Effect of purification process on the thermal conductivity and breakdown voltage of inhibited, isoparaffinic transformer oil used in electric train

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Abstract

Presence of water content or moisture promotes premature thermal aging which hampers the properties of inhibited, isoparaffinic transformer oil used in electric multiple unit (EMU) train. Unpurified aged oil with high water presence is collected from the traction transformer and contaminants is removed using Double-Stage Vacuum Insulation Oil Regeneration Filtration Machine to produce purified aged oil. New transformer oil is selected as a control sample. The objective of this study is to investigate the effect of oil purification process on the thermal conductivity and breakdown voltage of the oil samples. Thermal conductivity measurement was done from temperatures of 30°C to 70°C. Dielectric characteristics are shown by analyzing breakdown voltage. Unpurified oil shows an increment from 1.54% to 3.13% as compared to new oil in response to temperature variation whereas purified oil has the lowest thermal conductivity value. However, breakdown voltage of purified oil is higher than unpurified oil and slightly lower than new oil. From this, it can be inferred that presence of water gives positive impact towards thermal properties and vice versa to dielectric properties. A relationship between thermal conductivity, breakdown voltage and presence of water has been deduced at the end of the study.

Keywords: oil purification; thermal conductivity; traction transformer; transformer oil; water content; electric multiple unit train.

1. Introduction

Onboard traction transformer is one of the most vital electric components in any electric multiple unit (EMU) train or high-speed train. Traction transformer is an electromagnetic device, built with two or more coils. Transformer oil – immersed type traction transformer is most commonly used in high speed and EMU train [1]. It receives alternate current from overhead line through pantograph and feeds power to electrical components through stepping down process.

Transformer oil acts as an insulation and cooling medium for traction transformer [2]. Transformer oil plays a major role in heat transportation to atmosphere and closely affected by thermal conductivity.
specific heat, volumetric thermal expansion and density [3]. In this transformer oil-immersed traction transformer, cellulose insulation and transformer oil (mainly naphthenic mineral oil) are the favorite choices as insulating system especially in high voltage transformer [4], [5]. Due to high voltage, transformer oil is subjected to thermal, electrical, physical, and environmental stress which promotes degradation or deterioration of the transformer oil. Number of accidents related to high voltage oil immersed equipment was reported to remain high even numerous monitoring systems towards insulation condition were made [6] [7]. Failure experience in transformers can be caused by degradation or ageing of transformer oil, overheating and mechanical failure of coil windings [8]. Thermal and electric stress have been found to be the highest contributor for early ageing of transformer oil [9], [10] [11] thus making the insulation aging as the number one contributor for transformer breakdown [9], [12]. Well known as the major cause of problems in transformers, presence of water content is usually determined using Karl-Fischer method. A lot of studies have been made to investigate the effect of water and oxygen towards the aging of the transformer [13]–[16]. It was found that moisture or water content can make the insulation paper to be brittle and tearable, thus limiting the rail service operation [17] besides giving impact to the thermal and electric properties of transformer oil. Moisture in the oil leads to oxidation process thus triggering the formation of acids and sludge that ruins the dielectric properties of transformer [18]–[21]. This event will cause the oil to lose its isolation properties over time and decreases the value of breakdown voltage. Water is found in transformer oil through three forms [22]. The first one is through free water where in high concentration situation, water droplets might be formed. Second form is when dissolved water goes through chemical process where hydrogen bonds with oxidized, aged oil at high temperature. The third form is through emulsified form which always occurs in aged, old transformer oil. One of the distinguished methods to remove moisture is by using silica gel. Silica gel breather is fitted on the traction transformer to absorb moisture that was sucked in by the transformer due to the difference of pressure during the “breathing process”. Despite having the breather, presence of dissolved water within the oil and continuous aging of cellulose insulation are inevitable. Purification process of aged oil were practiced by the rail industry to comply their periodic maintenance routine or when the measured breakdown voltage of the oil is lesser than the desired value. The whole cycle involves thermal heating, vacuum process, filtration process and regeneration process. Saifiddine et al. [23] and Ridzuan et al. [24] also discussed about the importance of purification process especially for treating aged transformer oil in their research. Breakdown voltage is used as an indication to check the current health of dielectric properties and desirable value should be more than the maximum operation voltage or based on the needs of industry [25]. Thermal conductivity is a very crucial parameter which determines the heat transport properties for transformer oil. It is also dependent to the variation of temperature and water content. A significant relationship between thermal conductivity and water content for aged transformer oil has been reported by Lopatkiewicz et al [26].

A lot of effort were done to improve the thermal conductivity of transformer oil besides purification process such as mixing with other oils, replacement with other liquids such as synthetic ester or natural ester and vegetable oils. Fernandez et.al [27] has concluded in their work about the various attempts made to modify or seek for alternate fluid for possible replacement of current transformer oil. These attempts are mostly about enhancing the cooling and insulation mechanism of the transformer oil. Despite numerous studies about the close relationship between thermal and electric stress in the ageing process of transformer oil [28], [29], none of these studies evaluated to what extend the purification process can affect the thermal conductivity of aged transformer oil. Besides, to the best knowledge of the authors, relationship between water content, thermal conductivity and breakdown voltage has not been recorded in literature. The purpose of this study is to investigate the effect of purification process on the thermal conductivity and breakdown voltage of inhibited, isoparaffinic transformer oil used in electric train.


2. Experimental procedure

2.1 Transformer oil sampling

Inhibited, isoparaffinic Shell Diala S4 ZX-I transformer oil was used in this study. Shell Diala S4 ZX-I oil is produced through Gas-to-Liquid (GTL) technology which improves oxidation stability. Three types of oil sampling were considered in this study and tabulated in Table 1.

| Sample | Details of sample                  |
|--------|------------------------------------|
| NTO    | New Transformer Oil                |
| UPATO  | Unpurified Aged Transformer Oil    |
| PATO   | Purified Aged Transformer Oil      |

Oil sampling techniques, cleaning process and the sampling vessel/container selection were done based on IEC 60475:2011 standards (Method of sampling insulating liquids). Borosilicate glass type reagent bottle was used in this study for all the oil sample storage. Even though the bottles were cleaned and dried prior of usage, the bottles were rinsed again by filling them partially with the oil sample, swirled gently to avoid bubble formation and then the oil was emptied into the waste container. Each bottle was labelled with the identification of the transformer, date, and time of sampling together with the temperature of oil and ambient during the collection time. Taking the oil samples during rainy days must be avoided in order to reduce the impact of humidity. Besides, oil flow during collection process must be in laminar to avoid bubble. NTO sample was collected from new oil barrel. UPATO was collected from the drain valve of the traction transformer as shown in Figure 1 before pumping it into the purification machine. UPATO was in service for more than 10 years. This valve is located at the bottommost of traction transformer to ease oil transfer and to get the most contaminated part of the oil to get the exact health status of the oil. The closure cap or nut of the oil valve must be cleaned from any debris or dust before drawing out the oil. It is advisable that the train must be let to rest for at least 1 hour before sampling process of UPATO was done. The service-aged oil or UPATO will then be pumped into the purification machine with the help of mechanical pump due to the large volume of transformer oil. Each EMU has 2 units of traction transformer and each transformer consumes around 700 to 750 liters of transformer oil.

![Figure 1 Oil drain valve at traction transformer](image1)

![Figure 2 Oil samples – from left NTO, PATO and UPATO](image2)

Upon completion of purification process, PATO sample was taken from the purification machine through the oil sampling valve. 600ml of each oil samples were taken for both breakdown voltage and thermal conductivity measurement. Acidity level and water content concentration percentage
measurement (ppm) of UPATO, PATO and NTO will not be discussed further in this study. Figure 2 shows the oil samples collected from the mentioned locations.

2.2 Purification process of transformer oil

During the purification process, the whole train will be kept halt and UPATO will be drained out from the tank. UPATO will be pumped into Double-Stage Vacuum Insulation Oil Regeneration Filtration Machine for purification and treatment purposes. The purification process consists of five stages of repetitive cycles which are primary/coarse filtration, heating, vacuum separation, regeneration process and fine filtration. Once the filtration machine starts to operate, UPATO will be sucked into the primary filter due to pressure difference, thus removing big size impurities/ particles before heating process. During the heating process, water molecules in the aged oil will become diffusive as it will obtain more kinetic energy due to temperature increment. Thermal heating and filtration are considered as the most important method to remove contaminants especially moisture and dissolved gas in transformer oil [30]. Heated oil will then enter the vacuum separator, through the function of vacuum pump. Moisture content will be discharged under vacuum system process in the form of vapor or condensed to liquid water with the aid of the heat exchanger. The next stage is regeneration process which is a very important step to treat deteriorated transformer oil. Formation of oxidation by-products contributes to the increase of acidity, decrease of interfacial tension of the transformer oil and leads to sludge generation [31]. Oil regeneration process purifies deteriorated oil by removing the polarity materials, deep oxides and free carbon in the oil effectively besides improving the colour condition [32]. The last procedure is fine filter which removes tiny impurities in the size of 5μm and above completely. The entire process will undergo few cycles or until obtaining the minimum breakdown voltage value of 30kV based on IEC60296 standards (Fluids for electrotechnical applications – Mineral insulating oils for electrical equipment). Figure 3 summarizes the flow of transformer oil purification process.

![Figure 3 Double-Stage Vacuum Insulation Oil Regeneration Filtration Machine process](image_url)

3. Characterization of oil samples

3.1 Measurement of thermal conductivity

Thermal conductivity shows the ability of any fluid to conduct heat and considered one of the important characteristics considered for heat transfer besides viscosity and density. In this study, thermal conductivity was measured at 30°C to 70°C with intervals of 10°C using single needle thermal property analyzer (KD2 Pro, Decagon Devices Inc) with the aid of water bath (Memmert brand, 100 – 120 VAC). Water bath was used as it can generate better temperature distribution to the oil sampling vessel or beaker through natural turbulence. Figure 4 shows the thermal property analyzer used where measurement was taken in accordance with ASTM D7896 - 19 (Standard Test Method for Thermal Conductivity, Thermal Diffusivity, and Volumetric Heat Capacity of Engine Coolants and Related Fluids by Transient Hot Wire Liquid Thermal Conductivity Method). The dipped needle must not touch the side of the bottle container and should be in the center of the bottle containing oil samples. Any kind
of convection disturbance or vibration must be avoided throughout the analysis. Measurements must be taken every fifteen minutes to allow for thermal gradients to dissipate.

3.2 Measurement of breakdown voltage

Breakdown voltage of transformer oil reflects the maximum voltage that can be submitted in the oil without forming a voltaic arc; failing to behave as mentioned means that the oil will behave as conductor instead of being insulative [33]. Breakdown voltage was measured using Megger Dielectric Test OTS 60 SX2 set with automatic impeller stirrer mechanism and standard spherical electrode with spacing of 2.5 mm as shown in Figure 5. The experimental arrangement was as in accordance with IEC 60156: 2018 (Insulating liquids. Determination of the breakdown voltage at power frequency. Test method) standards where AC voltage with increasing rate of 2 kV/s and frequency of 50 Hz were applied. The gap between the electrodes was calibrated using gap gauge. As mentioned in the standard, six breakdown voltage tests for each sample were carried out with 2 minutes pauses between each testing and mean value of breakdown voltage was calculated and illustrated in Figure 5. The initial stand time was set to 5 minutes before every measurement were taken. While taking the measurement, the temperature of the oil and ambient should not differ within 5°C. The cell and electrodes were rinsed using the oil samples, prior taking each measurement. Based on standard IEC60296, minimum breakdown voltage value for untreated and treated oil are 30kV and 70kV, respectively.

4. Results and discussion

Figure 6 illustrates the findings from the thermal conductivity measurement. All three types of transformer oil agree with the standard nature of petroleum based mineral oil where the thermal conductivity decreases accordingly to the increase of temperature and verified with literature data [34]. Based on standards, thermal conductivity of new transformer oil/mineral oil is 0.135W/mK at 20°C and 0.125W/mK at 90°C [5]. With increasing temperature from 30°C to 70°C, the decrease in thermal conductivity of all the analyzed transformer oil was noticeable as the distance between oil molecules increase due to molecule vibration and decrease in attraction force causing difficulties of kinetic energy transfer. It can also be observed that molecules of transformer oil become less associated in term of heat transfer capacity with the temperature increment. This situation also proves the condition where viscosity of transformer oil has inverse relationship with temperature as well. These findings are aligned with the previous findings mentioned by Wang and team [35] where they have also studied about the relationship between temperature variance and thermal properties of transformer oil.

UPATO has higher thermal conductivity compared to NTO and PATO due to water molecules dissolved within the oil. Water has higher thermal conductivity value corresponding to temperature rises. For instance, at 50°C, thermal conductivity of NTO, PATO and UPATO falls in the range of 0.125 W/mK until 0.131 W/mK whereas at the same temperature, thermal conductivity of pure water falls in
the range of 0.6387 W/mK to 0.6445 W/mK [36]. Water transports heat through convection method and dependent to temperature variance. These findings prove that the presence of water could positively influence the thermal conductivity of unpurified oil. Thermal conductivity of UPATO has positive increment percentage in the range from 1.54% to 3.13% in comparison with NTO. At 30°C, thermal conductivity of UPATO is lower than NTO as water molecules in UPATO does not react yet at ambient temperature. PATO has the lowest thermal conductivity compared to NTO and UPATO as it has undergone the purification and filtration process besides losing the thermal properties due to the service ageing time.

The behavior pattern as illustrated in Figure 6 shows that purification process does change the thermal properties of transformer oil especially when the contaminants such as dusts and water have been removed. This novel finding justifies that thermal conductivity value is related to moisture presence and can be used to verify the efficiency of the filtration process too. This argument is also supported by previous research done by Lopatkiewicz et.al [26] where thermal conductivity was found to be positively affected with the increase function of water content from 0.5% to 4.8%.

![Figure 6 Variation of thermal conductivity with temperature difference](image)

![Figure 7 Breakdown voltage at ambient temperature](image)

Breakdown voltage of the samples was measured at ambient temperature and mean values are illustrated in Figure 7. As discussed before, moisture content in UPATO is expected to be higher compared to PATO and NTO. This can be deduced from the breakdown voltage of UPATO which is lower compared to PATO and NTO due to the presence of water that delivers charge carrier. Through the axiom findings, it can be observed that the breakdown voltage of PATO was increased by 46.13% compared to UPATO which indicates the reduction of moisture content after the purification process. Additionally, PATO possesses higher breakdown voltage, slightly 12.2% lesser than the value of NTO. In fact, the value of breakdown voltage for NTO is lower than the expected value of 60kV. This might be caused by the presence of moisture due to unavoidable environmental impact during storage process. Nevertheless, NTO was not been purified prior to the sampling process. Subsequently, this proves that eliminating or reducing water content will improve the insulation properties of aged oil thus ensuring the safety of the traction transformer. Even though the presence of water looks promising in positive contribution for thermal properties, but water content will be a negative factor for dielectric properties especially for breakdown voltage. A novel non-mathematical relationship can be deduced from the findings of this investigation as shown in Equation 1.

\[
\text{thermal conductivity} \propto \text{breakdown voltage} \land \text{water content}
\]

In other words, UPATO could not be continued in service and must be treated through purification and filtration process due to the critical damage towards dielectric properties.
5. Comparison with other investigators
The results of current study were compared to previous research to validate the trend. Toudja et al. [18] investigated the impact of ageing and moisture on the dielectric properties of naphthenic mineral oil. Three different oil samples were used in their study - new oil sample, oil sample from transformer after one year of operation and oil sample from a 15-year-old operating transformer. They have concluded that by increasing the number of water drops into the oil, it can decrease the breakdown voltage value regardless the earlier condition of any oil sample. Wang et al. [35] reported that thermal conductivity of transformer oil decreases linearly with increasing temperature from 253K to 363K. The similar trend is reported in the present study as well. They have extended their work by mixing different type of transformer oils to investigate the effect towards thermal properties. These comparisons between the present and previous studies justify the novel non-mathematical relationship as showed in Eq (1).

6. Conclusion
In this work, three types of different conditions of transformer oils were analysed to check the effect of water content presence on the thermal conductivity value, supported with breakdown voltage measurement. It can be clearly observed that UPATO has higher thermal conductivity compared to PATO and NTO due to influence of moisture. In addition, breakdown voltage of NTO is higher than PATO and UPATO, inferring that aged oil is losing the insulation properties over time. Presence of water was found to give negative impact towards dielectric properties and positive impact to thermal properties but considering the impact of water towards the insulation and oxidation, water molecules must be removed or minimised in the transformer oil thus prolonging the life span the traction transformer. In conjunction, this study also shows that purification process used by rail industry has significant impact towards removing water and impurities in the aged, used oil. In addition, the lack of thermal conductivity after years of service has led to numerous studies involving treatment of aged transformer oil or modifying the current aged oil such as replacement to natural ester, synthetic ester and addition of nanofluid.

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