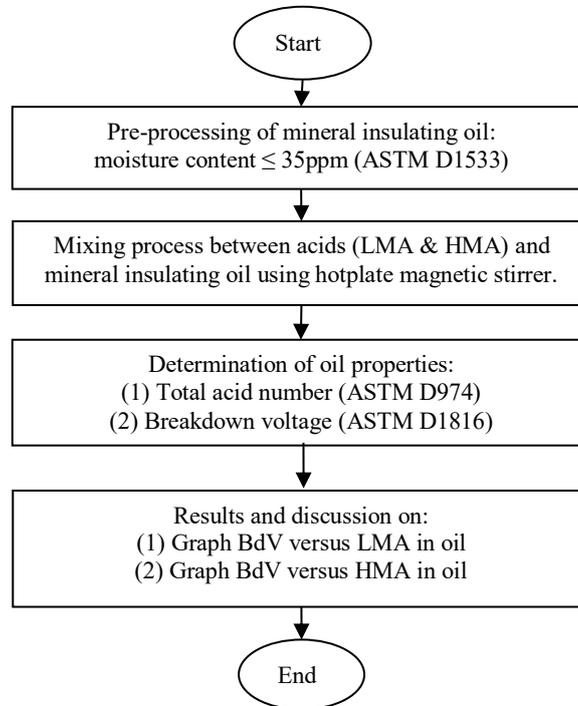


Figure 2: Flow chart of the methodology adopted in this study

5.1. Mixing process of acids and mineral insulating oil

Initially, mineral insulating oil was filtered using filter paper with a pore size of $0.2\mu\text{m}$. Then, the filtered oil was dried in oven for 24 hours at 105°C so that the moisture content will be less than 35 ppm. After that, different weight of LMA (formic) and HMA (stearic) were added into separate samples. Each sample consist of 500 ml mineral insulating oil that previously being filtered and dried. The acids and oil samples were mixed using hotplate magnetic stirrer at 50°C and 750 rpm for 3 hours. Following the mixing process, each oil samples was prepared for breakdown voltage measurements as well as titrated for level of acidity.

5.2. Water content, acidity and AC brekardown voltage

Water content, total acid number and breakdown voltage for all oil samples was measured in accordance with (ASTM D1533, 2012), (ASTM D974, 2014) and (ASTM D1816, 2012) standard test method, respectively. Water may be present in insulating oils either as free water or in dissolved form. Measurement of water content in oil is done in terms of milligrams/kilogram or parts per million (ppm). The water content in oil was determined using a coulometer based on the Karl Fischer titration method. The Karl Fischer titration method is based on the oxidation of sulphur dioxide by iodine in methanolic hydroxide solution. Acidity or total acid number (TAN) is a measure of acidic components present in the oil. New and unused mineral insulating oil is expected to be neutral and free from any acidic compound. However, during service, acidic by-products are formed due to oil's oxidation and cellulose's degradation. TAN of oil sample was measured using a TAN analyser, an equipment that measured basically based on the amount of potassium hydroxide (in mg) required to neutralize hydrogen ions (H^+) in 1 g of oil. Ability of insulating liquid to withstand electric stress without failure is called dielectric breakdown voltage (BdV). A low value of BdV indicates the existence of contaminants (*i.e.* air bubbles, moisture, and suspended solid particles). The BdV measurements were conducted using a portable oil tester. The minimum volume of oil used to perform this measurement is 350 ml. The portable

oil tester used two (2) cleaned electrodes (semi-sphere shape) with the gap distance between these two (2) electrodes was kept fixed at 1 mm while the rate of voltage rise was 0.5kV/s.

6. Results and discussion

Figure 3 shows a graph of BdV (kV) versus LMA in oil (mg KOH/g). Notice that, breakdown voltage decreased 37.5% from its initial value once 0.07 mg KOH/g of LMA in oil was detected. Next, as 0.50 and 0.70 mg KOH/g of LMA in oil were detected, the breakdown voltage drop 62.5% and 70.8% from its initial value respectively. Thus in general, the increment of LMA in oil resulting on decrement of breakdown voltage. Next, Figure 4 shows a relationship between BdV (kV) and HMA in oil (mg KOH/g). Notice that, there is fall and rise effect on breakdown voltage within the range of 0.10 to 1.5 mg KOH/g of HMA in oil. The breakdown voltage is steadily decrease as HMA in oil is bigger than 1.5 mg KOH/g. Noted that the breakdown voltage of mineral insulating oil drop 12.5% and 60% from its initial value as 1mg KOH/g and 9 mg KOH/g of HMA detected in oil respectively.

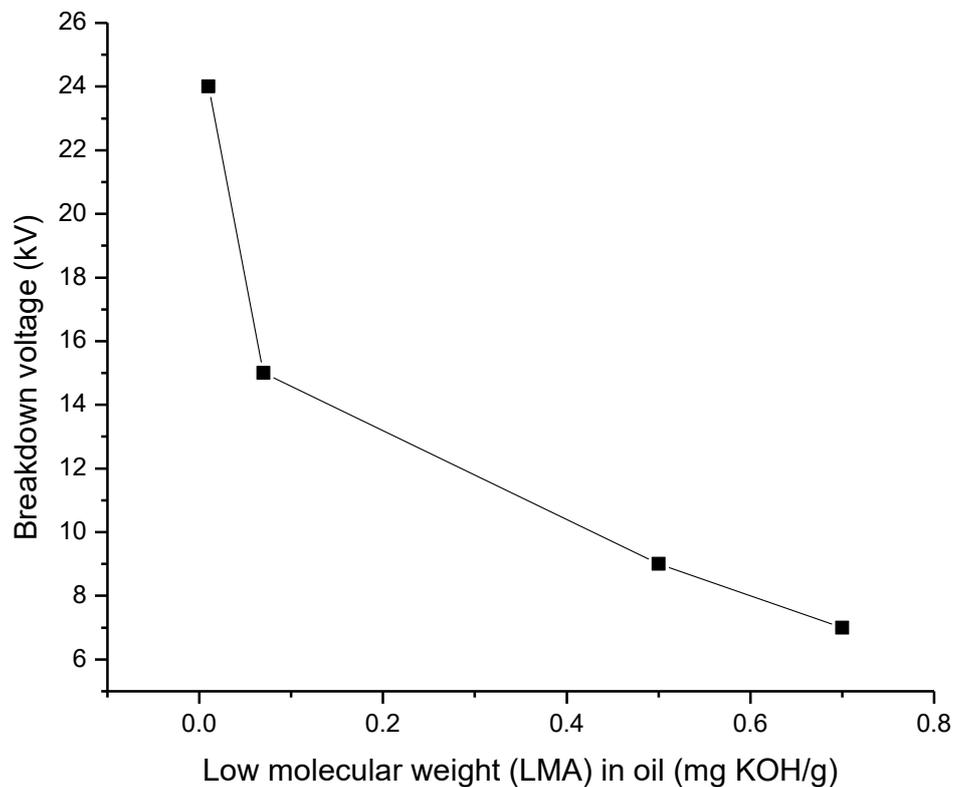


Figure 3: Graph Breakdown voltage (kV) versus Low molecular acid in oil (mg KOH/g)

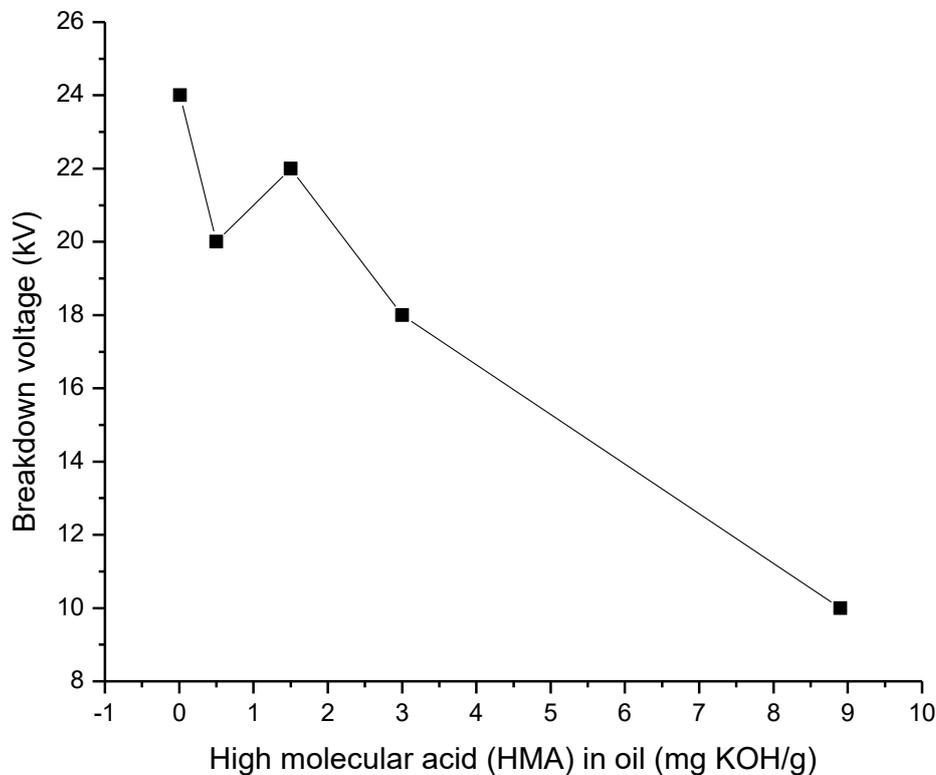


Figure 4: Graph Breakdown voltage (kV) versus High molecular acid in oil (mg KOH/g)

7. Conclusions

As acidity of mineral insulating oil for in-services transformer rarely reach 1 mg KOH/g (Azis, 2012), it can be concluded that the presence of LMA in oil gives more significant reduction on breakdown voltage of mineral insulating oil compared to HMA.

Acknowledgement

The authors gratefully acknowledge the financial support provided by the Ministry of Education Malaysia (MoE) and Universiti Teknikal Malaysia Melaka (UTeM) under the grant: (FRGS/1/2017/TK04/ FKE-CERIA/F00332). The authors amiably thank Ms. Norasmah Ismail from Faculty of Electrical Engineering, UTeM, Malaysia for providing assistance on the preparation and measurements of the materials used in this study.

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