Analysis and Experiments of Insulation Loss of Transformer Kraft Paper Based on Hotspot Variations

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Abstract – *The transformer is one of the important components in the electric power system which is used to transmit power from high voltage to low voltage or vice versa. When the transformer is working, there is an increase in temperature in the transformer which has an impact on the degradation of transformer paper and oil. If proper maintenance is not carried out, aging factors such as oxygen, heat, and humidity will produce acids and other substances that can affect transformer insulation. Insulating oil and transformer paper will experience electrical, mechanical and thermal stress which causes a decrease in performance. The remaining service life of the transformer is an important aspect that must be known. The most commonly used method for estimating the life of a transformer is by accelerated ageing experiments. Experiments were carried out by soaking kraft paper insulation in diala B shell mineral oil for 30 days with temperature variations of 120℃ and 160℃ . After the experiment, the transformer paper insulation was tested using the tensile strength testing method. Here the indicator of the end of the paper insulation life is the reduced tensile strength to 50% of the initial conditions. The test results show that temperature variations have an impact on the characteristics of paper insulation. Higher temperatures and longer heating durations result in a darker color of paper insulation. This causes depolymerization or a decrease in the mechanical strength of paper insulation with smaller tensile strength value. A decrease in the insulation strength of a transformer can cause damage to the transformer as well as reducing the lifetime of the transformer.*

Keywords:*paper insulation, thermal ageing, tensile strength, transformer*

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I. Introduction and Background

The transformer plays an important role in the electric power system, where the transformer functions to increase or decrease the voltage. When the transformer is working, there is an increase in temperature in the transformer which affects the degradation of the transformer paper and oil [1]. Transformer oil and paper insulation will experience electrical, mechanical and thermal stress which causes a gradual decrease in performance. Insulating paper on the transformer serves to prevent short circuits. The choice of insulation such as the type of insulation and the thickness of the paper insulation greatly affects the dielectric value and the ability of the paper insulation, where it will affect the reliability of a transformer[2].

If proper maintenance is not carried out, ageing factors such as oxygen, heat and moisture in the transformer will produce acids and other substances that can affect the transformer insulation. One of the reasons for the reduced lifespan of a transformer is loading. Loading results in an increase in temperature in the transformer [3]. A continuous rise in temperature that exceeds the existing tolerance limits and is not immediately resolved will also cause the transformer components to reach the permissible resistance and safety values.As a result, the transformer is unreliable and does not operate as it should. It can even cause the transformer to burn or explode.

The existence of transformer isolation is very important because apart from being used to separate the transformer cores, it also functions as a coolant in the transformer [4]. Therefore, in choosing a transformer, it is necessary to know the insulation class according to the applicable standards [5].The remaining service life of the transformer is an important aspect that must be known. The most commonly used method for estimating the service life or life of a transformer is by using accelerated ageing experiments [6]-[7].

Based on the above references, the current researcher conducts a loss of life experiment on transformer kraft paper insulation using the accelerated ageing method with hotspot variations. The hotspot in question is the temperature of the hottest point on the transformer insulation [8]. The temperatures used are 160 °C and 120 °C. The temperature of 160 °C is chosen because from the previous research, conducted experiments on accelerating ageing at 150 °C for 41 days and the result was that the transformer insulation was close to a loss of life condition. Based on that, a temperature of 160 °C for 30 days is used [9]. In addition, a temperature of 160°C is chosen also to prove that the insulation will reach loss of life condition on (706 hours) 30th day of heating [8]. While the temperature of 120°C iss chosen based on the recommended temperature limit for loading according to the nameplate of the distribution transformer [10].

II. Methodology

A. The Ageing Acceleration Experiment

The accelerated thermal ageing test is an effective method for simulating the degradation of insulating materials in oil-immersed transformers. In simple terms, cellulose paper and mineral oil are heated together at the same temperature while the thermal ageing test is carried out [11]. Accelerated thermal ageing is a method or experiment by speeding up time by increasing the temperature,where at normal temperature conditions of 105 °C, it takes 20,000 hours. While in this experiment, the temperatures of 120 °C and 160 °C are used for 30 days with the aim of shortening the ageing time of transformer insulation with reference to IEC 60216-3 [12].

B. Sampling Test

Sample testing is a process of data collection based on the test conducted on the samples taken during the experiment. The materials used in this test are insulation paper and oil which are put into the Accelerated Thermal Ageing Chamber which has a capacity of 3600 ml. The amount of insulation oil used is 3000 ml with the ratio between the insulation oil to the insulation paper rolled on copper is 10:1, which means that for 3000 ml of insulation oil, then the insulation paper rolled on copper weighs 300 grams. The sampling is carried out 4 times with an amount of 500 ml of insulation oil and 50 gram of insulation paper for each sampling. With that, the total samples taken are 2000 ml of insulation oil and 200 grams of insulation paper. The sampling flowchart is shon in Fig. 1.

B1. Insulation Oil

The type of insulation oil used is Shell Diala B mineral oil. This type of oil is chosen because Shell Diala B mineral oil is commonly used in State Electricity Company (PLN) distribution transformers. Mineral oil itself is an oil derived from petroleum and then processed so that it can be used as a medium for transformer insulation oil.

B2. Paper Insulation

The insulation paper used for this research is 0.8 mm thick insulation paper. Kraft paper is made of cellulose pulp and has good insulation properties. The paper is chosen because kraft paper is the most commonly used, has strong resistance and has a high degree of flexibility [13].

B3. Accelerated Thermal Ageing Chamber

Accelerated thermal ageing chamber is an equipment used in the experiment to accelerate the ageing process in transformer insulation. The temperatures to be used in this experiment are 120°C and 160°C.

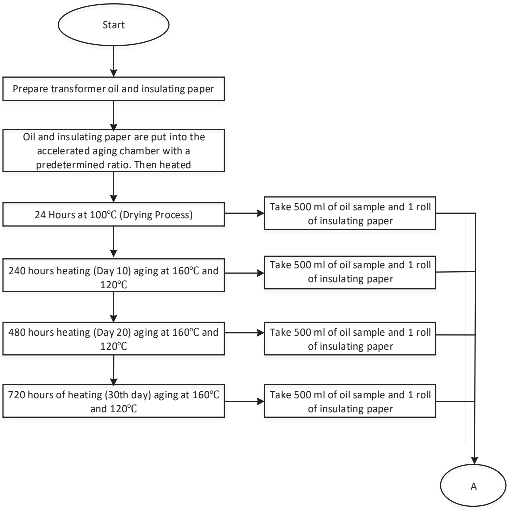

Fig. 1. Sampling flowchart

C. Tensile Strength

The selection of basic materials and the manufacturing process of the paper insulation can affect the tensile strength of cellulose insulation. The function of the electrical equipment is affected by the mechanical insulation strength of the paper used for the insulation conductors. The tensile strength of cellulose insulation materials is directly related to the degree of polymerization [14]-[15].

Tensile strength is the maximum stress that a material can withstand when it is stretched. This test is carried out by continuously measuring the force applied to pull the sample until it breaks with a constant withdrawal speed. The parameters to be obtained during the test include breaking strength, elongation percentage, and modulus of elasticity (young's modulus). The greater the value of the modulus of elasticity indicates the stiffer the material is. Breaking strength is the maximum strength of the material to withstand applied stress at a constant draw rate until the test sample breaks. It can be calculated with the following equation:

$$\sigma = \frac{F}{A} \tag{1}$$

where,
σ = stress (N/m^2 or Pa)
F = force (N)
A = surface area (m^2)

To prepare the kraft paper test samples, several sheets of paper are cut according to the specified requirements to meet the criteria for the tensile test. During the cutting process, it is advisable to avoid stopping abruptly from start to finish to minimize any potential defects in the samples. Before conducting the tensile test, the dimensions of the paper samples, including length, width, and height, are measured and recorded for reference.

An important indicator of the end of the paper insulation's life is the significant reduction in its tensile strength, specifically to approximately 50% of its initial value. This reduction in tensile strength indicates a loss of structural integrity and mechanical performance, highlighting the deterioration of the insulation over time [8]. Fig. 2 shows the flowchart of the tensil strength test procedure, while Fig. 3 and Fig. 4 show the dimensions and appearance of the insulation paper respectively.

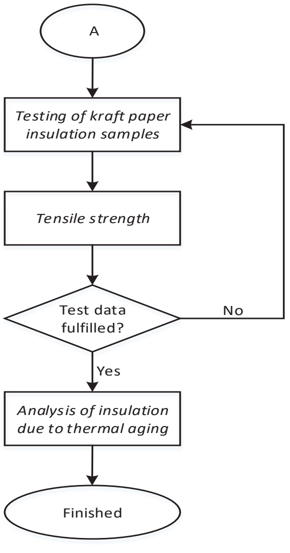

Fig. 2. Flowchart of the tensile strength test

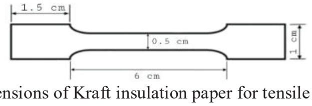

Fig. 3. Dimensions of Kraft insulation paper for tensile strength test

Fig. 4. Appearance of the sample for the tensile strength test

D. *Loss of Life Transformator*

The service life of the transformer can be estimated evaluating the materials used in the manufacturing of the transformer, for example the insulation materials and others. Life service is defined as the age of an isolation transformer from start to finish at a certain temperature [10]. Whereas 100-life is a decrease in the age of a transformer at a certain temperature and for a certain time. The improvement used to improve the life of a transformer is as follow.

$$100\text{-}Life = 100\text{-}\left[\frac{t}{\text{Exp}\left[\frac{15000}{T+273} - 28{,}082\right]} \text{ x } 100 \right] \tag{2}$$

where,
t : heating time (hours)
T : hottest point temperature (°C)

III. Results and Discussion

A. *The Effect of Temperature Differences on the Ageing of Kraft Paper Insulation*

The characteristics of the transformer insulating kraft paper that has been heated for 30 days (720 hours) at a temperature of 160°C above is shown in Table I. There is a clear change in the colour of the kraft paper. The longer the heating, the darker the colour of the kraft paper becomes. This causes a depolymerization or a decrease in the mechanical strength of the insulation paper. Decrease in the insulation strength of a transformer can cause damage to the transformer thus reducing its lifetime.

TABLE I
CHARACTERISTICS OF TRANSFORMER INSULATION KRAFT PAPER AT 160°C

Parameter	Accelerated Ageing Temperature 160°C			
	Reference Sample	240 Hours	480 Hours	720 Hours
Physical Appearance				

Example of calculation for Tensile Strength Retention on day 10:

$$\text{TSR} = \frac{\text{Experimental results of paper samples}}{\text{Reference sample experimental results}} \text{ x } 100 \tag{3}$$

$$\text{TSR} = \frac{0.321}{0.399} \text{ x } 100 = 80.419\ \%$$

Based on Table II and Fig. 5 which shows the graph of the tensile strength test results below, it can be seen that there was a significant decrease in the percentage of tensile strength retention in each sample, where as the duration of heating increases, the tensile strength retention decreases. That is, from 100% then it drops to 80.419% at day 10, then continues to drop to 66.365% at day 20 and further drops to 38.142% at day 30.

The most drastic decrease occurs in the third sample taken on the 30th day or of the heating process with 28.223% drop. Here the value of tensile strength retention is 38.142%, which means that kraft insulation paper continuously heated at 160°C for 30 days has reached the stage of loss of life in the last 10 days of heating. The criterion commonly used to mark the end of the paper insulation life is the reduction in the percentage value of the tensile strength to 50% from the initial condition [8].

TABLE II
INSULATION PAPER TENSILE STRENGTH TEST RESULTS AT 160°C

	Days	Result (Kg)	Wide	Tensile Strength (KgF)	Tensile Strength (mpa)	Tensile Strength Retention (%)
100	0	16.20	3.98	4.066	0.399	100
160	10	12.40	3.79	3.270	0.321	80.419
160	20	10.60	3.93	2.699	0.265	66.365
160	30	8.40	5.42	1.551	0.152	38.142

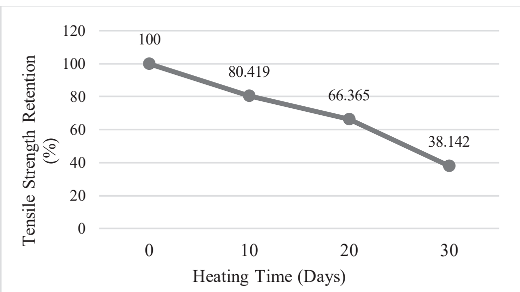

Fig. 5. Graph of Tensile Strength Test Results for Insulation Paper at 160°C

Based on the characteristics shown in Table III below, it is found that the longer the heating process, the darker the color of kraft insulation paper that has been heated at 120°C for 30 days (720 hours). The color change is not so significant compared to the kraft insulation paper that has been heated at 160°C. This is because the temperature used is lower, resulting in relatively lighter colour.

TABLE III
CHARACTERISTICS OF TRANSFORMER INSULATION KRAFT PAPER AT 120°C

Parameter	Accelerated Ageing Temperature 120°C			
	Reference Sample	240 Hours	480 Hours	720 Hours
Physical Appearance				

Table IV tabulates the data and Fig. 6 shows the graph of the tensile strength retention test results of kraft insulation paper at temperature of 120°C. It is found that there is a decrease in the test results, but not as significant as at a temperature of 160°C. The most drastic decrease occurred on the second sampling or the 20th day of heating, which is around 10%. On the 30th day or the last day of heating, a tensile strength value of 80.651% is obtained which is above 50% of the initial paper conditions. It can be concluded that the kraft insulation paper that has been heated at 120°C for 30 days has not reached its loss of life.

TABLE IV
INSULATION PAPER TENSILE STRENGTH TEST RESULTS AT 120°C

	Days	Result (Kg)	Wide	Tensile Strength (KgF)	Tensile Strength (MPA)	Tensile Strength Retention (%)
100	0	16.20	3.98	4.066	0.399	100
120	10	16.40	4.43	3.700	0.363	91.001
120	20	14.20	4.31	3.293	0.323	80.987
120	30	13.80	4.21	3.279	0.322	80.651

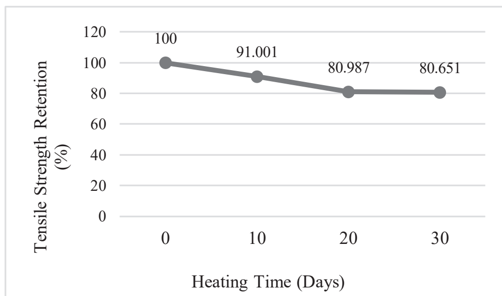

Fig. 6. Graph of Tensile Strength Test Results for Paper Insulation at 120°C

B. *Strength Test Results for Kraft Paper Insulation*

Example of calculating 100-Life temperature of 160°C on the 10th day of heating based on equation (2):

$$100\text{-}Life\ (\%) = 100\text{-}\left[\frac{240}{\text{Exp}\left[\frac{15000}{160+273} - 28{,}082\right]} \times 100\right] = 66.02\%$$

Based on the comparison shown in Table V and Fig. 7, it is found that there are similarities between the experimental results and the calculation results for the loss of life in the transformer kraft paper insulation. In the experimental results, it can be observed that the percentage of loss of life starts at 100% and gradually decreases over time. On the 10th day, the percentage drops to 80.419%, then further decreasing to 66.365% on the 20th day before finally, on the 30th day, the transformer kraft paper insualtion achieves the loss of life with a percentage value of 38.142%.

Similarly, in the calculation results, the percentage of loss of life begins at 100% and progressively decreases. On the 10th day, the percentage reaches 66.02%, then further dropping to 32.04% on the 20th day. On the 30th day, there is another decrease, resulting in a value of -1.94%. This indicates that, according to the calculations, the transformer kraft paper insulation has also reached the loss of life on the 30th day.

These similarities between the experimental and calculation results provide further validation for the estimation of the service life of the transformer kraft paper insulation.

TABLE V
COMPARISON OF LOSS OF LIFE WITH TENSILE STRENGTH RETENTION
TEMPERATURE 160°C

Ageing Days	*Ageing Hours*	*100 - Life (%)*	*Tensile Strength Retention (%)*
0	0	100	100
10	240	66.02	80.419
20	480	32.04	66.365
30	720	-1.94	38.142

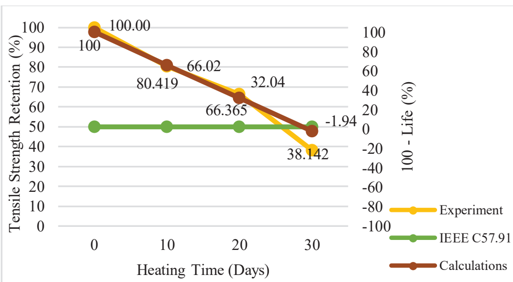

Fig. 7. Graph of Comparison of Calculations and Results of Temperature Experiments at 160°C

Example of calculating 100-Life temperature of 120°C on the 10th day of heating based on equation (2):

$$100\text{-}Life\ (\%) = 100\text{-}\left[\frac{240}{\text{Exp}\left[\frac{15000}{120+273}-28{,}082\right]} \text{ x } 100\right] = 99.00\ \%$$

Based on the Table VI data and Fig. 8 graph provided, there appears to be a slight difference between the end-of-life calculation results and the experimental results for the tensile strength of the kraft paper insulation.

In the experimental results, a significant decrease in the percentage of tensile strength can be observed at the beginning of the experiment, with the values dropping from 100% to 91% and further down to 80.987%. However, in the last 10 days of heating, the percentage of tensile strength only slightly decreases from 80.987% to 80.651%. This significant decrease at the beginning of the experiment is due to problems with the heater, which requires replacement and resulted in several interruptions during the experiment. While the experiment was paused, the kraft paper insulation remained immersed in the insulating oil within the accelerated thermal aging chamber to prevent oxidation and contamination from external substances. However, this lead to increased humidity on the insulating paper, contributing to the significant decrease in tensile strength.

On the other hand, the calculation results show a consistent and relatively smaller decrease in percentage. The values decline from 100% to 99% on the 10th day, and further drop to 98% on the 20th day. Finally, on the 30th day, the value remains at 98%.

Although there is a difference between the experimental and calculation results, both indicate that the loss of life has not yet been reached by the 30th day of heating. This suggests that further evaluation and analysis may be required to determine the exact point at which the kraft paper insulation reaches the end of its life.

TABLE VI
COMPARISON OF LOSS OF LIFE WITH TENSILE STRENGTH RETENTION
TEMPERATURE 120°C

Ageing Days	*Ageing Hours*	*100 - Life (%)*	*Tensile Strength Retention (%)*
0	0	100	100
10	240	99	91.001
20	480	98	80.987
30	720	97	80.651

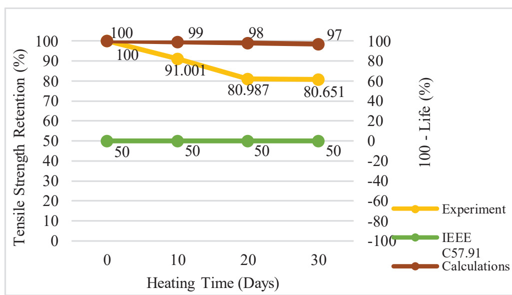

Fig. 8. Graph of Comparison of Calculations and Results of Temperature Experiments at 120°C

IV. Conclusion

Based on the experimental results of accelerated ageing at 120°C and 160°C for 30 days in an accelerated thermal ageing chamber and tensile strength testing of transformer kraft paper insulation, the following conclusions are drawn:

1. There is a change in the insulation characteristics of transformer kraft paper. The experimental results show that the longer the paper insulation is heated and the higher the temperature or loading, the darker the color of the paper insulation. This change may indicate depolymerization or a decrease in the mechanical strength of the paper insulation, which results in a decrease in the tensile strength. This decrease in insulation strength can potentially cause damage to the transformer and shorten the life of the transformer.

2. Kraft paper insulation at 120°C has not reached loss of life. Meanwhile, kraft paper insulation at 160°C has reached loss of life in the last 10 days of heating.
3. Between the results of the end of life calculations and the experimental results, there is a similarity, that is, at the temperature experiment of 160°C it is found that both kraft paper insulation (calculation results and experimental results) had reached loss of life on the 30th day of the experiment. Whereas in the 120°C temperature experiment, it was found that both of them has not reached loss of life.

Conflict of Interest

The authors declare no conflict of interest in the publication process of the research article.

Author Contributions

Author 1: experiment and data analysis; Author 2: supervision and draft editing; Author 3: draft review; Author 4: project administration; Author 5 & 6: draft review and research collaboration.

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