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Investigation Seebeck Effect of Industrial High Voltage Transformer Oil Towards Industrial Insulator Oil Condition Detection

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ABSTRACT

Transformer oil serves as the main dielectric and interacts with solid insulation, encounters the environment, and conveys a lot of information. However, undesirable contamination of transformer oil like water or moisture in the transformer oil will reduce the transformer's effectiveness. This study is the first investigation of the potential of using the thermoelectric effect for transformer oil condition testing towards high voltage insulator oil condition detection. This study has found that the used oil sample with various percentages of water content produced a different Seebeck coefficient which shows the potential of using the thermoelectric effect as a simple, cheap, and versatile method to test industrial oil insulator conditions. The results of the Seebeck coefficient for each condition are 0.0003 mV/K (original), 0.0107 mV/K (4 % of water added), and 0.0131 mV/K (40 % of water added), respectively. The industrial oil shows different Seebeck magnitude between oil before and after thermal aging which show a significant decrease of Seebeck magnitude of the industrial oil insulator with an increase of thermal ageing.

1. Introduction

Power transformers stand out as critical and expensive components in power systems, enduring various electrical, thermal, and chemical stresses [1]. The transformer health index, derived from meticulous test data and field inspections, serves to evaluate the transformer's condition, and estimate its remaining operational life. Essential to these systems is transformer oil, predominantly based on mineral oil, known for its stable electrical insulation at elevated temperatures and multifaceted functions including cooling, insulation, and prevention of corona discharge and arcing.

However, the susceptibility of insulation oil to degradation, especially under high temperatures in the presence of oxygen and moisture, poses a considerable risk of insulator oil ageing and lowering

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breakdown voltage. Detecting contaminants, particularly moisture, becomes imperative to forestall the development of partial discharges and prevent potential failures in high-power systems. Presently, engineers employ sophisticated diagnostic methods such as furan analysis, liquid chromatography (HPLC), dissolved gas analysis (DGA), degree of polymerization (DP) measurement, and moisture analysis in transformer oil [2]. Despite their efficacy, these methods are characterized by their high cost and complexity.

Factors influencing breakdown voltage, including contaminants, oil degradation, and moisture, must be mitigated to ensure the reliability of insulating oils in HV equipment [1,2]. Current monitoring procedures involve rigorous standards using analytical methods like furan analysis, HPLC, DGA, DP measurement, and moisture testing for transformer oil [2]. Despite their effectiveness, these methods are intricate and expensive, involving resource-intensive and inefficient processes [1].

In response to these challenges, this study proposes an innovative oil condition detection approach utilizing the thermoelectric effect, specifically the thermoelectric Seebeck effect. This effect involves generating electrical voltage from temperature differences within a material. The Seebeck effect's is expected to produce promising oil condition detection. The Seebeck effect phenomenon of conventional solid state thermoelectric is when a temperature difference between the ends of something like a thermocouple, allowing electrical potential to be generated between them [3,4]. According to the Seebeck effect Eq. (1), when a material is heated or cooled on one side, charge carriers diffuse along a temperature gradient, causing a potential difference (V) to build up across the semiconductor or conductor. The internal electrical field that is created as charges migrate from the hot to the cold side balances the gradient in the number of charge carriers at equilibrium. The sign of the potential difference, which is conventionally characterised as the potential of the cold side with respect to the hot side, is determined by the type of predominant charge carriers. The magnitude of this effect is described by the Seebeck coefficient. The potential difference could be either beneficial or negative depending on the kind of majority it conveys.

They also can produce the thermoelectric effect in a liquid state in the presence of temperature difference due to Soret effect [5]. This type of thermoelectric behaviour is usually called a thermal galvanic cell or thermoelectrochemical cell. The thermo-electrochemical cell Seebeck characteristic is driven by reaction entropy, $\Delta S_{reaction}$ where F stands for the Faraday constant and n indicates a number of electrons or Soret effect.

$$S_e = \frac{\Delta V}{\Delta T} = \frac{\Delta S_{reaction}}{nF} \tag{1}$$

According to Born's model, the ΔSreaction equation is written as in Eq. (2):

$$\Delta S_{reaction} = \frac{-e^2 N}{2\varepsilon T}\left(\frac{d\ln\varepsilon}{d\ln T}\right)\left(\frac{Z_{ox}^2}{r_{ox}} - \frac{Z_{red}^2}{r_{red}}\right) \tag{2}$$

where e is the electronic charge, N is Avogadro’s constant, ε is the dielectric constant, Z_{ox} is the oxidant valence charges, Z_{red} is the reductant valence charges and r_{ox} and r_{red} are the corresponding radius. Water contained in insulator oil provides cations and anions that can generate voltage generation due to the Soret effect and thermoelectric effect. The utilization of the Seebeck effect in determining moisture level, oil degradation, and breakdown voltage levels in transformer oil is rooted in their shared characteristic of dielectric permittivity. The dielectric permittivity serves as a common ground, providing a basis for establishing a connection between the known breakdown voltage and the corresponding Seebeck trend through interpolation of the graph. The equation governing the Seebeck effect incorporates a natural logarithm of dielectric permittivity, which, although conceptually intricate, fundamentally aligns with this observed trend.

Thus, this study investigates the proof of concept of the thermoelectric method as a simple new method to detect contaminants such as moisture contained and thermal ageing of insulator oil for breakdown prevention for the first time. Seebeck coefficient of difference transformer oil condition is tested such Seebeck of transformer oil of various water content and the transformer oil Seebeck before and after thermal aging as a proof of concept to proof the different of condition of transformer oil will producing Seebeck magnitude and sign toward HV insulator oil condition detection.

2. Methodology

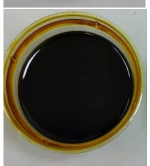
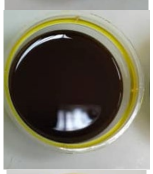
2.1 Industrial Transformer Oil Sample Preparation with Various Conditions for Seebeck Measurement

The industrial transformer oil type paraffin purity 99.99 % is donated from the industrial company in Sabah, Malaysia, Penulaju Sdn. Bhd. The experiment was conducted using different industrial oil conditions that are shown in Table 1 and Table 2, for proof of concept using thermoelectric effect application for insulator oil condition detection. The industrial transformer oil that has been tested was paraffin oil (mineral oil). Different volumes (in ml) of water percentages of 4% and 40 % were added to the original oil. Industrial transformer oil that has thermal aging has also been tested by baking the oil at fixed low temperature of 85 °C in the baking oven for 7 days and 14 days. The colour of the industrial oil changes from colourless to dark solution as shown in Table 2.

Table 1
Sample prepared for different water content

Sample type	ml % water added
A	0 %
B	4 %
C	40 %

Table 2
Sample prepared for different thermal aging condition

Sample type	Thermal aging	
D	0 days	
E	7 days	
F	14 days	
G	28 days	

2.2 Seebeck Measurement Setup

This study measured Seebeck of industrial transformer oil in two conditions. First use a non-isothermal two-compartment setup as shown in Figure 1, where there are a cold side and hot side that consist of an inert working electrode and counter electrode for the hot side and cold side respectively. The two compartments were connected using a single glass tube and the distance between the hot and cold side is 5 cm. The hot compartment was heated using a ceramic heater under water bath conditions whilst the cold compartment is exposed to ambient room temperature. The temperature for all measurements is confirmed by using a thermometer and thermocouples Type-K. This non-isothermal setup is used for industrial oil that has different water content percentages.

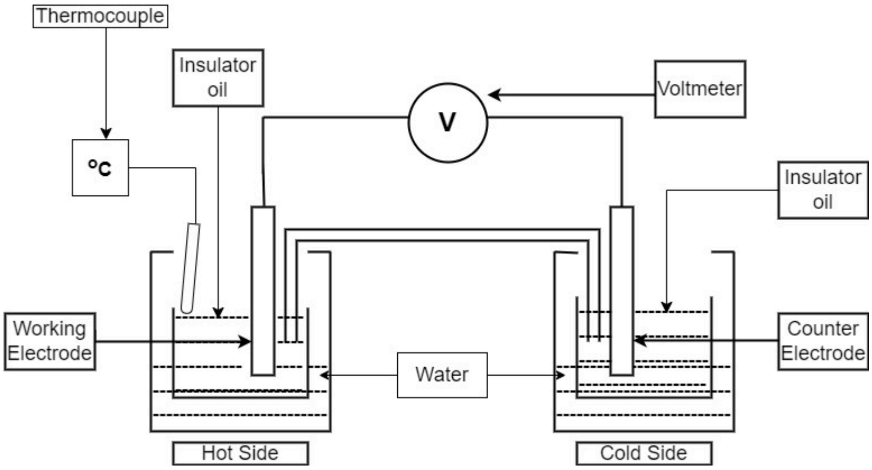


Fig. 1. Schematic diagram for non-isothermal Seebeck measurement testing of different water content in industrial transformer oil

Then for more user-friendly oil testing with more control environment, isothermal chamber oil for Seebeck testing is designed using SOLID work and printed using Anycubic resin 3D printer and assembled using silicon rubber gasket to avoid leakage. Two inert Platinum electrodes were used for working electrode and counter electrode for hot side and cold side respectively. The measurement setup in detail is as shown in Figure 2 below and the setup is used to test the Seebeck coefficient of industrial transformer oil that has different thermal aging conditions. The temperature is confirmed using RTD type thermocouple and Peltier cooler and Peltier heater is used to create temperature difference of the chamber.

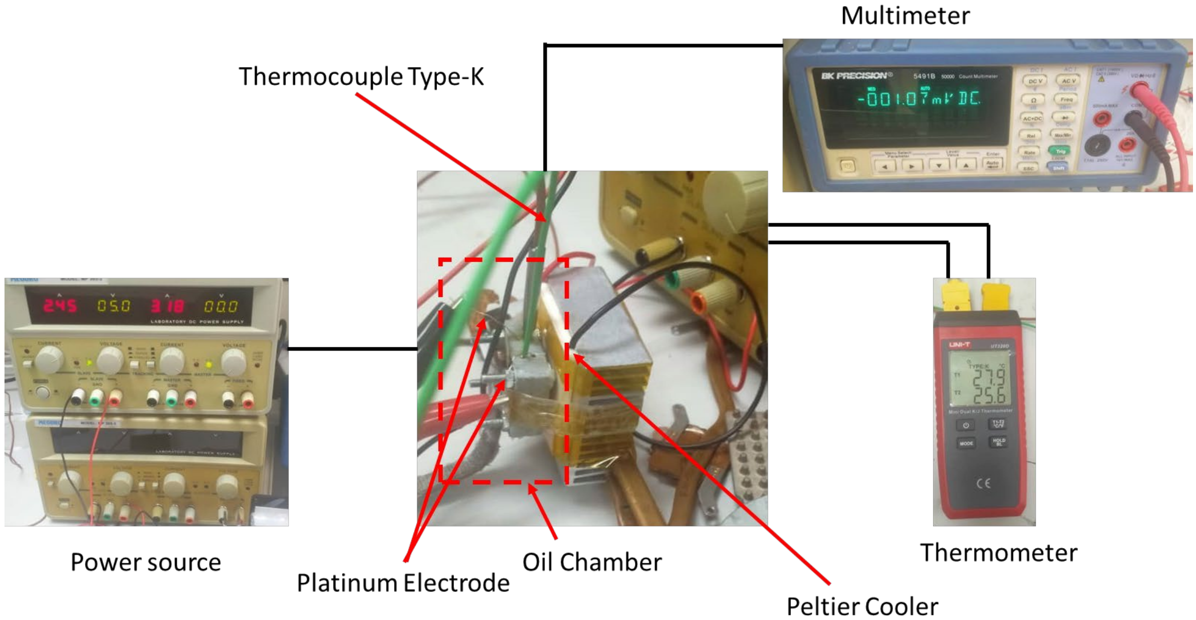


Fig. 2. Seebeck measurement testing setup using 3D printed isothermal oil chamber for test different thermal aging condition of industrial transformer oil

3. Results

3.1 Seebeck Effect of Different Water Content in Industrial Transformer Oil using Non-Isothermal Condition

The plot in Figure 3 illustrates the relationship between the Seebeck coefficient and the reading temperature, obtained from a non-isothermal experiment. The graph was generated by plotting the voltage readings from the voltmeter against the corresponding temperature. The Seebeck was extracted from the gradient of the voltage plot versus temperature differences based on Eq. (1). The results indicate that when no water was added to the oil, the Seebeck coefficient was -0.0003 mVK^{-1}. However, when 4% water was added, the coefficient increased to -0.0107 mVK^{-1}, and further increased to -0.0131 mVK^{-1} when 40% water was added. These findings demonstrate that the addition of different amounts of water leads to distinct variations in the Seebeck coefficient, suggesting a novel and straightforward approach for detecting water in insulating oil. This outcome suggests that the differing diffusion rates of water within the oil give rise to distinct trends in the Seebeck coefficient.

The Soret effect, in this context, refers to the phenomenon where the presence of a concentration gradient in a mixture (such as oil and water) leads to a thermoelectrical potential generation. In other words, when there is a variation in the concentration of water within the oil due to the presence of a thermal gradient [6], it causes a difference in electrical potential. This effect arises due to the unequal diffusion rates of different components in the mixture, resulting in a different Seebeck trend in functions of water content. In the given experiment, the varying Seebeck coefficient can be attributed to the Soret effect caused by the differing diffusion rates of water in the oil [7].

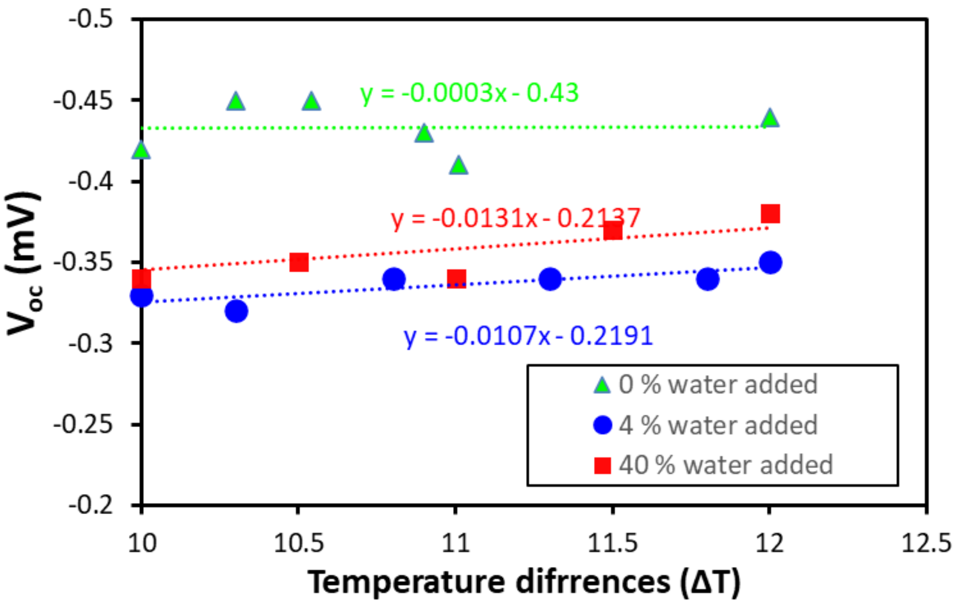


Fig. 3. Thermolectric potential of different various industrial oil transformer water content using non-isothermal cell

Figure 4 shows plot of Seebeck coefficient versus percentage of water content. The Seebeck trend shows exponentially increase with the increase of water content. The Seebeck coefficient, which measures the thermoelectric voltage produced in a material in response to a temperature gradient, typically depends on the composition of the material. In the case of oil transformers, the addition of water content can have a significant impact on the Seebeck coefficient. When water is introduced into the oil of a transformer, it creates a heterogeneous mixture. The water molecules can disrupt the uniformity of the oil, leading to variations in the composition and resulting in localized concentration gradients [7,8]. These concentration gradients give rise to the Soret effect, where temperature gradients produce different carrier concentrations and different diffusion rates of water and oil molecules. As the concentration of water in the oil increases, the Soret effect becomes more pronounced. At low water concentrations, this study inferred that there is a large non-uniform distribution of water that leads to enhanced different carrier concentrations within the oil. This, in turn, causes a greater temperature difference across the material and subsequently amplifies the Seebeck effect at very low concentrations.

The exponential rise in the Seebeck coefficient with increasing water content in oil transformers can be attributed to the non-linear relationship between the concentration gradient and the resulting temperature gradient. The Soret effect intensifies as the concentration of water rises, leading to a more substantial carrier concentration gradient and a corresponding exponential increase in the Seebeck coefficient [9]. From the results, it is important to note that the relationship between the water content and the Seebeck coefficient may not be a simple linear correlation [10-13]. Other factors, such as the type of oil used, the specific electrode type and active area, and the temperature range of the experiment, can also influence the observed behaviour [14-17]. Therefore, careful experimental investigation and analysis are necessary to fully understand and characterize the relationship between water content and the Seebeck coefficient in oil transformers. Figure 4 shows the breakdown voltage testing using IEC 60156 standard breakdown testing has shown significant Seebeck coefficient indication to actual breakdown voltage level. The enhancement of the Seebeck effect with an increase of water content can indicates lower of actual breakdown voltage.

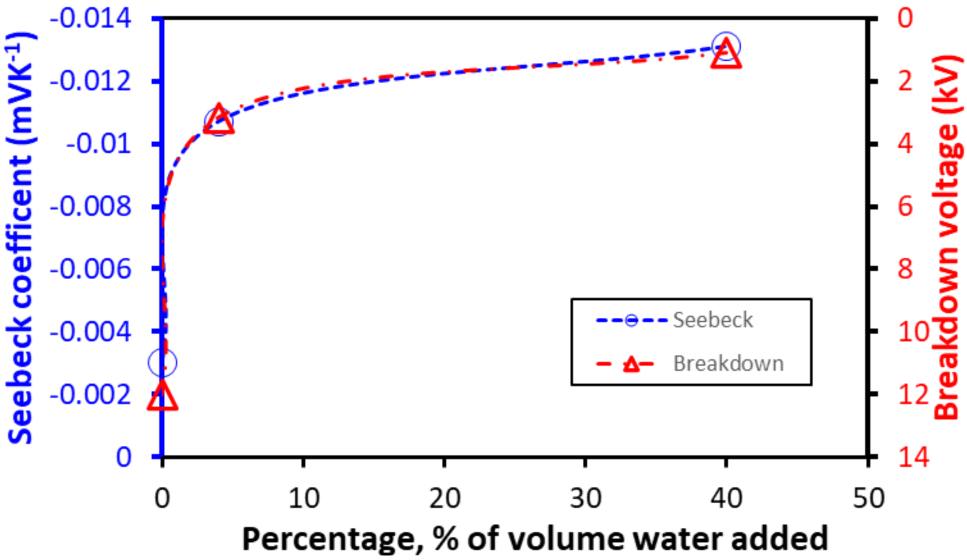


Fig. 4. Comparison of Seebeck coefficient and breakdown voltage

3.2 Seebeck Effect of Different Thermal Ageing Conditions of Industrial Transformer Oil using Isothermal Condition

In this study, the non-isothermal setup is improved by testing the Seebeck in isothermal conditions to improve the experimental setup to be more practical towards industrial oil testing applications. Figure 5 shows the Seebeck trend of different oil thermal ageing conditions 0, 7, 14 and 28 days. The result for the original oil shows improvements of Seebeck value due to the distance of the electrode where the Seebeck coefficient is increasing from -0.0003 mVK^{-1} to -0.0743 mVK^{-1} non-isothermal conditions at low-temperature operation and temperature difference since the distance between hot and cold electrode is decreased from 5 cm to 1 cm. Thus, the thermal diffusion length shows an important parameter to be further investigated in future for producing high-sensitivity detection of oil conditions using the thermoelectric effect [18-21].

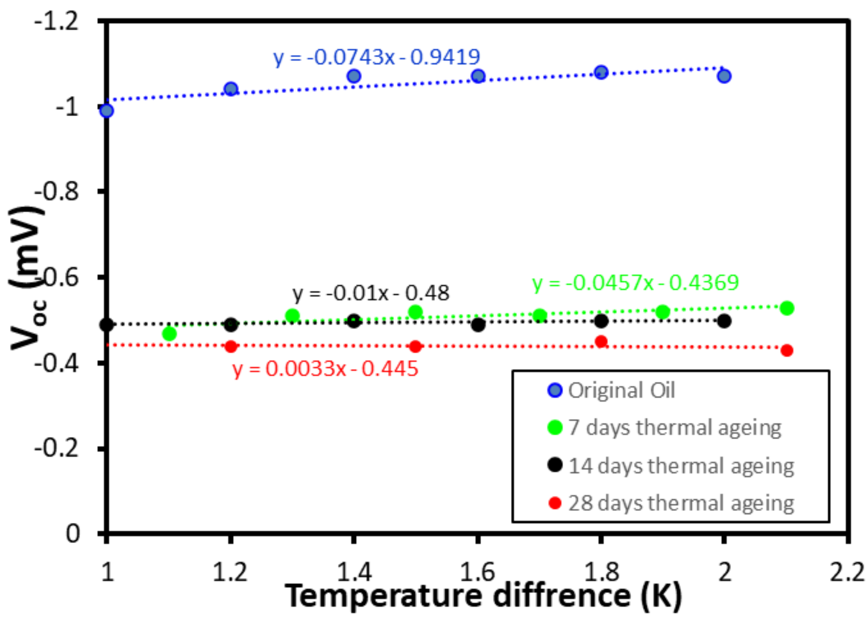


Fig. 5. Thermoelectric potential of various thermal ageing oil condition using isothermal cell

The trend of the Seebeck coefficient with respect to thermal aging is depicted in Figure 6. The results obtained from this study indicate notable variations in the Seebeck coefficient due to thermal aging with decrease of Seebeck coefficient with an increase of thermal ageing. These findings highlight the considerable potential of utilizing this method to distinguish the condition of industrial oil as it undergoes thermal ageing. The observed changes in the Seebeck coefficient are inferred that can be attributed due to the combined effects of Seebeck and Soret phenomena. The Seebeck effect refers to the generation of an electric potential difference when there is a temperature gradient across a material. In this case, as the industrial oil undergoes thermal ageing, it experiences changes in its molecular composition and structure. These alterations lead to variations in the diffusion rates of different components within the oil, resulting in the generation of concentration gradients.

The Soret effect, which is influenced by these concentration gradients, gives rise to temperature gradients within the oil. Consequently, the temperature gradient impacts the Seebeck coefficient, leading to the observed changes. The extent and nature of the variations in the Seebeck coefficient can provide valuable information about the condition of the industrial oil, specifically its level of thermal aging. By analyzing the trend of the Seebeck coefficient as a function of thermal aging, it becomes possible to differentiate the condition of industrial oil based on its unique Seebeck characteristics. This approach offers a promising method for assessing the state of the oil and monitoring its degradation due to thermal aging. It is important to note that the Seebeck effect and the Soret effect are interrelated phenomena in this context. The variations in the Seebeck coefficient observed in Figure 6 are a consequence of the Soret effect caused by the concentration gradients resulting from thermal ageing. By studying and understanding these effects, researchers and industry professionals can gain insights into the condition of industrial oil and make informed decisions regarding maintenance and replacement strategies.

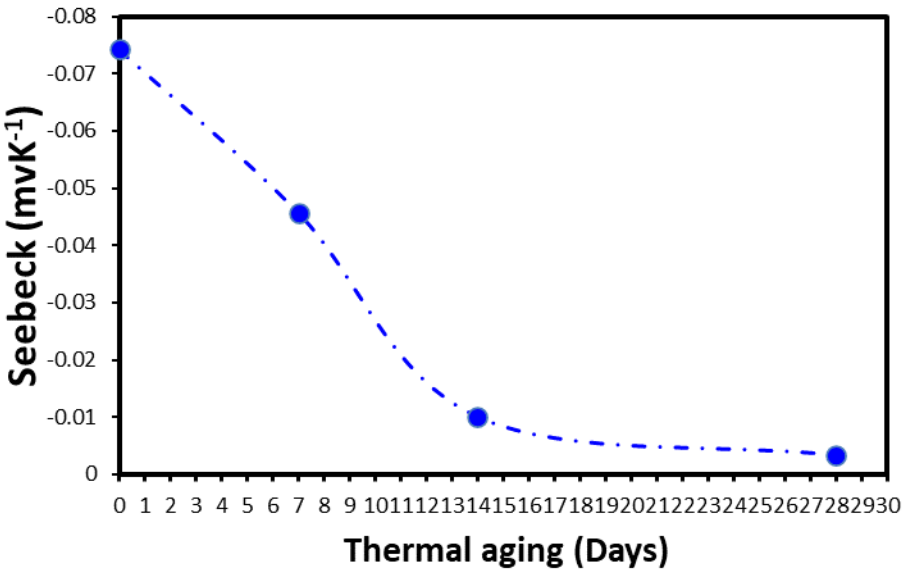


Fig. 6. Different various industrial oil transformer

4. Conclusions

The studies explored the use of thermoelectric effects, specifically the Seebeck effect, for detecting contaminants in high-voltage insulating oil. The Seebeck coefficient proved effective in indicating water content, displaying a clear increase with rising water levels. Additionally, thermal aging was investigated, revealing a significant decrease in the Seebeck coefficient, making it a potential indicator of oil condition and degradation. The observed variations were attributed to the combined effects of Seebeck and Soret phenomena, influenced by molecular composition changes and diffusion rates. These findings offer valuable insights for utilizing thermoelectric methods, particularly the Seebeck effect, in assessing the health and lifespan of power transformers. The simplicity and cost-effectiveness of this approach provide a promising alternative to traditional diagnostic methods. The studies lay the foundation for further research, emphasizing the potential of thermoelectric diagnostics for transformer health assessment and predictive maintenance through ongoing investigations and method refinements.

Credit Authorship Contribution Statement

Mohd Aszwan Jimal-Investigation, Writing; Megat Muhammad Ikhsan Megat Hasnan - Project administration, Conceptualization, Writing Methodology; Pungut Ibrahim- Formal analysis, Visualization; Ahmad Razani Haron- Data curation, Validation; Nur Aqilah Mohamad- Funding acquisition, Resources; Herwansyah Lago-Proof reading; Hazlihan Haris and Chai Chang Yii- review & editing-Markus DIantoro-3D-printing and physics validation.

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