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A Preliminary Study on Optimizing the In-Lab Reclamation Process Parameters of Used Transformer Oils Using the Taguchi Method

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ABSTRACT

In this study, the Taguchi method is used to optimize the in-lab reclamation process parameters of used transformer oils. The main benefit of this method is that one can determine the optimum parameters of the reclamation process in a simple, efficient, and cost-effective manner. The L_4 (2^3) Taguchi design is used to optimize the following process parameters: (1) weight of the Fuller's Earth adsorbent, (2) stirring speed, and (3) oil temperature. These parameters are optimized in order to minimize the AC breakdown voltage, total acid number, and dynamic viscosity of the reclaimed transformer oil samples. The signal-to-noise ratios are determined for each process parameter in order to identify the significance of each factor on the three output responses. Based on the results, the oil temperature has the most significant effect on the AC breakdown voltage whereas the weight of the Fuller's Earth adsorbent has the most significant effect on the total acid number and dynamic viscosity of the reclaimed transformer oils. Tests are carried out to verify the results using the optimum reclamation process parameters and indeed, it is found that there is significant improvement in the mean AC breakdown voltage, total acid number, and dynamic viscosity for the reclaimed transformer oil compared with those for the used transformer oil. It is believed that this method can be an indispendable tool to determine the optimum parameters for the reclamation process without going through the hassle of trial and error associated with conventional experimentation.

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1. INTRODUCTION

Transformer oil is a multi-functional medium, where it serves as an insulator, coolant, and a qualitative indicator of the health status of oil-immersed power transformers used in electrical power networks [1]. The dielectric media typically used in transformers are petroleum-derived oils such as such as mineral insulating (MI) oils and silicone insulating (SI) oils. The lifetime of a transformer is primarily dependent on the insulating medium used in the transformer, which can be either solid or liquid [2]. Insulating liquids are generally preferable because these liquids serve a dual purpose: insulator and coolant. It is expected that MI oils will continue to be in use for at least a decade and it is known that the dielectric properties of the oils will be altered as a consequence of aging, which will degrade the efficiency of the transformers. In addition, it is common knowledge that the insulating systems of transformers will deteriorate gradually due to their high operating temperatures as well as high levels of moisture and oxidation of the transformer oils. The insulating systems deteriorate due to changes in the chemical structures of the dielectric media as a result of high thermal stresses which adversely affect the transformer operation and if left unchecked, will lead to catastrophic failure of the transformers [3], [4]. MI oils are commonly used in insulating systems of high-voltage power transformers because these oils are tried-and-tested, cost-effective, and easily manufactured. However, MI oils, like all oils, will age over time with continuous use. For this reason, it is imperative to maintain the transformers to ensure that they are fit for service. The maintenance program includes refurbishing the transformers or replacing the MI oils with new ones, which is rather costly approach [5]. As the MI oil ages, oxidation takes place in the MI oil which will alter its dielectric properties and ultimately deteriorate the efficiency of the transformer [6]. Hence, much effort has been made over the years to reclaim MI oils so that these oils can be reused in the transformers before refurbishment becomes necessary [5], [7], [8].

There are three ways in which MI oils can be treated: (1) re-refining, (2) reconditioning, and (3) and reclamation. Reclamation is an economically viable technique because it reduces the disposal of used MI oils into the landfill and minimizes the need to purchase new MI oils, which is unwise considering the escalating price of petroleum-derived oils. The main purpose of reclamation is to rejuvenate the transformer oil by eliminating the presence of contaminants. The reclamation process involves removing conataminants and degradation by-products such as polar, acidic, or colloidal materials from used transformer oils by using a chemical or adsorbent. Clay or activated carbon have been used in the reclamation process [7]. The main advantage of the reclamation process is that the properties of used transformer oils can be restored such that the properties are comparable to those for new transformer oils. Recent studies have shown that reclamation effectively reduces the levels of undesirable molecular species found in in-service transformer oils, such as sludge, acids, ketones, other polar species and water generated as a result of oil degradation [9]–[11]. Fuller’s Earth is adsorbent clay found in nature, which is an active material that consists of internal and external polar active sites. These polar active sites allow the non-polar components of the oil to pass through without retention. However, the polar contaminants or degradation compounds dissolved in the used transformer oil are retained in the adsorbent clay [7]. Furthermore, Fuller’s Earth is proven to be the most satisfactory adsorbent clay to purify used transformer oils because of its ability to neutralize acids, adsorb polar compounds, and decolorize the used transformer oils, resulting in clear oils with favorable properties. The Taguchi method is a design of experiment technique used to determine multiple output responses despite natural variations in the inputs. The Taguchi method enables one to propose two-level, three-level, and mixed-level fractional factorial design in the form of orthogonal arrays [12]–[16]. The Taguchi method identifies the controlled factors that will minimize the effects of noise factors. Furthermore, the Taguchi method involved the use of orthogonal arrays in order to estimate the effects of the factors on the mean and variation of the response. More importantly, in the Taguchi method, one factor does not affect the estimation of a different factor because each factor is assessed independently of other factors.

Therefore, in this study, the Taguchi method is used to optimize the in-lab reclamation process parameters of used transformer oils. The reclamation process parameters (i.e., controlled factors) used in this study are: (1) weight of the Fuller’s earth adsorbent, (2) stirring speed used to mix the used transformer oils with the adsorbent, and (3) temperature of the used transformer oils when they are mixed with the adsorbent. The Taguchi method is used to optimize the aforementioned parameters in order to maximize the AC breakdown voltage (BdV), and minimize the total acid number (TAN), and dynamic viscosity of the reclaimed transformer oils. The method implemented in this study is superior to the one-factor-at-a-time (OFAT) method because it is reduces the number of experiments, time, and overall cost associated with traditional experimentation.

2. EXPERIMENTAL DESIGN

2.1. Design of experiments

The L_4 (2^3) orthogonal array was used in this study, which consists of four rows (corresponding to the number of experimental runs) and two columns for two levels. As mentioned previously, three reclamation process parameters (weight of Fuller’s Earth adsorbent, stirring speed, and oil temperature) were chosen for the experiment in order to observe the degree of significance of each process parameter on the output responses (AC BdV, TAN, and dynamic viscosity). Two levels were considered for each reclamation process parameter, as shown in Table 1. Table 2 shows the list of experimental runs according to the L_4 orthogonal array generated using Minitab Version 17 statistical software.

Table 1. Reclamation process parameters and the levels considered for the Taguchi method

	Reclamation process parameters		
Level	Weight of Fuller's Earth adsorbent (g)	Stirring speed (rpm)	Oil temperature (°C)
1	50	500	60
2	100	1000	80

Table 2. L_4 (2^3) orthogonal array for the reclamation process

	Reclamation process parameters		
Experimental run	Weight of Fuller's Earth adsorbent (g)	Stirring speed (rpm)	Oil temperature (°C)
1	50	500	60
2	50	1000	80
3	100	500	80
4	100	1000	60

The AC BdV, TAN, and dynamic viscosity of the reclaimed transformer oil were analyzed for each test run based on the signal-to-noise (S/N) ratio. The S/N ratio is an important parameter in the Taguchi method and it is used to analyze the output responses by reducing the sensitivity of the system to the sources of variation, which in turn, produces better results [17], [18]. There are three categories of S/N ratio: (1) "smaller is better", (2) "nominal is best", and (3) "larger is better". In this study, the "larger is better" S/N ratio was used to maximize the AC BdV for the reclaimed transformer oil, as given by Equation (1). The "smaller is better" S/N ratio was used to minimize the TAN and dynamic viscosity of the reclaimed transformer oil, as given by Equation (2).

$$\frac{S}{N} = -10 \log \left| \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right| \quad (1)$$

$$\frac{S}{N} = -10 \log \left| \frac{1}{n} \sum_{i=1}^{n} y^2 \right| \quad (2)$$

Here, n is the number of repetitions under the same design parameter conditions, y_i is the measured result, and the subscript i indicates the number of design parameters in the orthogonal array. Following this, the S/N ratios of the reclamation process parameters were analyzed based on the delta and rank to determine the contribution of each reclamation process parameter on the AC BdV, TAN, and dynamic viscosity of the reclaimed transformer oil. Tests were carried out using the optimum reclamation process parameters and the AC BdV, TAN, and dynamic viscosity of the transformer oil (before and after reclamation process) were measured in order to verify the process parameters predicted using the Taguchi method.

2.2 Sample preparation

The used MI samples (courtesy of Tenaga Nasional Berhad) were collected from an in-service distribution transformer manufactured by ACEC Transformers, as shown in

Figure 1. The transformer rating is 500 kVA, 11/0.433 kV. It shall be noted that the MI oil has undergone severe aging for nearly 30 years because the MI oil has never been filtered, replaced, or reclaimed since the transformer was manufactured in 1986. Table 3 shows the properties of the used transformer oil prior to the reclamation process.

(a) (b)

Figure 1. (a) In-service distribution transformer manufactured by ACEC Transfomers; (b) Nameplate of the distribution transformer

Table 3. Properties of the used transformer oil before the reclamation process

Property	Mean value
AC BdV (kV/mm)	8
TAN (mg KOH/g)	0.1923
Dynamic viscosity (cP)	8.01

The reclamation process consists of two steps: (1) contact process and (2) filtration process. The contact process involves mixing a certain amount of adsorbent with the used transformer oil. In this study, the used transformer oil was mixed using a digital hot plate magnetic stirrer, as shown in

Figure 2(a). The weight of the Fuller's Earth adsorbent, stirring speed, and oil temperature for the contact process were set according to the L_4 orthogonal array (Table 2). Next, in the filtration process, the oil mixture was separated using filter paper to remove sludge (i.e., combination of adsorbents and dissolved decay products present in the used transformer oil). Whatman No. 42 filter paper was used for the filtration process, having a pore size of 2.5 µm.

Figure 2(b) shows a photograph of the filtration process, where the oil mixture was poured directly into a fleaker. The oil mixture was filtered through the filter paper placed in between the fleaker and Erlenmeyer flask. A vacuum pump was connected to the Erlenmeyer flask using a rubber hose in order to speed up the flow rate of the oil mixture as well as to remove air and moisture present in the Erlenmeyer flask. The filtration process was completed within 2 hours with the aid of the vacuum pump.

(a) (b)

Figure 2. (a) Contact Process; (b) Filtration Process

2.3 AC breakdown voltage measurement

The oil samples were tested to determine their dielectric strength (AC BdV) using Megger OTS60PB 60-kV portable oil test set which complies with the ASTM D1816 standard test method. The dielectric strength represents the potential difference in which electrical failure occurs in the electrical insulator under AC test conditions. Following the procedure outlined in the ASTM D1816 standard test method, the test setup consisted of two Verband Deutscher Elektrotechniker (VDE, Specification 0370) electrodes with a gap distance of 1.0 mm. The rate of voltage rise was kept fixed at 0.5 kV/s. At least two samples were prepared for each set of tests to ensure a high confidence level. In this study, a total of 30 tests were performed for each oil sample and the mean AC BdV for each set of tests was determined.

2.4 Total acid number measurement

The procedure of the total acid number (TAN) test is complies according to the ASTM D974 (Standard Test Method for Acid and Base Number by Color-Indicator Titration). The following chemical reagents (potassium hydroxide, isopropyl alcohol, and potassium hydrogen phthalate) were used to determine the TAN of the oil samples. Firstly, 5 g of the oil sample were weighed into a titration vessel and 20 mL of isopropyl alcohol were added. Next, the solution was titrated, where the concentration of potassium hydroxide in isopropyl alcohol was 0.1 mol/L. The TAN of the oil sample was then recorded.

2.5 Viscosity measurement

The viscosity tests were performed using a viscosity bath, which complies with the ASTM D7042 (Standard Test Method for Dynamic Viscosity and Density of Liquids by Stabinger Viscometer). The viscosity bath consists of a viscometer, which is used to measure the dynamic viscosities of the oil samples at different temperatures. The volume of each oil sample was ~6.7 mL for each viscosity test. In this study, the unit used for dynamic viscosity is centipoise (cP), where 1 P equals to 1 g/cm.s.

3. RESULTS AND ANALYSIS

3.1 Analysis of the S/N ratios on the AC breakdown voltage

The AC BdV values measured from the tests and their corresponding S/N ratios are shown in Table 4. It can be seen that the AC BdV of the reclaimed transformer oil increases with an increase in the S/N ratio. Table 5 shows the response table for S/N ratios for the AC BdV, including the delta and rank for each reclamation process parameter. It is apparent that the oil temperature has the most significant effect on the AC BdV, followed by the stirring speed and least of all, weight of the Fuller's Earth adsorbent. Figure 3 shows the main effect plot of the S/N ratio on the AC BdV. The optimum reclamation process parameters were determined from the points above the reference line of the S/N ratio. The optimum reclamation process parameters that will maximize the AC BdV of the reclaimed transformer oil are as follows: (1) weight of Fuller's Earth adsorbent: 50 g, (2) stirring speed: 1000 rpm, and (3) oil temperature: 60°C.

Table 4. Experimental outputs for the AC breakdown voltage

Experimental run	Mean AC BdV (kV/mm)	S/N ratio (dB)
1	12	21.5836
2	10	20.0000
3	7	16.9020
4	15	23.5218

Table 5. Response table for S/N ratios: AC breakdown voltage

Level	Weight of Fuller's Earth adsorbent (dB)	Stirring speed (dB)	Oil temperature (dB)
1	20.79	19.24	22.55
2	20.21	21.76	18.45
Delta	0.58	2.52	4.10
Rank	3	2	1

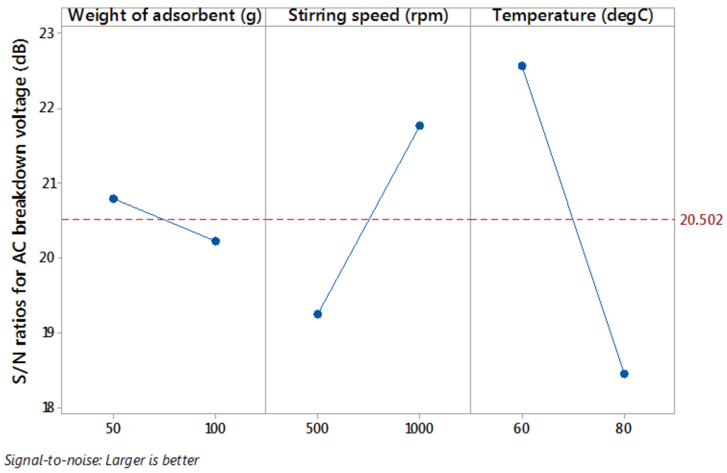

Figure 3. Main effect plot of the S/N ratio on the AC breakdown voltage

3.2 Analysis of the S/N ratios on the total acid number

The TAN values measured from the tests and their corresponding S/N ratios are shown in Table 6. Contrary to the results for AC BdV, it can be seen that the TAN of the reclaimed transformer oil decreases with an increase in the S/N ratio. Table 7 shows the response table for the S/N ratios for the TAN, including the delta and rank for each reclamation process parameter. It is evident that the weight of the Fuller's Earth adsorbent has the most significant effect on the TAN, followed by the stirring speed, and least of all, oil temperature. Figure 4 shows the main effect plot of the S/N ratio on the TAN. The optimum reclamation process parameters were obtained from the points above the reference line of the S/N ratio. The optimum reclamation process parameters that will minimize the TAN of the reclaimed transformer oil are as follows: (1) weight of Fuller's Earth adsorbent: 100 g, (2) stirring speed: 1000 rpm, and (3) oil temperature: 60°C.

Table 5. Experimental outputs for the total acid number

Experimental run	Mean TAN (mg KOH/g)	S/N ratio (dB)
1	0.0783	22.1248
2	0.0782	22.1359
3	0.0512	25.8146
4	0.0365	28.7541

Table 6. Response table for the S/N ratios: Total acid number

Level	Weight of Fuller's Earth adsorbent (dB)	Stirring speed (dB)	Oil temperature (dB)
1	22.13	23.97	25.44
2	27.28	25.45	23.98
Delta	5.15	1.48	1.46
Rank	1	2	3

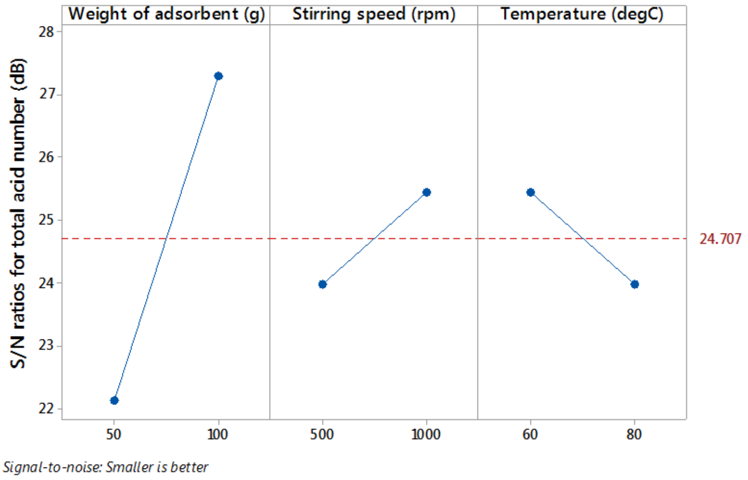

Figure 3. Main effect plot of the S/N ratio on the total acid number

3.3 Analysis of the S/N ratios on the dynamic viscosity

The dynamic viscosities determined from the tests and their corresponding S/N ratios are shown in

. Similar to the results for the TAN, it can be seen that the dynamic viscosity of the reclaimed transformer oil decreases with an increase in the S/N ratio. **Error! Reference source not found.** shows the response table for the S/N ratios for the dynamic viscosity, including the delta and rank for each reclamation process parameter. It is notable that the weight of the Fuller's Earth adsorbent has the most significant effect on the dynamic viscosity, followed by the oil temperature, and least of all, stirring speed.

Figure *4* shows the main effect plot of the S/N ratio on the dynamic viscosity of the reclaimed transformer oil. The optimum reclamation process parameters were determined from the points above the reference line of the S/N ratio. The optimum reclamation process parameters that minimize the dynamic viscosity of the reclaimed transformer oil are as follows: (1) weight of Fuller's Earth adsorbent: 100 g, (2) stirring speed: 500 rpm, and (3) oil temperature: 60°C.

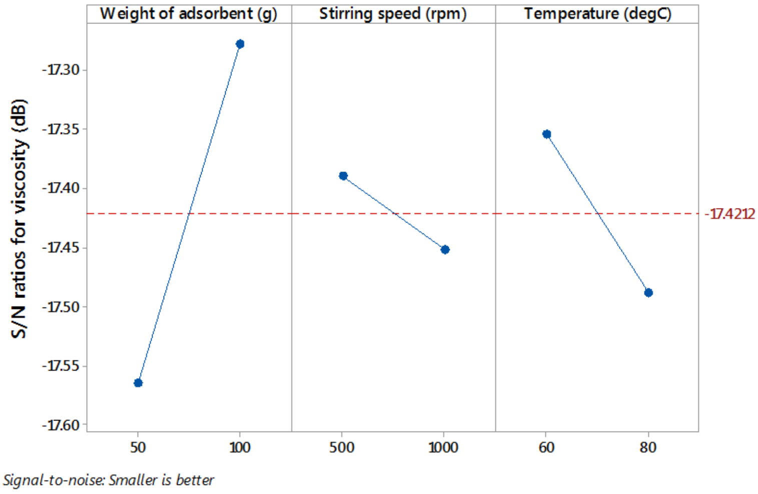

Figure 4. Main effect plot of the S/N ratio on the dynamic viscosity

3.4 Verification of the optimum reclamation process parameters predicted using the Taguchi method

Tests were conducted in order to verify the optimum reclamation process parameters predicted using the Taguchi method and the results are presented in Table 7. Based on the results, it is confirmed that the properties of the reclaimed transformer oil (AC BdV, TAN, and dynamic viscosity) are superior to those for used transformer oil (prior to the reclamation process), which indicates that the the optimum reclamation process parameters predicted using the Taguchi method are reliable.

Table 7. Comparison of the transformer oil properties before and after reclamation process using the optimum process parameters predicted using the Taguchi method

Property	Optimum reclamation process parameters			Oil properties after reclamation process	Oil properties before reclamation process
	Weight of Fuller's Earth adsorbent (g)	Stirring speed (rpm)	Oil temperature (°C)		
AC breakdown voltage (AC BdV)	50	1000	60	15 kV/mm	8 kV/mm
Total acid number (TAN)	100	1000	60	0.0365 mg KOH/g	0.1923 mg KOH/g
Dynamic viscosity	100	500	60	7.225 cP	8.01 cP

4. CONCLUSION

In this study, the Taguchi method is used to determine the optimum reclamation process parameters which will maximize the AC breakdown voltage and minimize the total acid number and dynamic viscosity of reclaimed transformer oils. The main benefit of the Taguchi method is that one can determine the factors which will have a significant effect on the AC breakdown voltage, total acid number, and dynamic viscosity of the reclaimed transformer oils from fewer experiments, based on the signal-to-noise ratios of the reclamation process parameters and the rank values of these parameters. The Taguchi method provides a simple, economically feasible means of optimizing the reclamation process parameters which considerably reduces both time and cost, which is typically an issue with conventional experimental techniques.

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