

Stability of Dielectric Insulation System in GSUT Transformer of Pertamina Geothermal Energy Lahendong: A Diagnostic Approach Based on DFR (Dielectric Frequency Response)

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Abstract

Generator Step-Up Transformer (GSUT) is a vital component in the power system that serves to raise the voltage level before the transmission process. The operational reliability of the transformer is highly dependent on the condition of the dielectric insulation system which consists of mineral oil and insulating paper. A decrease in the quality of the insulation system can have a significant impact on the performance and operational life of the transformer. This study aims to analyze the results of Dielectric Frequency Response (DFR) testing on the GSUT Unit 6 Transformer at PGE Lahendong to evaluate the moisture content in insulating paper and the conductivity of transformer oil based on the IEC 60422 and IEC 61620 standard references. The test results based on the dissipation factor (DF) graph show that the moisture content in the insulating paper is 0.9% (dry category) and the oil conductivity is 1 fS/m, which indicates that the condition of the insulation system is still good with an estimated remaining operational life of up to 70 years by calculating the ratio between the average operating temperature value of the transformer and its dielectric rate (Dp.t). However, electromagnetic interference or bushing contamination can cause negative dissipation factor (DF) values, leading to invalid measurements. Therefore, DFR testing using the OMICRON DIRANA device proved effective in monitoring the condition of the dielectric insulation system and providing an accurate estimation of the remaining insulation life, as well as supporting the implementation of predictive maintenance strategies in power transformers.

Keywords: DFR (Dielectric Frequency Response), GSUT (Generator Step-Up Transformer), Dielectric Insulation Moisture Content, Oil Conductivity, Negative Dissipation Factor.

1. Introduction

Stability and reliability of electricity generation and transmission units are important in ensuring an adequate and stable supply of electrical energy. PGE LAHENDONG units 5 and 6 operating since 2016 is a geothermal power plant company with a capacity of 2x20 MW that supplies electrical energy in North Sulawesi. One of the critical components in the generating system is GSUT or Generator Step Up Transformer (Kaliappan & Rengaraj, 2021). PGE LAHENDONG has 2 GSUTs with a capacity of 26,000 MVA each which functions to increase the voltage from generator output voltage to transmission regulation voltage (Sukhanov, 2024).

In GSUT, there are two main windings, namely primary (high voltage - HV) and secondary (low voltage - LV). The voltage ratio is determined by the number of windings based on the principles of magnetic flux and eddy current (Singh et al., 2015). The GSUT insulation system consists of solid insulation materials (kraft paper and cellulose-based pressboard) and



liquid insulation (mineral oil). This system serves to prevent breakdown voltage and partial discharge.

Maintaining the reliability of GSUT (Generator step up transformer) is very important (Sermasukroongsakul & Premrudeepreechacharn, 2018). Seeing the condition of the transformer in the geothermal area which contains gas that can be inhaled by the transformer even the transformer is completely sealed which will affect the water content in the transformer insulation, it is necessary to monitor the insulation moisture periodically is required through DFR (Dielectric Frequency Response) testing using the DIRANA device (Prauzek et al., 2023). This test is carried out by injecting a frequency spectrum (1 kHz-1 MHz) into the isolated winding, causing resonance and polarization in the dielectric insulation. The resulting polarization characteristics were visualized in the form of curves to analyze the conductivity and moisture content of the insulation. The conductivity and moisture content values of the insulation will refer to the IEC 60422 and IEC 60422 regulatory standards.

2. Literature Review

2.1. Dielectric Insulation

Dielectric material is an insulator-like material that can be polarised by placing it in a magnetic field (Fiedziuszko et al., 2002). GSUT transformers are high-voltage electrical equipment so it is certain that the transformer itself is insulated with a dielectric material so that there is no explosion or short circuit. Kraft paper with a combination of mineral oil the most common and effective dielectric insulation used to insulate a transformer equipment both between the winding layer and the winding core with the body (Jusner et al., 2021).

Figure 1 shows the internal geometry structure of the transformer where the Primary (HV) and Secondary (LV) windings are filled or insulated by mineral oil and limited by kraft paper or pressboard to increase the level of insulation strength. Not only as insulation, mineral oil is also used as a cooling medium for transformers (Kaliappan & Rengaraj, 2021).

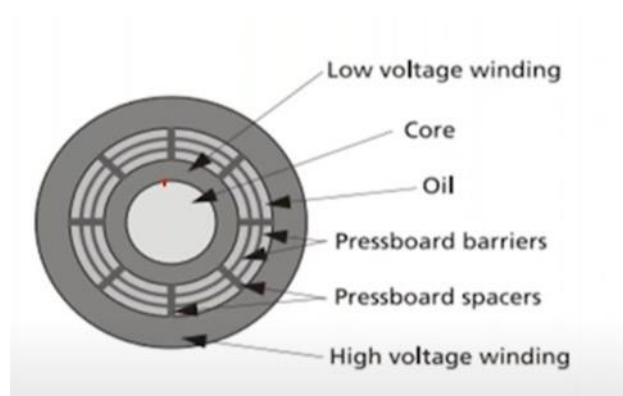


Figure 1. Internal structure of transformer

2.2. Insulation Degradation in Transformer

Ninety-nine percent of the moisture in the insulation system is located in the solid insulation (kraft paper/pressboard) and 1% of the water is located in the insulating oil (Amirouche, 2019). Kraft/pressboard paper made of 85% cellulose, 10% hemicelluloses, and 5% residual lignin will experience an increase in moisture of +0.1-0.2% annually due to the normal aging process and the breakdown that occurs in the sellusocene material and produces water as a by-product (Jusner et al., 2021).

This moisture content will be distributed into the mineral oil resulting in a decrease in the insulation breakdown stress value of the oil. This degradation causes three harmful effects:

- a) Decrease in dielectric resistance strength.
- b) Acceleration of the aging process of cellulose materials.
- c) Emission of gas bubbles at high temperatures.

The degradation of paper insulation is a combination of hydrolysis, pyrolysis and oxidation reactions influenced by the parameters of humidity, temperature and reactive oxygen (Haque et al., 2019).

a. Pyrolysis

The process of decomposing chemical compounds in the insulation due to exposure to high temperatures of 95-110 ° C when the transformer is fully loaded and produces by-products such as water.

b. Hydrolysis

When paper insulation absorbs the moisture content of the transformer oil and lowers its dielectric strength.

c. Oxidation

The same reaction with a slower process but accelerated by reactive oxygen (the insulation is exposed to oxygen even though the transformer is fully sealed).

2.3. DFR (Dielectric Frequency Responses) Analysis

As previously explained, the Dielectric Frequency Response (DFR) test involves applying a frequency spectrum (typically 1 mHz to 1 kHz) and a DC voltage of 120–140 V across the transformer winding. This induces a magnetic field that polarizes the dielectric insulation around the winding (Anglhuber & Krüger, 2016). The insulation then responds to the frequency spectrum via polarization and dielectric loss mechanisms. Figure 2 represents the polarisation process where E_0 is the external magnetic field moving forward.



Figure.2. Electrical polarisation phenomenon in dielectric materials

The character of the polarisation produced by the dielectric material is then represented in the form of an equilibrium curve. This equilibrium curve mathematically displays the ratio between the imaginary and real parts of the complex relative permittivity:

$$\tan \delta (\omega) = \frac{\varepsilon''(\omega)}{\varepsilon'(\omega)} \quad (1)$$

Describes how the values of real permittivity (ε'), imaginary permittivity (ε''), and loss tangent delta ($\tan\delta$) change with frequency. At low frequencies, the values of ε'' and $\tan\delta$ tend to be higher, indicating the dominance of conductive effects due to moisture in the insulation. At high frequencies, $\tan\delta$ values decrease, as the polarisation effect of the material gets smaller, indicating when polarisation gets larger linearly with the moisture content of the material

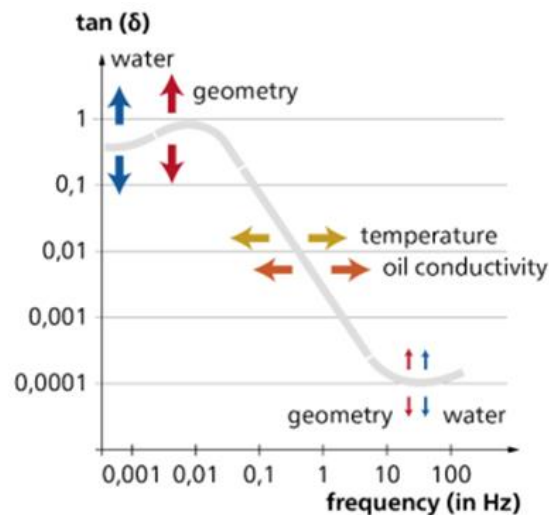


Figure 3. Dielectric properties of transformer oil-paper in HV-LV winding insulation (CHL)

The graph shows the relationship between loss tangent delta ($\tan\delta$) and the varying frequency spectrum. Low frequencies are sensitive to moisture in the insulating paper, intermediate frequencies are affected by oil conductivity and temperature, while high frequencies are affected by geometric factors. CIGRE 15.01.09, evaluates the three main techniques of what is referred to as 'dielectric response', namely:

- Return voltage measurement, which is sometimes also referred to as recovery voltage - (Return Voltage Measurement, RVM).
- Variation of polarisation and depolarisation currents in the time domain - (Polarisation and Depolarisation Current, PDC).
- Variation of capacitance and dissipation factor against frequency - (Frequency Domain Spectroscopy, FDS).

Referring to international regulations, namely IEC 60422 which regulates the standard of moisture content in insulating paper and IEC 61620 for oil conductivity. In this discussion, it is used as a reference and benchmark value in determining whether the DFR test results are good or not.

Table 1. Standard criteria for moisture content in insulating paper based on IEC 60422

Value	criteria
< 2.2%	dry
2.2% - 3.7%	Moderately wet
3.7% - 4.8%	Wet
>4.8%	Extremely wet

Table 2. Standard oil conductivity criteria based on IEC61620

Value	criteria
< 3 pS/m	"very good"
≥ 3 pS/m - < 20 pS/m	"good"
≥ 20 pS/m - < 57 pS/m	"satisfactory"
≥ 57 pS/m	unsatisfactory

3. Methods

3.1. DIRANA (Dielectric Response Analysis) measurement method

The result of the moisture content in the transformer is based on the comparison of the dielectric response in the transformer with the modelling of the dielectric response, so it can be called the XY model, combining the dielectric response taken from the database, comparing the quality of the oil with the insulation temperature. The corresponding algorithm models the dielectric response and sends the moisture content and conductivity of the transformer oil. The software will automatically compensate for the effect of aging. In this discussion, the measurement of "dielectric response analysis" will refer to the combination technique of PDC (Polarisation and Depolarisation Current) + FDS (Frequency Domain Spectroscopy) using the OMICRON DIRANA device with the tested unit being the GSUT UNIT 6 transformer.

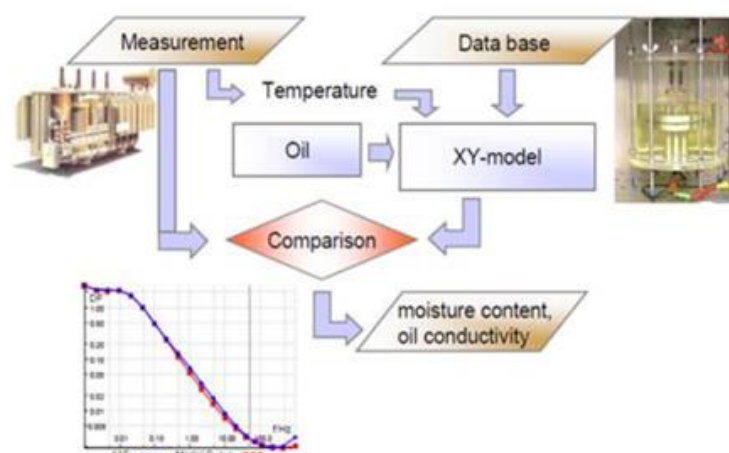


Figure 4. Flowchart of algorithm analysis

3.2. Measurement Procedure

The process starts with the identification of the transformer insulation to determine the moisture content and conductivity of the insulating oil. Initial parameters such as ambient temperature and transformer specifications are included for measurement accuracy. Measurements are made using PDC (Polarisation and Depolarisation Current) + FDS (Frequency Domain Spectroscopy) methods with, then the results are analysed to evaluate the moisture content and conductivity of the oil. If the moisture value exceeds 2.2%, a drying and purification process is performed before re-measurement. On the other hand, if the moisture value is below or equal to 2.2%, the results are declared good and the measurement is completed.

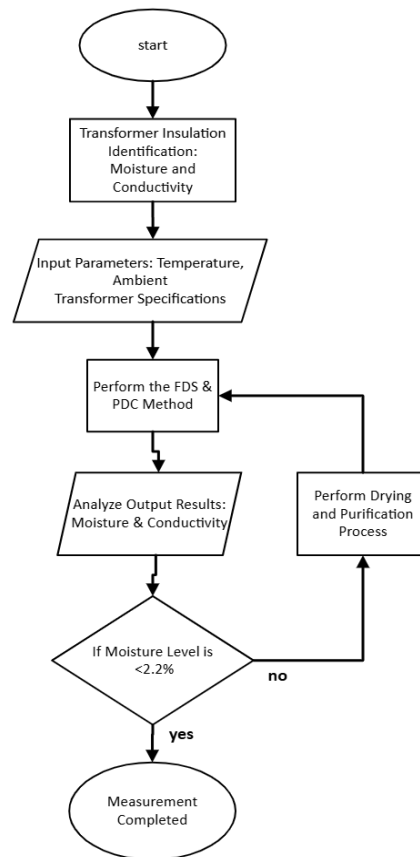


Figure 5. Flowchart of measurement procedure

4. Results and Discussion

4.1. First Experiment

In the testing process of the first experiment, an error occurred during testing, namely the testing curve had a negative dissipation factor.

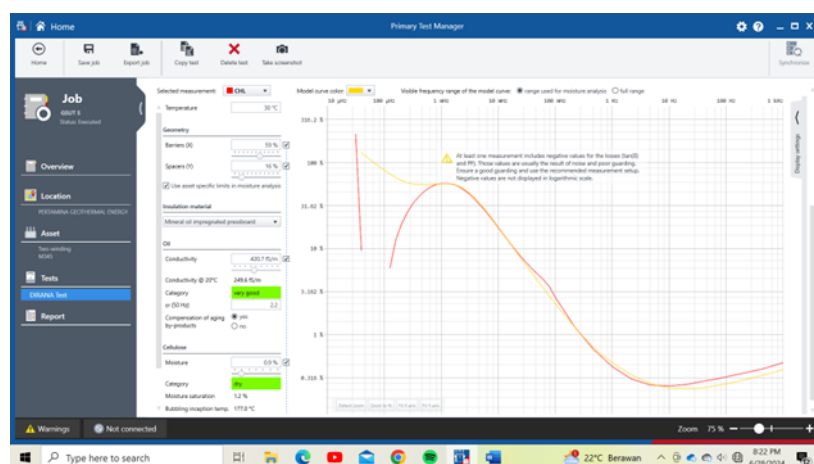


Figure 6. Dielectric measurement with negative dissipation factor at GSUT unit 6 transformers

DFR testing includes three terminals: output voltage, rated current voltage and shielding. Generally, the output voltage must be connected to the bushing, which is mostly exposed to electromagnetic disturbances in the scale (noise) especially on the HV side bushing.

These disturbances have a significant effect on the measurement curve results and cause a Negative Dissipation.

Problems can also be caused by high shield impedance, small measured capacitance in relation to large, shield capacitance, high shield current (dirty bushings). Guarding is necessary to prevent interference due to unwanted current paths caused by dirty bushings and external electromagnetic fields (noise). Figure 7 illustrates the guarding principle in DFR testing. When installing the shielding cable, the leakage current I_{sur} , as well as the capacitive current through CH and CL, will bypass the ammeter and flow directly to the voltage source. Thus, only the relevant volume current is measured and CH and CL will not affect the measurement.

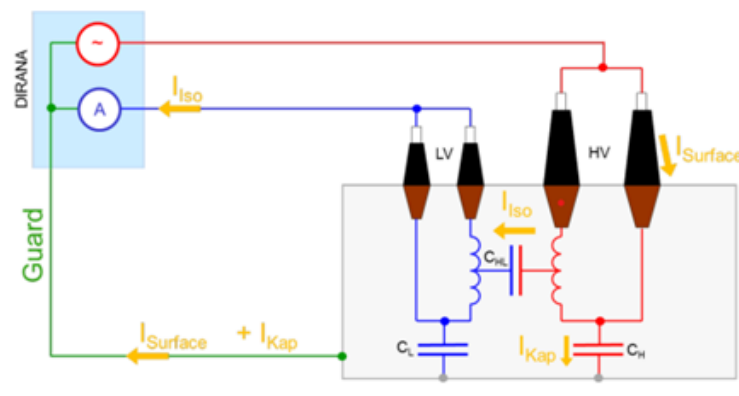


Figure 7. Dielectric response measurement with shielding

4.2. Second Experiment

After preventive measures have been taken:

- Check all shielding on the DIRANA measurement cable to the transformer tank.
- Try to reduce the protective current (clean the bushings, remove any devices that may still be connected to the transformer).

Then the test process is resumed again and a normal and error-free measurement graph is obtained.

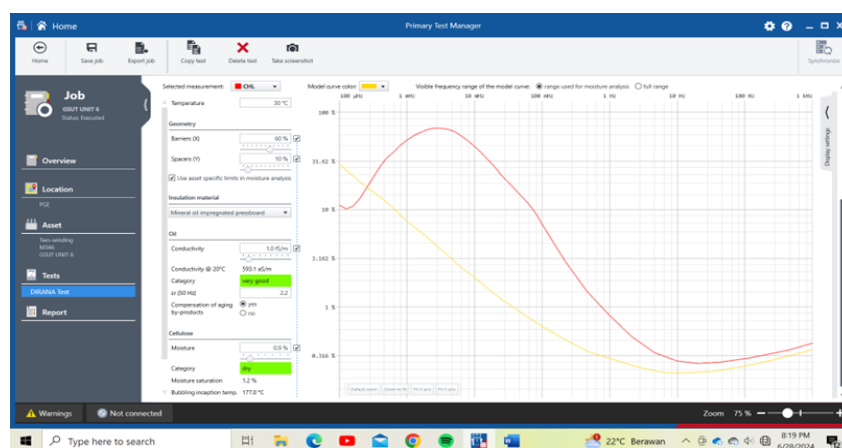


Figure 8. CHL dielectric measurement graph - GSUT Unit 6 transformer

Table 3. DIRANA test results

Measurements			
Name	CHL	Channel	CH1
Moisture in cellulose	0.9 %	Capacitance @ 50 Hz	3.788 nF
Moisture category	dry	Capacitance @ 60 Hz	3.787 nF
Moisture saturation	1.2 %	Tan δ / power factor @ 50 Hz	0.28% / 0.28%
Bubbling inception temperature	177.0 °C	Tan δ / power factor @ 60 Hz	0.28% / 0.28%
Compens. of aging by-products	yes	C (10 mHz) / C (50 Hz)	1.100
Oil conductivity	1.0 fS/m	Barriers (X)	60 %
Oil conductivity @ 20°C	593.1 aS/m	Spacers (Y)	40 %
Oil category	very good	Polarization index	26.292
Max. stop frequency reached	yes	DAR	1.420

4.3. Discussion

Based on the above data, it can be analyzed that the moisture content value of the transformer insulation paper is 0.9% so that it is included in the dry moisture category according to the standard category in the IEC 60422 table. The conductivity value of the transformer oil from the measurement results is 1 fS / m, the conductivity value of the transformer oil is included in the very good category of oil conductivity criteria standards based on IEC61620 which is 0.1 pS / m - 1.0 pS / m. Then the calculation of the estimate of the transformer insulation life is calculated by the formula:

$$[L = \frac{1}{D_{p,t}} \cdot A \cdot \exp\left(\frac{E}{RT}\right)]$$

With the average operational temperature of the transformer insulation of 75 ° C, the estimated calculation results are obtained, namely:

$$[L = \frac{1}{1.5 \times 10^{-3}} \times 2.365 \times \exp\left(\frac{11000}{8.314 \times (75 + 273)}\right)]$$

$$[L \approx 70,614 \text{ years}]$$

This estimation can be visualized in the form of a graph of the relationship between temperature and insulation life.

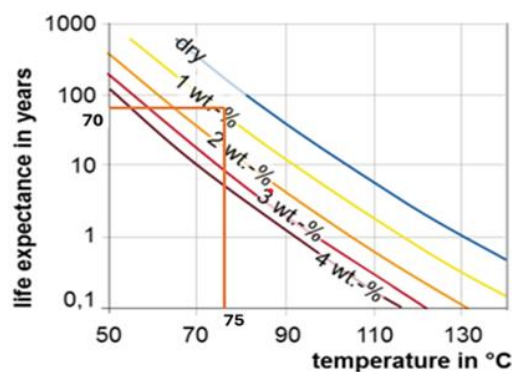


Figure 9. Dependence graph of insulation life on Humidity and Temperature

Based on the results of calculations and graphs, the estimated life of the transformer insulation is around 70 years. The accuracy of testing and analysis of calculations on the condition of transformer insulation humidity with dirana is shown in the chart graph

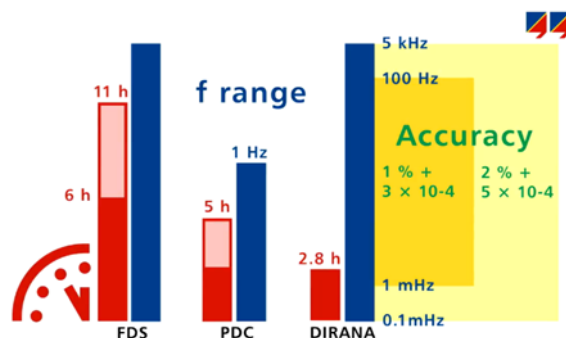


Figure 10. Comparison of three methods of testing dielectric response in transformers

DIRANA is superior to the FDS and PDC methods because it has a shorter measurement time, a wider frequency range, and still maintains good accuracy. The accuracy of the measurement methods is shown in ranges:

- 1% + 3×10^{-4} for high frequency.
- 2% + 5×10^{-4} for low frequency

In addition, further analysis of the dissipation factor in the first experiment showed an anomaly in the form of a negative value in the curve. This is the effect of parasitic capacitance or noise during measurement caused:

- Dirty bushings
- Clamp probe loose
- Incorrect input parameters
- Earth guarding is less than optimal

5. Conclusion

Based on the results of measurements and analysis using the Dielectric Frequency Response (DFR) method on the GSUT Unit 6 transformer at the Lahendong PLTP, it can be concluded that the condition of the transformer insulation is still in the good category. The moisture content in the insulating paper is 0.9%, which falls within the dry category, and the oil conductivity value is 1 fS/m, indicating an excellent condition. Therefore, there is no need for a drying process—such as vacuum drying or hot oil circulation—as long as the moisture content in the insulation paper remains below the dry threshold of 2.2%. The estimated transformer insulation life, calculated at an operational temperature of 75°C, indicates a projected lifespan of approximately 70 years.

However, anomalies such as negative dissipation factor values—attributed to factors like dirty bushings, poorly sealed probe connections, incorrect input parameters, and suboptimal earth guarding—highlight that the quality of measurements is highly sensitive to installation procedures and surrounding environmental conditions. The DFR method, utilizing the OMICRON DIRANA device, proved to be more efficient compared to other techniques such as Frequency Domain Spectroscopy (FDS) and Polarization Depolarization Current (PDC), offering a significantly shorter measurement time of 2.8 hours versus 11 hours for FDS and 5 hours for PDC. Additionally, the DFR method provides a wider frequency range (0.1 mHz to 5

kHz) and high measurement accuracy, making it a reliable tool for detecting insulation moisture and evaluating overall transformer condition effectively.

5.1. Acknowledgments

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