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Comparative study of moisture treatment techniques for mineral insulating oil

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ABSTRACT

The presence of moisture is one of the factors that promote degradation of transformer insulating oils and deterioration of cellulose insulation materials in oil-immersed power transformers, which affect the lifespan of the transformers. Realizing the importance of moisture in transformer insulating oils, this study compares the effectiveness of three moisture treatment techniques nitrogen bubbling technique (NBT), molecular sieve technique (MST), and vacuum oven technique (VOT)) for mineral oil (MO). The moisture content and AC breakdown voltage of the MO samples before and after moisture treatment were measured using Karl Fischer coulometric titrator and portable oil tester, respectively, in accordance with the American Society for Testing and Materials (ASTM) D1533 and ASTM D1816 standards. The results showed that NBT is the best moisture treatment technique for the MO, where the NBT reduced 80.79% of moisture present in the oil, followed by MST and VOT, which reduced 72.87 and 42.28% of moisture, respectively. The results also showed that the AC breakdown voltage of the MO samples after moisture treatment was improved owing to the reduction in moisture content.

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1. INTRODUCTION

Power transformers are expensive, valuable assets in electrical power networks. The performance of power transformers is mostly dependent on their insulation system, where better insulation condition means a longer lifespan for the transformers. The insulation system of oil-immersed power transformers is a combination of solid insulation (paper, pressboard) and liquid insulation (insulating oil). The insulating oil serves as insulator, coolant, and indicator of the health status of the power transformer.

To date, mineral oils (MOs) are the most widely used insulating oils in power transformers owing to their low cost and good oxidation stability, cooling performance, and dielectric strength. In general, insulating oils are subjected to thermal, electrical, and chemical stresses during transformer operation. These stresses age the insulating oils, producing by-products such as moisture. It has been reported that the presence of moisture in the insulating oils significantly accelerates the ageing process of cellulose insulation materials. In addition, moisture is a product of cellulose ageing [1]. The existence of moisture in the insulating oil influences the dielectric strength of both the insulating oil and cellulose paper insulation in the transformer

[2]–[4]. This can reduce the partial discharge inception voltage and bubbling temperature [5]. Furthermore, a high moisture content can result in the emergence of gas bubbles, especially when there is a sudden spike in temperature, which is the case during emergency overload [6].

Moisture in insulating oils exist in three forms: i) free water, ii) dissolved water, and iii) chemically bound water [7]. The origin of moisture in power transformers is reportedly from i) residual moisture left after manufacturing of the transformer, ii) moisture ingress through the seals and breathing system, and iii) moisture produced through decomposition of the cellulose insulation materials. According to IEEE Std 62 [8], the paper insulation can be classified as wet paper (moisture content: 2–4%) or dry paper (moisture content: <2%).

Because of the adverse effects of moisture in power transformers, it is necessary to reduce the moisture content of the insulation materials. In practice, the insulating oil is passed through an oil processor combined with a heating and vacuum system to remove moisture. However, the oil processor is incapable of removing moisture from the cellulose insulation materials. Another technique involves purging dry, high purity nitrogen gas on the surface of the insulating oil for free-breathing transformers using a dissolved oxygen and moisture removal system [9]. The dissolved gases (e.g., oxygen) in the insulating oil as well as moisture will initially diffuse into the gaseous space of the conservator, which is above the surface of the insulating oil. This occurs because of the volatile nature of the dissolved gases and the tendency of moisture to migrate from higher concentrations towards lower concentrations (i.e., the moisture migrates from the cellulose insulation materials to the insulating oil and then to air) [10]. Hence, continuous purging of nitrogen on the surface of the insulating oil transports the gases and moisture from the insulating oil to the atmosphere. At the same time, the moisture from the silica gel is also removed as the nitrogen flows through the dehydrating breather. In-laboratory moisture removal techniques involve drying, adsorption, and nitrogen bubbling. For example, Jin *et al.* [11] reduced the moisture content of fullerene nanofluids to ~20–25 ppm by drying the nanofluids in a vacuum oven at 70 °C for 24 h. Raof *et al.* [12] filtered the palm-based neopentyl glycol diester using a membrane filter, followed by drying in an oven at 90 °C for 48 h. Wada *et al.* [13] used nitrogen bubbling treatment to reduce the moisture content of the insulating oil samples. Sitorus *et al.* [14] performed adsorption using molecular sieve 3 A (MS3A) to reduce the moisture content of *Jatropha curcas* methyl ester oil samples.

Moisture content can be assessed by chemical testing (Karl Fischer titration) or electrical testing (dielectric response measurements). There are two types of dielectric response measurements, depending on whether the measurements are carried out in the time domain (polarisation and depolarisation current test) or frequency domain (frequency domain spectroscopy). Karl Fischer titration is a simple method to determine the moisture content of cellulose paper insulation because it is based on analysis of the insulating oil. However, this technique requires moisture equilibrium curves between the insulating oil and paper insulation [15] to interpret the moisture content of the paper insulation. In contrast, dielectric response measurements are effective to directly determine the moisture content of the paper insulation.

Based on the literature survey, there are many techniques available to reduce the moisture content of insulating oils. In this study, three moisture treatment techniques for MO are compared, namely, i) nitrogen bubbling technique (NBT), ii) molecular sieve technique (MST), and iii) vacuum oven technique (VOT), each with a different working principle. The best moisture treatment technique will be proposed at the end of this paper based on the effectiveness of the technique in reducing the moisture content of the MO as well as convenience and time consumption.

2. METHOD

2.1. Materials

The materials used in this study as well as characterization on oil samples are explained in this section. The Nynas Nytro Libra MO [16] is a colourless, uninhibited transformer insulating oil. The general specifications of the MO fulfil the IEC 60296:2012 standard. Nitrogen gas, which is a chemically inert gas with a purity of 99%, was used for the NBT. On the other hand, molecular sieve used for the MST is Sigma Aldrich MS3A, which are beads with a mesh of 8–12. Characterization of oil samples are moisture content, and AC breakdown voltage.

2.2. Nitrogen bubbling technique

The first technique, namely, NBT, was adapted from a few studies [17], [18]. Firstly, 500 mL of MO was poured into a Büchner flask (Figure 1). One end of a glass hose was dipped into the MO while the other end was connected to the nitrogen gas tank. The glass hose was fixed to the Büchner flask using a stopper. Next, nitrogen gas was pumped into the Büchner flask, channelling the nitrogen gas into the MO, resulting in bubbling of the MO sample. The nitrogen bubbling treatment was carried out for 30 min. Following this, the moisture content and AC breakdown voltage of the MO sample were measured and recorded.

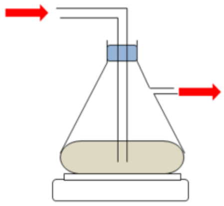

Figure 1. Experimental set-up used for the NBT

2.3. Molecular sieve technique

The second technique, namely, MST, was adapted from a number of studies [19], [20]. Firstly, 500 mL of MO was poured into a 1-L beaker. Next, 2.2 wt % of MS3A was added into the MO sample. The MO–MS3A mixture was then stirred using a hot plate magnetic stirrer for 1 h at room temperature. Next, the temperature of the MO–MS3A mixture was increased to 70 °C while the stirring was continued for another 1 h. The stirring speed was maintained at 500 rpm. After the stirring process, the MO–MS3A mixture was kept in a closed flask to avoid contact with the surrounding air overnight. Next, the MO–MS3A mixture was filtered using a vacuum filtration assembly to separate the MS3A from the MO sample. A filter paper with a pore size of 0.22 µm was used for this purpose. After the filtration process, the moisture content and AC breakdown voltage of the MO sample were measured and recorded.

2.4. Vacuum oven technique

The third technique, namely VOT, was adapted from a couple of studies [21], [22]. First, 500 mL of MO was poured into a beaker. The beaker was then placed inside the vacuum oven chamber and the vacuum oven door was closed tightly. A vacuum condition was created with the aid of a vacuum pump. The vacuum oven temperature was set at 60 °C and the moisture removal treatment was carried out for 24 h. After 1 day of drying in the vacuum oven at 60 °C, the MO sample was left to cool down to room temperature. Finally, the moisture content and AC breakdown voltage of the MO sample were measured and recorded.

2.5. Moisture content measurements

The AC breakdown voltage and dissipation factor (or power factor) of insulating oils may be affected by the moisture content of the oils. According to the American Society for Testing and Materials (ASTM) D3487 standard [23], the moisture content of MOs should be ≤35 ppm. In this study, the moisture content of the MO samples after moisture treatment was determined using Metrohm 899 Karl Fischer coulometric titrator in accordance with the ASTM D1533 standard [24]. The method is based on the oxidation of sulphur dioxide by iodine in methanolic hydroxide solution.

2.6. AC breakdown voltage measurements

AC breakdown voltage is one of the crucial properties of insulating oils. According to the ASTM D3487 standard, the AC breakdown voltage of MOs is ≥20 kV for an electrode gap distance of 1 mm and ≥35 kV for an electrode gap distance of 2 mm. In this study, the AC breakdown voltage of the MO samples was measured according to the ASTM D1816 standard [25] using Megger OTS60PB portable oil tester. Two semi-spherical (mushroom-shaped) *Verband Deutscher Elektrotechniker* electrodes with a gap distance of 1 mm was used for the measurements. The steps involved for the AC breakdown voltage measurements are described as follows. First, a minimum volume (350 mL) of MO sample was poured into the oil test vessel, and the oil temperature and room temperature were recorded. It shall be noted that the measurements should be conducted at a room temperature of 20–30 °C. Next, the vessel containing the MO sample was placed into the test chamber of the Megger OTS60PB portable oil tester, and the MO sample was left to rest for 3–5 min. Following this, the AC voltage was applied to the MO sample beginning from 0 kV and the AC voltage was gradually increased at a rate of 0.5 kV/s ±5% until breakdown occurred. In this study, five AC breakdown voltage measurements were performed for each MO sample and the mean AC breakdown voltage values were determined.

3. RESULTS AND DISCUSSION

The initial moisture content and AC breakdown voltage of the MO freshly taken from the barrel were 43.94 ppm and 8 kV respectively. The MO samples were then treated using three types of moisture treatment techniques (NBT, MST, and VOT) and the moisture content and AC breakdown voltage of the MO samples were measured. The moisture content and AC breakdown voltage of the MO samples before and after moisture treatment are presented and discussed in this section.

3.1. Moisture content

Figure 2 shows the moisture content of the MO freshly taken from the barrel (FMO), and MO after moisture treatment by VOT (MO-VOT), MST (MO-MST), and NBT (MO-NBT). It is apparent that the FMO sample had the highest moisture content (43.94 ppm) compared with the other MO samples, irrespective of the moisture treatment technique. It is worth noting that the moisture content of the FMO sample is not only high, but it also exceeds the permissible limit (≤35 mg/kg) specified in ASTM D487 standard. In contrast, the moisture content of the MO-NBT, MO-MST, and MO-VOT samples were well below the permissible limit. The high moisture content of the FMO sample may be likely due to the storage of the MO barrel on the cold cement floor, which may cause the warm air inside the barrel to condense, resulting in moisture ingress into the MO. In addition, the MO was stored in the barrel over an extended period of time and there may be leakage at the top of the barrel, which leads to contact between the MO and surrounding air. Hence, it is recommended that the cement floor should be covered with a poor conductivity material such as a wood pallet so that the barrel is not in direct contact with the cement floor.

After moisture treatment by VOT, the moisture content of the MO reduced to 25.36 ppm. This corresponds to a reduction of 18.58 ppm (42.28%), as shown in Table 1. The VOT involves a combination of heat (60 °C) and vacuum for 1 h to remove moisture from the MO. Following moisture treatment, the MO was cooled down to room temperature (20–30 °C) before the moisture content and AC breakdown voltage measurements. During the cooling period, the MO was kept in an amber bottle and the bottle was stored in a cabinet away from sunlight. However, the cabinet is not in a vacuum condition and therefore, there is a possibility for the MO to contact with the surrounding air, which leads to higher moisture content of the MO-VOT sample compared with the moisture content of the MO-MST and MO-NBT samples.

After moisture treatment by MST, the moisture content of the MO reduced to 11.92 ppm, which corresponds to a reduction of 32.02 ppm (72.87%). The reduction in moisture content is likely due to the structure of the MS3A. The porous structure of the MS3A absorbs moisture from the MO and the MS3A (and hence, moisture) is then removed from the MO by filtration. The presence of sodium, calcium, and potassium in the MS3A as well as the large internal surface area (~1,000 m^2/g), and strong ionic forces of the MS3A enable considerable amounts of moisture to be absorbed from the MO. However, the higher moisture content of the MO-MST sample compared with that of the MO-NBT sample is likely due to the contact between the MO-MST sample with the surrounding air during filtration, which is a time-consuming process.

After moisture treatment by NBT, the moisture content reduced drastically from 43.94 to 8.44 ppm, which corresponds to a reduction of 35.5 ppm (80.79%), as shown in Table 1. This is a significant improvement in moisture removal of the MO. This result is similar with the results of Wada *et al.* [13], who discovered that the moisture content of the insulating oil reduced from 50 ppm to ~10 ppm (reduction of 80%) after nitrogen bubbling treatment. In addition, NBT requires a short time (30 min) compared with MST and VOT (>24 h).

The significant reduction in moisture content of the MO-NBT sample is likely due to the fact that the moisture content is determined directly after the moisture treatment. The NBT does not require a cooling process because there is no heating involved, and the NBT is carried out at room temperature. Thus, there is only a small likelihood that the MO-NBT sample reacts with the surrounding air. According to Sabau *et al.* [9], continuous purging of nitrogen gas on the surface of the insulating oil helps extract moisture from the insulating oil. Based on the results, it can be deduced that the most effective technique to reduce moisture content of the MO is NBT, followed by MST and VOT (i.e., NBT>MST>VOT).

3.2. AC breakdown voltage

Figure 3 displays the AC breakdown voltage of the FMO, MO-VOT, MO-MST, and MO-NBT samples. It can be observed that there is an improvement in the AC breakdown voltage of the MO, regardless of the moisture treatment technique. However, only the AC breakdown voltage of the MO-MST and MO-NBT samples fulfil the requirement of >20 kV stipulated in the ASTM D3487 standard. The mean AC breakdown voltage of the FMO, MO-VOT, MO-MST, and MO-NBT samples are tabulated in Table 2, and it can be seen that the initial AC breakdown voltage of the FMO sample was 8 kV. After moisture treatment by VOT, the AC breakdown voltage of the MO increased from 8 kV to 9 kV, which is equivalent to an increase of 1 kV (12.5%). After moisture treatment by MST, the AC breakdown voltage of the MO was 20 kV, which corresponds to a remarkable improvement of 150%. After moisture treatment by NBT, the AC breakdown voltage of the MO improved dramatically from 8 kV to 25 kV, corresponding to an increase of 212.5%. The improvement in AC breakdown voltage for the MO-VOT, MO-MST, and MO-NBT samples can be attributed to the reduction in moisture content of the MO.

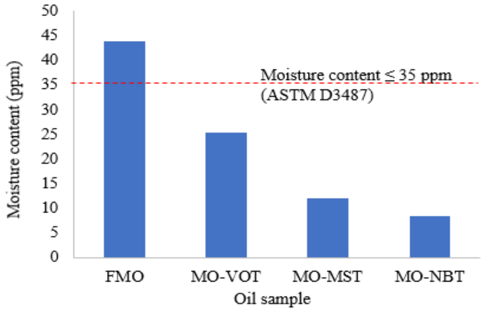

Figure 2. Moisture content of the MO samples before and after moisture treatment

Table 1. Moisture content of the MO samples after moisture treatment.

Sample	Moisture content (ppm)	Percentage improvement (%)
MO-VOT	25.36	42.28
MO-MST	11.92	72.87
MO-NBT	8.44	80.79

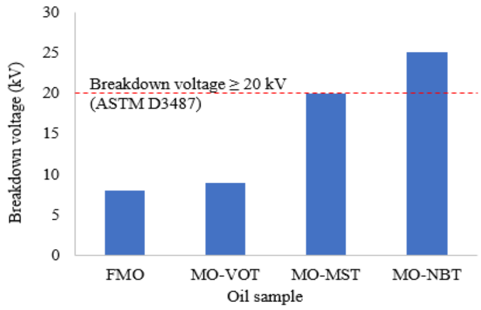

Figure 3. AC breakdown voltage of the MO samples before and after moisture treatment

Table 2. AC breakdown voltage of the MO samples after moisture treatment

Sample	AC breakdown voltage (kV)	Percentage improvement (%)
MO-VOT	9	12.5
MO-MST	20	150.0
MO-NBT	25	212.5

4. CONCLUSION

In this study, three moisture treatment techniques (NBT, MST, and VOT) in reducing the moisture content of MO have been compared. The following conclusions can be drawn based on the results of this study: i) NBT is the most effective technique in reducing the moisture content of MO, followed by MST and VOT; ii) the NBT only requires 30 min to remove moisture from the MO. In contrast, the MST and VOT require more than 24 h. Hence, the NBT is not only the most effective moisture removal technique, but it is also the least time-consuming technique; and iii) the AC breakdown voltage of the MO is dependent on its moisture content, where a higher moisture content results in a lower AC breakdown voltage.

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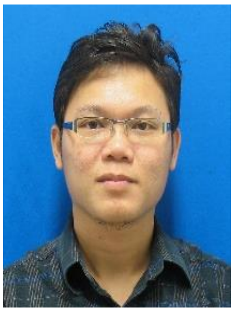

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