FEASIBILITY TEST OF TRANSFORMER INSULATING OIL LIFETIME BASED ON BREAKDOWN VOLTAGE (BDV) AND FURAN ANALYSIS

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ABSTRACT

Optimization of transformer performance in distributing electrical energy is determining by transformer insulating oil quality. Insulating oil temperature increases with the great of transformer workload released during the distribution of electric power to consumers. Then, it will be affected to the breakdown voltage (BDV) value and oil quality which can even lead to the insulating oil failure. This research is carried out by taking a sampling of new deck oil and used oil at different temperatures. Then insulating oil is tested by using BDV test and Dissolved Gas Analysis (DGA) to determining furan value and workability of insulating oil lifetime. Thus, this research expected to identify the feasibility of transformer insulating oil lifetime based on breakdown voltage and furan value.

Keywords: *Transformer Performance, Insulation Oil, Breakdown Voltage, Furan Analysis*

1. INTRODUCTION

Power transformer is the main equipment for distributing electrical power to consumers, which the reliability of the transformer must be controlled continuously for the effectiveness of transformer operation system. Cases that occurred in the distribution and transmission systems are a small explosion in the power transformer caused by the increasing of transformer workload and transformer oil quality. Then, affected the transformer working at maximum capacity and insulating oil being at the highest hot point continuously for long.

Transformer that operate in a state of overload continuously without periodic control, causing the high temperature of hot oil and breakdown voltage occurs in transformer oil. When oil in overheated condition for some time, transformer oil will boil and produce water vapor in the transformer ceiling. The water vapor that arises fall into the transformer oil and will settle on the insulation between the transformer cores. This causes the decreasing of oil breakdown voltage (BDV) because of the oil has become impure. The higher the impurity of insulating oil, the worse the condition of insulating oil.

In this research, feasibility of insulating oil tested by BDV test to determining the oil purity and Dissolved Gas Analysis (DGA) to determining the oil content. Level of oil content will be analyzed by using furan analysis to calculate the prediction of the remaining lifetime of the transformer insulating oil can last up to how many percent more.

2. BASIC THEORY

2.1 Insulating Oil Transformer

Transformer oil (also known as insulating oil) is a special type of oil which has excellent electrical insulating properties and is stable at high temperatures. Transformer oil is used in oil-filled electrical power transformers to insulate, stop arcing and corona discharge, and to dissipate the heat of the transformer. Transformer oil is also used to preserve the transformer's core and windings – as these are fully immersed inside the oil. The properties (or parameters) of transformer oil are:

- Electrical properties: Dielectric strength, specific resistance, dielectric dissipation factor.
- Chemical properties: Water content, acidity, sludge content.

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- Physical properties: Interfacial tension, viscosity, flash point, pour point.

Transformer oil needs to be tested to ensure that it works for today's standards. Oil testing consists of measuring the breakdown voltage, and other chemical and physical properties of the oil. Transformer oil testing is important to:

- Determine essential electrical properties of transformer oil
- Identify if a certain oil is suitable for future use
- Detect whether regeneration or filtration is needed
- Reduce oil costs and enhance component life
- Prevent untimely failures and maximize safety

2.2 Dielectric Strength

Dielectric strength is defined as the electrical strength of an insulting material. In a sufficiently strong electric field the insulating properties of an insulator breaks down allowing flow of charge. Dielectric strength is measured as the maximum voltage required to produce a dielectric breakdown through a material. It is expressed as Volts per unit thickness. For a plastic material the dielectric strength varies from 1 to 1000 MV/m. Higher dielectric strength corresponds to better insulation properties.

2.3 Mechanism Failure of Liquid Insulation

The failure of the liquid insulation is caused by the electron mechanism. The initial electrons required are from each electrode emitted by an electric field as described in the gas failure process. The failure strength of some hydrocarbons is determined by the size density for the free space of the liquid), from the partial pressures and their components, as well as their ionization energies. In this case, it is assumed that there is an empty space between the liquid molecules. This empty space contains oil components that move easily or contain other gases dissolved in the oil. The free space in the oil occurs due to the separation of gases under the influence of an electric field and they collide with each other resulting in the formation of a balanced charge (positive ion and negative ion). Due to the electric stress, the heat caused by the ionization and dissociation process.

2.4 Transformer Oil Purification

Transformer oil purification is a process of purifying transformer oil through a tool called Transformer Oil Purification Plant by eliminating or reducing physical contamination; in the form of particulate contamination, water content, gas content, and others. In short, the transformer oil purification process is a combination of two processes, namely the filtration process and the vacuum process. Filtration is to filter out particles > 0.2 microns, while the vacuum process is to remove most of the dissolved water and eliminate the gas content in the transformer oil.

This simple process is usually sufficient to correct low breakdown voltages (caused by a combination of high particles and water content). For the record, purification of transformer oil can be done on-line (when the transformer is operating), or when the transformer is off-line (not operating).

3. TEST METHOD

3.1 Dissolved Gas Analysis (DGA)

The dissolved gas testing process is carried out by 2 test methods, namely using the gas chromatography test method which refers to the ASTM 3612 standard and analysis of calculating the amount of dissolved gas content referring to the IEC 60422 standard and SK.DIR.0520. In the Gas Chromatography test, several parameters are used for this test, as shown in Table 3.1 below:

Table 1. DGA Test Parameters

Parameters used for test	Description
Types of Oil	New Oil: Nynas, Diala, Total Used Oil: Nynas, Diala, Total
Temperature of Test	70ºC
Oil Volume	12ml
Time of Test	20minutes

Oil samples to be tested are taken from different transformers and different insulating oil conditions. The new insulating oil directly taken from the transformer which is still operating for < 5 years at a transformer operation temperature of 40ºC – 50ºC. Meanwhile, used oil is taken from a transformer that has been operating for > 10 years at a transformer operation temperature of 40ºC – 50ºC and some of oil is taken from the drum at an ambient temperature of 30ºC – 40ºC. Insulating oil taken from the drum that is no longer used as an insulating medium.

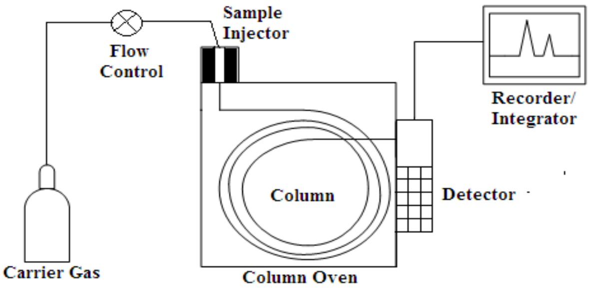

Figure 1. Scheme of Gas Chromatography Test on DGA Test Equipment

Figure 1 above shows a description of the carrier gas which functions as a driver to drain the dissolved gas to be brought to the detector. Gas flow pressure from the carrier gas is regulated by the flow control to adjust the reading signal on the detector. Flow control continue the process of heating oil sample in the sample injector. The oil is heated and placed in the sample injector for the oil heating process. The heating process of transformer oil is carried out for 20 minutes at a temperature of 70ºC with the aim of producing maximum steam.

The vapor collected in the vial, will be extracted to the column to describe the dissolved gas content in the oil and every gas content in the insulating oil is detected by a detector in the form of a signal.

Column is part of the DGA test equipment which use for separate the dissolved gas content in the insulating oil, so that it can be detected by the detector. Detector functions to convert the signal from the carrier gas and its components into an electronic signal that useful for analyzing the quality and quantity of separate gases to calculate the value of the flammable and the non-flammable dissolved gas content. Then a graph of dissolved gas content result in the insulating oil will be seen, then an analysis of the Total Dissolved Combustion Gas (TDCG) calculation will be carried out

3.2 Total Dissolved Combustion Gas (TDCG) Analysis

Total Dissolved Combustion Gas (TDCG) analysis used to determine the amount of dissolved combustible gas that has been separated. The amount of dissolved gas in the transformer oil, referenced by the number of distribution conditions of transformer oil or called as concentration of Dissolved Gas. The TDCG method can be run on transformers that use dissolved gas history. If there is no history, you can use the IEEE standard reference, as shown in Table 3.2, and if the gas level is known to be in an abnormal condition, it will be classified into several conditions which state the most likely fault condition.

Table .2 Concentration of Dissolved Gas

Types of Dissolved Gas	**Concentration Level**			
	1 (ppm)	**2 (ppm)**	**3 (ppm)**	**4 (ppm)**
Hydrogen (H_2)	100	700	1800	>1800
Nitrogen (N_2)	–			
Methane (CH_4)	120	140	1000	>1000
Carbon Monoxide (CO)	350	570	1400	>1400
Carbon Dioxide (CO_2)	2500	4000	10000	>10000
Ethylene (C_2H_4)	50	100	200	>200
Ethane (C_2H_6)	65	100	150	>150
Acetylene (C_2H_2)	35	50	80	>80
TDCG	≤ 720	1920	4630	> 4630

Table 3.2 above represents the dissolved gas concentrations. The table shows the distribution of transformer oil conditions based on dissolved gas content in *ppm* units. The TDCG values in the table do not involve N_2 and CO_2 gases, because they are not flammable gases. So that the TDCG value uses the following Equation 3.1 formula:

$$TDCG\ Value = H_2 + CH_4 + C_2H_2 + C_2H_4 + C_2H_6 + CO \ldots\ldots\ldots\ldots \quad (3.1)$$

The value of the gas contained in the insulating oil in Table 3.2 above is adjusted for 4 levels of the transformer insulating oil condition. The 4 condition level criteria are made to classify the transformer condition when there is no previous DGA data. Classification uses the concentration of gas separately as well as the total amount of combustible gas. level 1-2 indicates the gas is still in good condition and within normal limits. Level 3-4 indicates the gas is in a bad condition which can impair transformer performance.

3.3 Oil Heating

Prior to the breakdown voltage test stage, the oil heating process is carried out in the oven to reduce and eliminate the moisture content in the oil. The oil process in the oven aims to determine the differences of breakdown voltage value in different hot oil temperatures. Thus, it can be seen the results of the maximum breakdown voltage value. Oil samples were new oil that used for < 5 years and used oil for > 10 years.

3.4 Breakdown Voltage (BDV) Test

Breakdown voltage (BDV) test is carried out to determine the presence of contaminants such as water content and particles, as well as to determine the quality of transformer oil. The decreasing of BDV value indicates the presence of these contaminants. The higher the BDV value, the better the quality of the oil. So, it is necessary to test the breakdown voltage to determine the characteristics of the insulating oil. The breakdown voltage test of transformer oil is carried out using a BDV tester using electrodes spaced 2.5 mm apart with a round shape like a mushroom, as shown in Figure 3.2 below:

Figure 2. Breakdown Voltage (BDV) Test Equipment

In this test, several parameters needed which are used for testing the breakdown voltage according to the testing stage determined by PT. PLN Distribution of Jawa & Bali - Surabaya. The following will explain the breakdown voltage test process according to the IEC 60156 standard, as shown in Table 3.3 below:

Table 3 BDV Test Parameters

Parameters Used for Tested	**Description**
Insulating Oil Type	New Oil and Used Oil
Variable of Temperature	40°C, 80°C, 120°C
Oil Volume	±400ml
Electrode Gap	2,5mm
Max. Voltage	100kV AC
Mesh Tension	220V AC

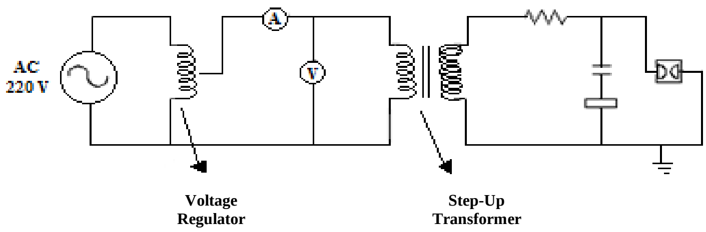

Figure 3. Breakdown Voltage Circuit

The BDV working system based on the above circuit is a 220V grid voltage with a frequency of 50 Hz connected to a voltage regulator. The voltage on the secondary side (HV) of the transformer on the breakdown voltage test equipment is the result of the voltage that has been increased by the ratio of the primary side and the secondary side. Thus, if the primary side of the transformer test is increased, then the secondary side will experience an increase in voltage. Breakdown voltage on transformer oil is obtained by increasing the voltage from 0kV to 100kV AC, until the appearance of arching and a large breakdown voltage value will appear as the standard limit of BDV quality.

Table 4 Standard Limit Value of Breakdown Voltage

Standard Limit Value of BDV		
Good	**Not Enough**	**Bad**
> 50	40 – 50	< 40

3.5 Furan Test Analysis

The furan test was carried out to determine and predict the remaining of transformer operational life by calculating the value of furan group 2Fal (ppb) from furan test. From the large content of the 2Fal furan group detected, it is possible to estimate the DP (depolymerization) condition and the estimated remaining life of the transformer insulating oil by calculating the formula, as shown in Equation 3.2 below:

$$DP = \frac{[\log_{10}(2Fal\,.0{,}88) - 4{,}51]}{-0{,}0035} \quad (3.2)$$

$$\%\,Eprl = 100 - \left(\frac{[log_{10}\,(DP) - 2{,}903]}{-0{,}00602}\right) \quad (3.3)$$

If the value of 2Fal which known from the furan test results is processed based on the calculation of the equation above, it will get the estimated DP and %Eprl (Estimated percentage of remaining life). The value of 2Fal content obtained from the furan test results will be calculated using furan analysis to determine the remaining of transformer operational life from the transformer operation that has been determined in the transformer specifications. Furan analysis calculation must be adjusted to the standard furan test results that have been determined according to the ASTM D5837 standard, as shown in Table 3.8 below:

Table 5. Standard Value of Furan Test Result

Furan 2Fal (ppb)	**Estimated Degree of Polymerization (DP)**	**Percentage of Transformer Estimated Life (%)**	**Interpretation**
0 – 292	>600	67 – 100	*Normal Aging Rate*
293 – 2,021	360 – 599	39 – 66	*Accelerated Aging Rate*
2,022 – 3,277	300 – 359	25 – 38	*Excessive Aging Danger Zone*
3,278 – 4,524	260 – 299	14 – 24	*High Risk Failure*
>4,525	200 – 259	0 – 13	*End of Expected Life of Paper Insulation and the Transformer*

Table 5 shows the lower the furan - 2Fal (ppb) value, the better and longer the estimated operating life of transformer insulating oil. On the other hand, the higher the furan - 2Fal (ppb) value detected, the worse the interpretation of estimated operating life of insulation oil.

4. TEST RESULT AND DATA ANALYSIS

4.1 Dissolved Gas Analysis (DGA) Test Result

Dissolved Gas Analysis (DGA) test is carried out to determine the amount of dissolved hydrocarbon gas content in new and used transformer oil. The dissolved gas value detected by the detector on the DGA test equipment will be analyzed for the condition of the insulating oil to determine whether the operation of the transformer will experience interference and damage or not. If there has been a disturbance in the work of the transformer, this DGA test is to determine the formation of dissolved gases in the transformer insulating oil. This can be seen and analyzed based on the level of conditions that have been determined.

Table 6. DGA Test Result in 3 Types of Used Insulation Oil

GAS CONCENTRATION DETECTED IN USED OIL						
Gas Component	**Nynas**		**Diala**		**Total**	
	Gas Value (ppm)	**Status Level**	**Gas Value (ppm)**	**Status Level**	**Gas Value (ppm)**	**Status Level**
Hydrogen (H_2)	480,63	2	65,13	1	241,81	2
Nitrogen (N_2)	569,691	-	509,630	-	835,701	-
Methane (CH_4)	4,02	1	168,57	2	41,12	1
Carbon Monoxide (CO)	8,21	1	-	1	-	1
Carbon Dioxide (CO_2)	38,02	1	376,22	1	811,01	1
Ethylene (C_2H_4)	0,00	1	5,43	1	0,78	1
Ethane (C_2H_6)	164,03	4	0,00	1	86,72	2
Acetylene (C_2H_2)	0,00	1	24,55	1	0,87	1
TDCG	**659,90**	**1**	**263,69**	**1**	**371,28**	**1**

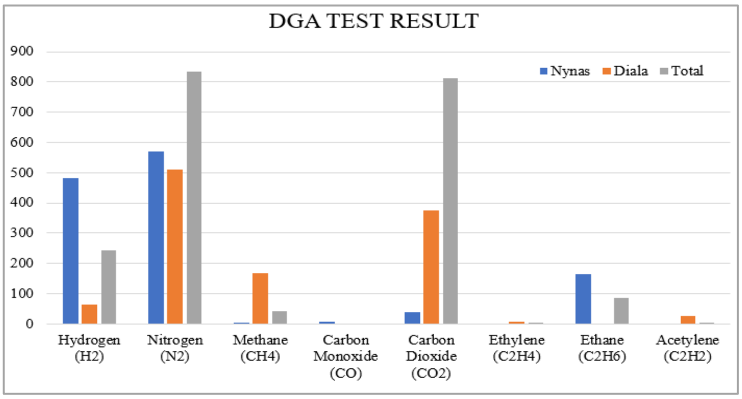

Figure 4. Graph of DGA Test Result

Table 4.1 shows the DGA test results from 3 types of used oil (Nynas, Diala, Total) in a working operating period of > 10 years at PT. PLN Jawa & Bali of Distribution System - Surabaya. Overall oil testing using DGA test shows the oil TDCG is at level 1-2, where the insulating oil is still in normal condition and suitable for transformer operation. This condition should be checked periodically to anticipate an increasing in gas value.

The table above also shows the value of dissolved combustible gas in each oil. DGA testing is only carried out on used oil because the dissolved gas is detected from the usage of insulating oil that has undergone a heating process during the working period of the transformer operation. The new oil is not tested because it has not been used for transformer isolation for a long time, so the gas content value is too small.

4.2 Breakdown Voltage (BDV) Test Result

Transformer oil will experience an increase in heat pressure caused by the current flow and losses as the electrical power load increases. This causes the transformer oil produces oil temperatures that vary with changes in load. In order to find out how far the change in the transformer oil temperature to the failure of the insulating oil, oil tests are carried out at several different temperatures in 3 types of oil, that is: 40ºC, 80ºC, 120ºC. The insulating oil sample to be tested is new insulating oil which still fresh. Then, its purity is maintained from contaminants, and used insulating oil is taken directly from transformers that have been used for a long time as an insulating medium, and some has been taken from drums that are no longer used.

Table 7. BDV Test Result in 3 Types of New Insulation Oil

Oil Heating Temperature	**BDV OF NEW OIL**					
	Nynas		**Diala**		**Total**	
	BDV (kV)	**Oil Status**	**BDV (kV)**	**Oil Status**	**BDV (kV)**	**Oil Status**
40ºC	39.8	Bad	27.5	Bad	18.6	Bad
80ºC	40.3	Not Enough	28.1	Bad	27.5	Bad
120ºC	60.5	Good	50.9	Good	51.1	Good

Table 8. BDV Test Result in 3 Types of Used Insulation Oil

Oil Heating Temperature	**BDV OF USED OIL**					
	Nynas		**Diala**		**Total**	
	BDV (kV)	**Oil Status**	**BDV (kV)**	**Oil Status**	**BDV (kV)**	**Oil Status**
40ºC	24	Bad	21.8	Bad	15.6	Bad
80ºC	29.1	Bad	26.5	Bad	22.7	Bad
120ºC	49.4	Not Enough	31.4	Bad	43.2	Not Enough

Seen in the table, the highest BDV is at oil heating at a temperature of 120ºC which indicates that the higher the temperature of the hot oil, the greater the BDV value (as long as it is below the maximum limit for heating the oil). The BDV comparison between new and used oil can be seen in the image below:

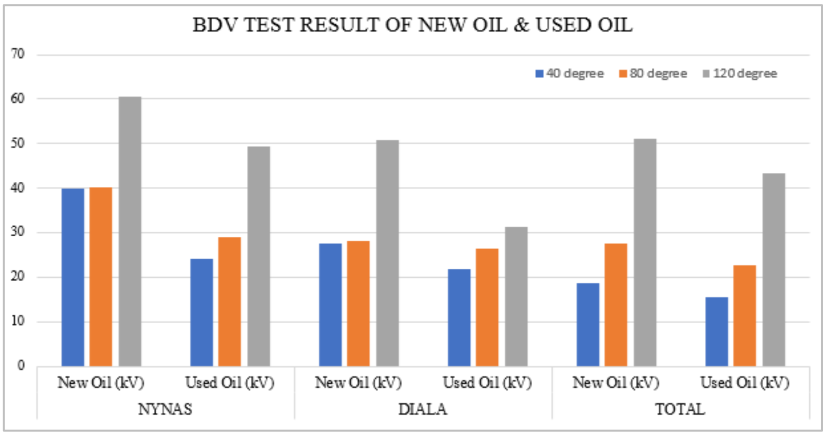

Figure 5 BDV Graph of New Oil & Used Oil

The test results show that the BDV value of 120ºC is greater than at a temperature of 40ºC and 80ºC. The best condition for the BDV value is new oil of Nynas which heated at a temperature of 120ºC, which is 60.5kV. This caused by the higher the influence of oil heating temperature, the lower the water content in the insulating oil. But this oil heating process cannot be done continuously, because if the insulating oil is heated continuously at a higher temperature above 120ºC, the longer the insulating oil will reach the saturation point and the dielectric strength of the insulating paper decreases, and causes the reducing of the insulating oil properties. This will cause the breakdown value to be smaller (down).

4.3 Furan Analysis Result

Table 9. Furan Result and Estimated Remaining New Oil Life

New Oil Types	**Furan 2Fal (ppb)**	**DP Estimation**	**Eprl (%)**	**Insulating Oil Status**
Nynas	24	910,1	109,3	Normal
Diala	19	939,1	111,6	Very Good
Total	27	895,5	108,1	Normal

Table 10. Furan Result and Estimated Remaining Used Oil Life

Used Oil Types	**Furan 2Fal (ppb)**	**DP Estimation**	**Eprl (%)**	**Insulating Oil Status**
Nynas	300	596,7	78,9	High Level Drop
Diala	390	564,1	74,8	High Level Drop
Total	450	546,4	72,5	High Level Drop

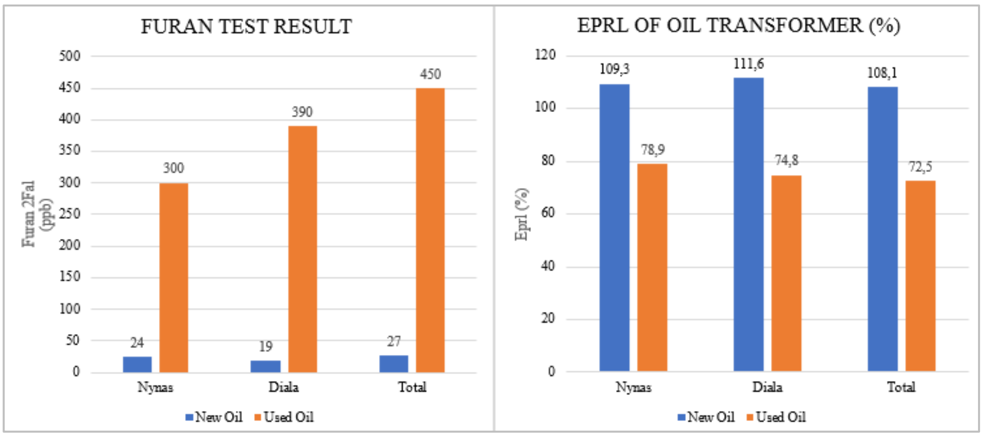

Figure 6. Furan & Eprl Graph of New Oil & Used Oil

Figure 6 shows the graph of the estimated percentage remaining life (Eprl) of new and used insulating oil from furan test. The graph shows that the estimated remaining working life of Nynas of new and used oil is longer than the Diala and Total types, that is 109,3% and 78,9%. The remaining working life of the Total of new and used oil is much smaller than of Nynas and Diala oil, that is 108,1% and 72,5%. This caused by the Total oil sample is taken from the drum, which is no longer used as an insulating medium.

The 3 types condition of used insulating oil tested by furan has been filtered, because the operational conditions of the transformer have been > 5 years of operation. The strength of this new oil insulator has also decreased. Especially for Total oil, before being discharged into the drum and before being replaced with new oil, Total oil has been filtered. This filtering of total oil is carried out to improve the breakdown voltage (BDV) value. Thus, the resulting value can be even greater and so that the DGA condition can return to level 1 status.

CONCLUSION

Oil temperature greatly affects the breakdown voltage value. Increasing of BDV value is proportional to the increasing of hot oil temperature within normal limits (40^o C –120^o C). Thus, indicating a high BDV value and oil quality is suitable for use. When the hot oil temperature rises beyond the normal limit, it will damage the insulating properties of the oil, thereby reducing the BDV value rating and oil usage quality in the transformer.

The breakdown voltage test value for new insulating oil is greater than the breakdown voltage test value for used insulating oil. This is directly proportional to the furan testing with a new type of oil which results in a higher estimated percentage of the remaining working life of the transformer is 100% compared to used oil is 70%.

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