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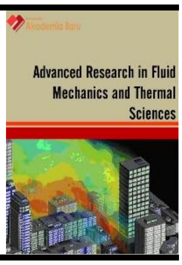

In-Service Transformer Oil Regeneration Based on Laboratory-Scale Process

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ABSTRACT

This paper described in-laboratory oil regeneration process of aged transformer oil using adsorbent; Fuller's earth. The niche of this paper is the usage of real aged transformer oil taken from an 11kV/433V in-service power transformer made by ACEC Transformer in 1986. The regeneration process is achieved by forcing a mixture of aged transformer oil and Fuller's earth through a filter paper with the aid of a vacuum pump, hence producing reclaimed transformer oil. This oil was then inserted in an amber glass bottle, blanketed with nitrogen, tightly sealed, and labelled. To test the effectiveness of Fuller's earth as adsorbent, parameters of Dissolved Decay Product (DDP) were measured using UV-Visible Spectrophotometer (UV-Vis) by referring to ASTM D6802. In addition, Total Acid Number (TAN) and Breakdown Voltage (BdV) measurement were carried out complying the ASTM D974 and ASTM D1816 respectively. Results of UV-Vis indicated that Fuller's earth can adsorbed 25.24% of DDP in aged transformer oil. As the DDP decreased, TAN is 84.62% reduced while BdV increased 50%. These findings are parallel with the breakdown voltage mechanism due to acidity emergence. It is proved that Fuller's earth is effective adsorbent for oil regeneration process.

1. Introduction

Lifespan of a power transformer depends on its insulation; liquid (transformer oil) [1] and solid (cellulose-based paper/pressboard) [2]. Transformer oil such mineral oil and natural ester oil also acts as coolant for power transformer's winding due to oil ability to dissipate heat by convection [3]. Ageing of transformer oil usually cause by electrical and thermal stresses but can be speed up if humidity, high heat, oxidation and level of acidity are present in the oil [4]. Since mineral oil; a

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petroleum-based product is commonly used as transformer oil, ecosystem can be threatened if aged mineral oil are improperly disposed. The disposing problem can be overcome by recycling the aged mineral oil through regeneration process [5–7]. This process helps improving the quality of aged mineral oil by removing contaminants as well as sludge present in the aged mineral oil using various adsorbents such Fuller's earth [5], palm shell activated carbon [8] and activated bentonite [7]. Although many studies have been conducted previously, the niche of this study is a regeneration process carry out on real aged transformer oil taken from an 11kV/433V in-service power transformer made by ACEC Transformer in 1986. An almost 30 year's aged mineral oil samples. The regeneration process is conducted in laboratory using Fuller's earth as adsorbent.

2. Methodology

Figure 1 shows a flowchart of research methods for this study. All works were done in a laboratory. The study starts with collecting few liters of aged mineral oil samples. This oil will be used in regeneration processes. The regeneration process is based on IEEE Guide for Regeneration of Insulating Oil [5] and [8] while works of detecting Dissolved Decay Product (DDP) using UV-Visible Spectrophotometer (UV-Vis), measuring Total Acid Number (TAN) as well as determining Breakdown Voltage (BdV) are referred to standards of ASTM D6802 [9], ASTM D974 [10] and ASTM D1816 [11] respectively. Aged mineral oil samples for this research were courtesy of Tenaga Nasional Berhad (TNB) taken from an in-serviced power transformer made by ACEC. The transformer is as shown in Figure 2(a) and 2(b). The transformer's rating is 500 kVA, 11kV/433V. Mineral oil in the transformer have undergoes ageing process for nearly 30 years because it never been filtered, replaced or reclaimed since manufactured in 1986.

Regeneration processes [5] used in this study is combination between contact process and filtration. Contact process is mixing an amount of adsorbent with aged mineral oil samples producing mixed oil. The mixing was done using digital hotplate magnetic stirrer as shown in Figure 3(a). The stirrer speed and temperature is maintained at 750 rpm and 60℃ for 4 hours so that the mixture can be homogenized. The mixed oil produced from contact process will be filtered through filtration process. Filtration is separating the mixed oil using filter paper to remove sludge (adsorbents and DDP formed during ageing of mineral oil) producing reclaimed oil. As the filter paper used (Whatman No 42) is a 2.5 μm in pore sizes, time taken for filtration process will take several days to complete. This delay can cause the mixed oil under filtration, exposed to moisture and oxidation. Therefore, the aid of a vacuum pump is used to speed up the process as well as preventing any moisture or oxidation. Figure 3(b) shows a filtration process. Mixed oil from contact process is poured directly to a fleaker. The oil is filtered through a filter paper initially put between the fleaker and a flask. A vacuum pump is connected to the flask using rubber hose to speed up the flow rate of the mixed oil as well removing air and moisture in the flask. With the aid of a vacuum pump, filtration can be completed within 2 hours.

Figure 4 shows a UV-Vis set used to determine a relative content of DDP. Initially, a cuvette is filled with 5 ml of oil sample using a syringe. Then, the cuvette is placed into the UV-Vis set. When light radiations interact with the oil sample, the passing lights are carried to the spectrophotometer through an output fiber. The fiber is connected to a screen that displaying an absorption spectrum curve. As for analysis, the absorption spectrum of oil samples are measured over a wavelength range between 360 to 600 nm in accordance with ASTM D6802 [9]. Chemical substances such Potassium Hydroxide (KOH), Isopropyl Alcohol (IPA) and Potassium Hydrogen Phthalate (KHP) are required to determine TAN in oil samples. Procedures for this test are referred as in [12]. Firstly, 5g oil samples are weighed into a titration vessel and 20 mL IPA solvent are added. The solution is then titrated using c(KOH in IPA) = 0.1 mol/L. TAN of oil samples are displayed and recorded. Figure 5 shows a TAN test set. Initially, BdV test electrodes are cleaned using acetone and dried. Next, the gap between electrodes is set to 1mm. After that, the electrodes were immersed into a beaker of 500 ml oil samples and placed into the BdV set as shown in Figure 6. The electrodes must fully immerse into the oil and there should be no air bubbles present in the oil before BdV measurement can be done as per ASTM D1816 [11].

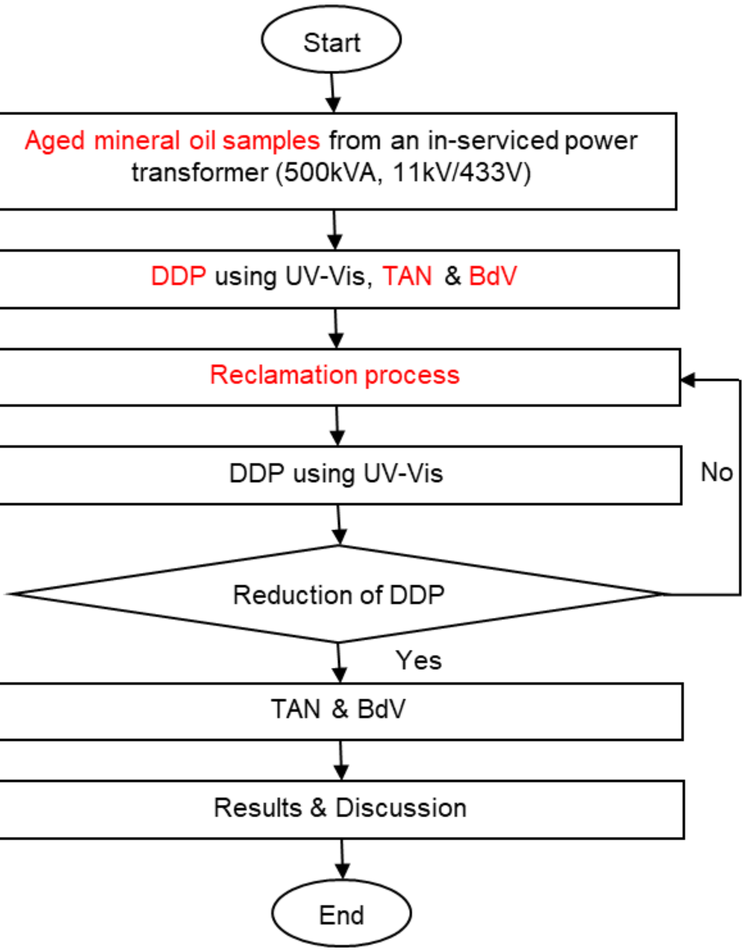
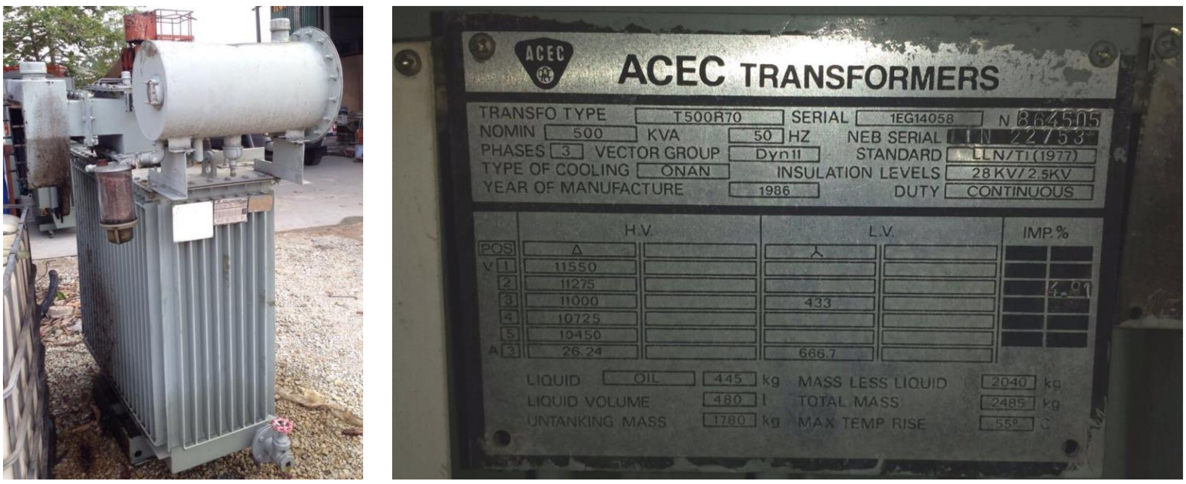
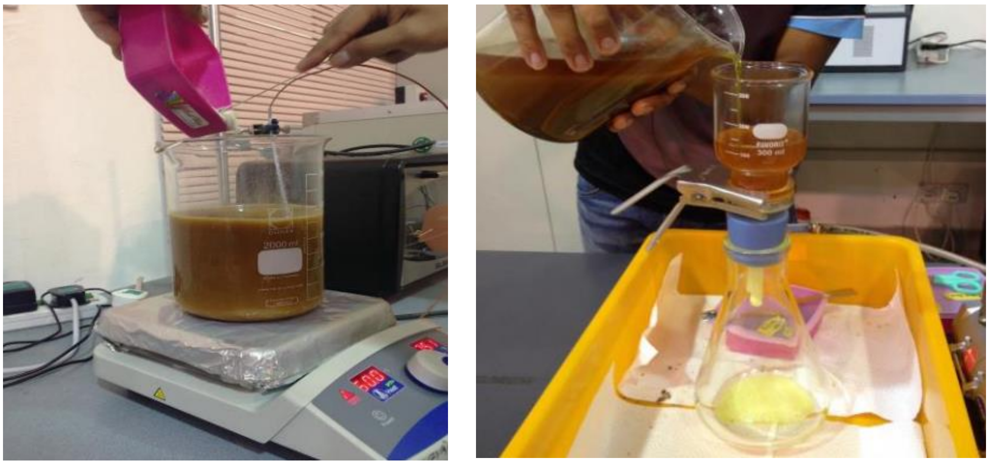


Fig. 1. Flowchart of research methods



(a) (b)

Fig. 2. (a) In-Serviced ACEC's power transformer (b) Nameplate of ACEC's power transformer



(a) (b)

Fig. 3. (a) Contact process (b) Filtration process

Fig. 4. UV-Visible Spectrophotometer (UV-Vis) Set

Fig. 5. Total acid number (TAN) test set

Fig. 6. Breakdown voltage (BdV) set

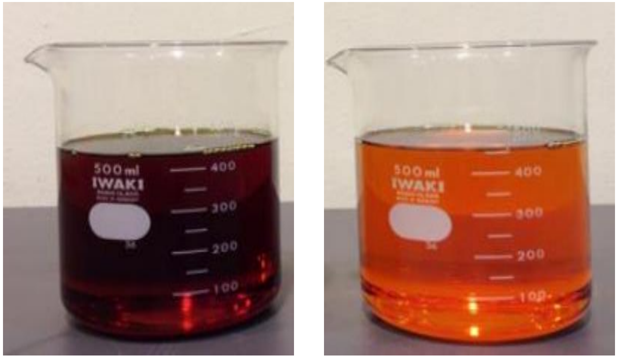
3. Results and Discussion

Parameters of Dissolved Decay Product (DDP) were measured using UV-Visible Spectrophotometer (UV-Vis) by referring to ASTM D6802 [9]. In addition, Total Acid Number (TAN) and Breakdown Voltage (BdV) measurements were carried out complying the ASTM D974 [10] and ASTM D1816 [11] respectively. All tests were carried out on aged mineral oil samples and reclaimed oil for comparison. Regarding regeneration process, there are two (2) different oil samples were prepared namely Sample 1 and Sample 2. Sample 1 is a mixture between 100g adsorbent and 1000ml aged mineral oil while Sample 2 is a mixture of 5g adsorbent with 500ml aged mineral oil. Adsorbent used for this study is Fuller's earth from Sigma-Aldrich [13]. This adsorbent is in powder forms and harmful if exposed to skin or inhale. Thus, safety gears of mask, rubber gloves and safety goggles were worn. The weights of adsorbent were measured using digital analytical balance whereas the aged mineral oil volumes were measured using beaker. The summary on quantities of adsorbent and aged mineral oil to prepare Sample 1 and 2 are shown in Table 1. The different quantities are by referring to previous research in [7] and [14].

Table 1
Quantities of adsorbent and aged mineral oil

Oil sample	Adsorbent (g)	Aged mineral oil (ml)
Sample 1	100	1000
Sample 2	5	500

Sample 1 is reclaimed once to produce reclaimed oil but Sample 2 will undergoes several cycles of regeneration process. The reclaimed oil from the first cycle of Sample 2 will be reused for the second cycle of regeneration process. During new cycle, new 5g of adsorbent is used. The process is repeated 5 times. Transformer oil is exposed to oxidation process due to present of dissolved oxygen in oil. Presence of oxidation by-product as well as deterioration of transformer oil can be indicated by colour changes of oil. Figure 7(a) shows colour of aged mineral oil (AMO) while Figure 7(b) shows colour of Sample's 1 reclaimed oil (S1RO). It shows that the colour of AMO will change from dark brown to light brown due to regeneration process. Same result is achieved for Sample's 2 reclaimed oils (S2RO) as shown in Figure 8(a)-(e). The colour is lighter after each cycle of regeneration process. This decolourized of aged mineral oil from dark to lighter brown is due magnesium and calcium ion contain in Fuller's earth.



(a) (b)

Fig. 7. (a) Colour of aged mineral oil (AMO). (b) Colour of sample 1's reclaimed oil (S1RO)

(a) (b) (c) (d) (e)

Fig. 8. (a) Colour of sample 2's reclaimed oil after 1st regeneration. (b) Colour of sample 2's reclaimed oil after 2nd regeneration. (c) Colour of sample 2's reclaimed oil after 3rd regeneration. (d) Colour of sample 2's reclaimed oil after 4th regeneration. (e) Colour of sample 2's reclaimed oil after 5th regeneration

The wavelength range chosen for this study is between 360 nm and 600 nm as referred to ASTM D6802 [9]. The absorbance unit is a value that indicates the amount of UV-light absorb by the DDP. High value of absorbance indicates high DDP. The DDP's relative content of oil samples is determined by integrating the area under an absorbance versus wavelength curves'. Figure 9 shows curves of absorbance (range of 0-4.5a.u) with respect to wavelength (range of 360-600nm) for aged mineral oil (red line), Sample's 1 reclaimed oil (green line) and Sample's 2 reclaimed oil-after 5 cycle of regeneration process (blue line).

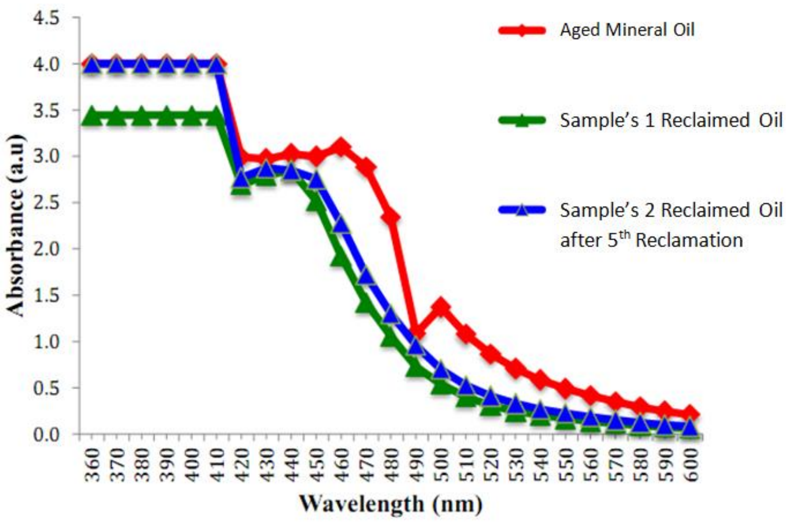


Fig. 9. Curves of absorbance (a.u) versus wavelength (nm)

The wavelength at 420 nm is chosen as reference to analyze the regeneration process. As shown in Figure 9, at 420nm, absorbance unit of aged mineral oil, Sample's 1 reclaimed oil and Sample's 2 reclaimed oil-after 5 cycle of regeneration process is 2.9929a.u, 2.771a.u and 2.6919a.u respectively. These decrement value of absorbance unit indicate that DDP or oxidation by-products such low molecular weight acid decrease after regeneration process as found in [8]. Figure 10 shows graphs of DDP's of aged mineral oil (red), Sample's 2 reclaimed oil-after 5 cycles of regeneration process (blue) and Sample's 1 reclaimed oil (green). The DDP values are 498.34a.u, 422.8625a.u and 372.57a.u accordingly.

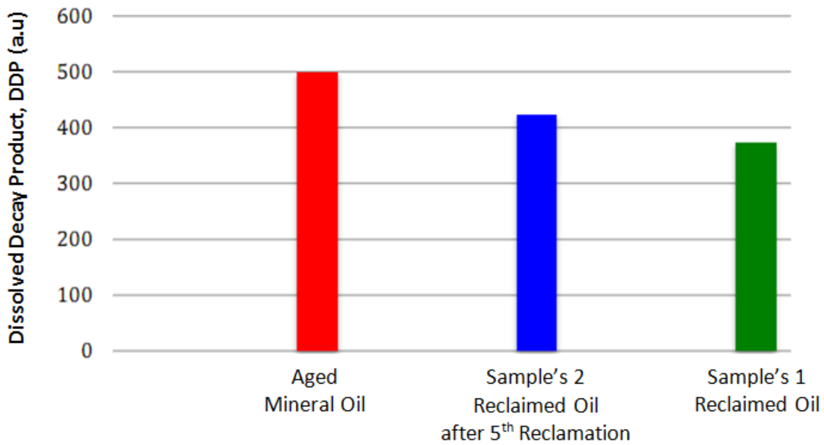


Fig. 10. Dissolved Decay Product, DDP (a.u)

DDP values' signified that oil has undergone oxidation during service and by doing regeneration on the aged mineral oil such have been done on Sample 1 and Sample 2, decrement of DDP values' are shown. Yet, Sample 1 show 25.24% decrement compared to Sample 2 with only 15.15% DDP reduction. These results implying that using 100g of Fuller's earth for one cycle of regeneration (Method 1) is more effective compared to using 5g of Fuller's earth for 5 cycles of regeneration (Method 2). Additionally, the different amount of Fuller's earth used in Method 1 & 2 matching with results of reduction in DDP values of Sample 1 and Sample 2. This is because amount of adsorbent is directly proportional to the ability of adsorbents to absorb polar contaminants. Due to the effectiveness and lesser time required, Method 1 is chosen for the next two (2) study phases, Total Acid Number (TAN) and Breakdown Voltage (BdV). TAN measurements as per ASTM D974 were repeated three (3) times to find out the average value of acids in mineral oil. Figure 11 show results of average TAN for AMO and S1RO. The values are 0.13mgKOH/g and 0.02mgKOH/g respectively. As per reference, the suggested TAN limits for transformer is 0.10mgKOH/g [5]. High TAN values' proved that there is formation of acid in AMO accumulated during in-services due to oxidation process. The process can occurred between dissolved oxygen presence in oil with the mineral oil molecule or with cellulose-based insulation such as Kraft paper. Molecules of mineral oil that mainly consist of hydrogen and carbon can form carboxylic acids if interact with oxygen [1], while according to Bronsted-Lowry and Lewis Acids, the hydroxyl group (OH) in cellulose based paper can react with carboxylic acid and water to produce donating proton (H+). This donating proton (H+) can react with other molecule to form acid such as acetic and levulinic.

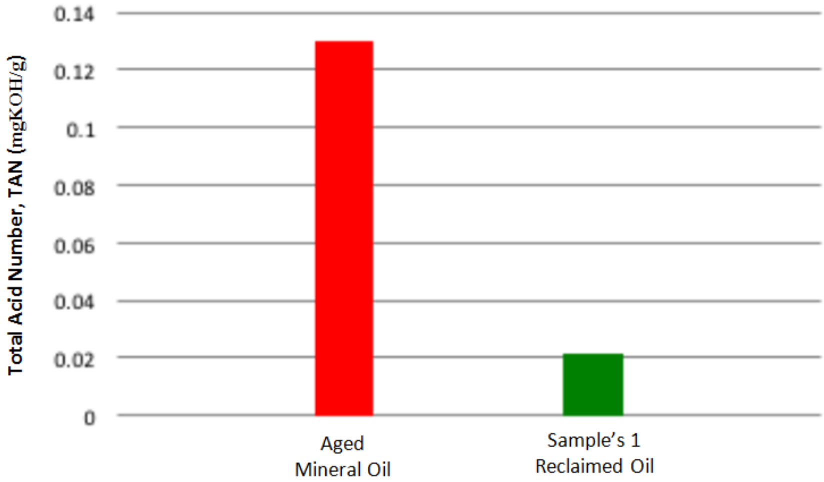


Fig. 11. TAN of aged mineral oil & sample's 1 reclaimed oil

Subsequently, this decay product reaction will produce sludge, which can cause the dielectric strength decreases as the breakdown will occur at the sludge. Eventually, after the AMO undergone regeneration process, the S1RO average TAN values' decreased to 0.02mgKOH/g. This indicates the effectiveness of Fuller's earth as adsorbent for regeneration process thus also reducing acids in oil by 84.62%. This is due to chemical structure of Fuller's earth that containing internal and external polar active sites. It allowed the non-polar substances in the oil to flow but block or adsorb the polar contaminants dissolved in the oil. Acid is a polar molecule as they have opposing charge on their molecule [15]. 25 BdV measurements were recorded for each aged mineral oil AMO and Sample's 1 reclaimed oil S1RO. All measurements were done using Megger Oil Tester OTS60PB as per ASTM D1816. Figure 12 shows the average values for both oil samples. The values clearly indicate that the breakdown voltage for both AMO and S1RO are lower than the limit suggested by IEEE where a transformer that runs below 69kV, the BdV limit of oil insulation used should be 23 kV and above [5], Yet, BdV of S1RO is 4kV bigger than AMO's BdV or 50% improvement through regeneration process. As BdV of transformer oil is primarily depending on factors such moisture content, void or bubbles, sludge or suspended particles and acidity of oil [8], this improvement of BdV can be due to decrement of DDP, sludge and acids that have been absorbed by Fuller's earth during regeneration process. Hence, it is believed that if the regeneration process is done repeatedly for several cycles, more DDP, sludge and acids can be removed from the AMO thus increasing BdV steadily.

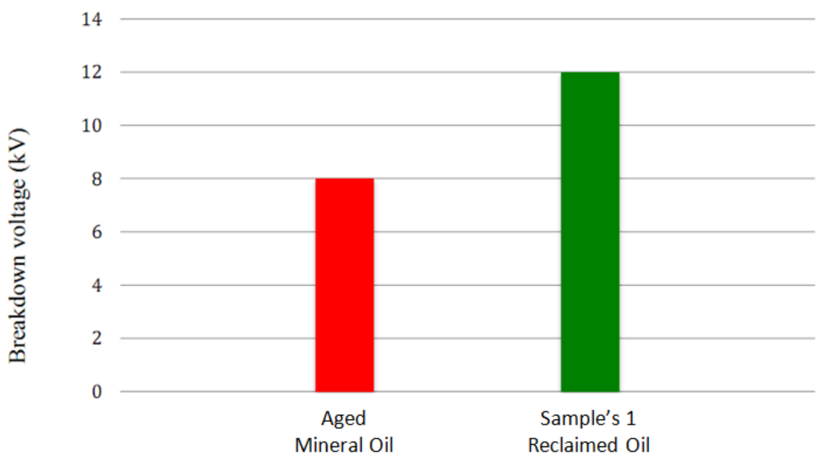


Fig. 12. BdV of aged mineral oil & sample's 1 reclaimed oil

4. Conclusions

Parameter of DDP was measured and analyzed by using UV-Vis according to ASTM D6802. In addition, TAN and BdV measurements were carried out by complying ASTM D974 and ASTM D1816 respectively. Through this study, it can be concluded that regeneration process using Fuller's earth can reduce 25.24% of DDP and 84.62% of acids present in aged mineral oil hence improving its' BdV by 50%. These findings are parallel with breakdown voltage mechanism due to acidity emergence. It is also proved that Fuller's earth is effective adsorbent for oil regeneration process and as Fuller's earth is harmless to environment, it can be disposed safely on landfill.

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References

[1] Lelekakis, Nick, Jaury Wijaya, Daniel Martin, and Dejan Susa. "The effect of acid accumulation in power-transformer oil on the aging rate of paper insulation." *IEEE Electrical Insulation Magazine* 30, no. 3 (2014): 19-26. https://doi.org/10.1109/MEI.2014.6804738

[2] Chairul, I. Sutan, S. Ab Ghani, MS Ahmad Khiar, YH Md Thayoob, and YZ Yang Ghazali. "Kraft paper insulation's life assessment and effects of oxygen and moisture to paper insulation's deterioration rate." In *2012 IEEE International Conference on Power and Energy (PECon)*, pp. 728-731. IEEE, 2012.

[3] Naidu, Motukuru S., and M. KAMARAJU NAIDU. *High voltage engineering*. Tata McGraw-Hill Education, 2013.

[4] Liapis, Ioannis, and Michael G. Danikas. "A study of parameters affecting the ageing of transformer oil in distribution transformers." In *2011 IEEE International Conference on Dielectric Liquids*, pp. 1-4. IEEE, 2011. https://doi.org/10.1109/ICDL.2011.6015050

[5] C57.637™-2015. "IEEE Guide for the Reclamation of Insulating Oil and Criteria for Its Use." *IEEE Standards Association* (2015).

[6] N'cho, J. S., Issouf Fofana, Abderrahmane Beroual, Thomas Aka-Ngnui, and John Sabau. "Aged oils reclamation: Facts and arguments based on laboratory studies." *IEEE Transactions on Dielectrics and Electrical Insulation* 19, no. 5 (2012): 1583-1592. https://doi.org/10.1109/TDEI.2012.6311504

[7] Raymon, A., and R. Karthik. "Reclaiming aged transformer oil with activated bentonite and enhancing reclaimed and fresh transformer oils with antioxidants." *IEEE Transactions on Dielectrics and Electrical Insulation* 22, no. 1 (2015): 548-555. https://doi.org/10.1109/TDEI.2014.004094

[8] Ab Ghani, Sharin, Nor Asiah Muhamad, and Hidayat Zainuddin. "Performance of palm shell activated carbon as an alternative adsorbent for reclamation of used transformer oil." *ARPN Journal of Engineering and Applied Sciences* 10 (2006): 10752–10758.

[9] Loiselle, Luc. *Influence des produits de dégradation sur la stabilité thermique et diélectrique des fluides isolants pour les transformateurs de puissance*. Université du Québec à Chicoutimi, 2013. https://doi.org/10.1522/030617331

[10] Hamblin, Peter, Isabelle Rapenne-Jacob, José Reyes-Gavilan, and Peter Rohrbach. "Standard Test Methods for TAN Assessment and Modifications Thereof©." *Tribology & lubrication technology* 60, no. 11 (2004): 40.

[11] Lick, Werner, G. J. Pukel, Hans Michael Muhr, and M. Baur. "New test method for dielectric breakdown voltage of insulating oils." In *2008 IEEE International Conference on Dielectric Liquids*, pp. 1-4. IEEE, 2008. https://doi.org/10.1109/ICDL.2008.4622486

[12] Jingyan, Li, Chu Xiaoli, and Tian Songbai. "Research on determination of total acid number of petroleum using mid-infrared attenuated total reflection spectroscopy." *Energy & fuels* 26, no. 9 (2012): 5633-5637. https://doi.org/10.1021/ef3002372

[13] Parsons, Charles L. "Process of treating fullers' earth." U.S. Patent 1,112,650, issued October 6, 1914.

[14] Wilhelm, H. M., G. B. Stocco, and S. G. Batista. "Reclaiming of in-service natural ester-based insulating fluids." *IEEE Transactions on Dielectrics and Electrical Insulation* 20, no. 1 (2013): 128-134. https://doi.org/10.1109/TDEI.2013.6451350

[15] R. Kurtus. "Polar and Non Polar Molecules." (2016).