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Analysis of Leakage Current Calculation Through Thermal Failure Voltage on 150/20 kV Transformers in GIS Simpang, Surabaya

Reza Sarwo Widagdo[1], Aris Heri Andriawan[1], Imam Suri Tauladan[2], Ade Ivan Maulana[1]

[1] Department of Electrical Engineering, Universitas 17 Agustus 1945 Surabaya, Surabaya, Indonesia
[2] Department of Electrical Engineering, Universitas Riau, Pekanbaru, Indonesia
Corresponding Author: rezaswidagdo@untag-sby.ac.id

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Abstract

In the current test, leaks really need to be carried out at GIS Simpang. This test was carried out by strengthening the 20 kV incoming cable in the GIS Simpang 150/20 kV transformer bay. The impact of measuring this leakage current is to reduce the occurrence of leakage currents so that they are not too severe because this can determine how much the leakage current increases in the incoming cable. The trend test results were measured to determine the comparison between the leakage current in January and the leakage current measurement process at GIS Simpang. Based on the results of leakage current testing on transformer 1 and transformer 2 incoming 20 kV cables from several phases, it shows that the results of the leakage current trend in the cables have not increased significantly. However, from the calculation results listed, it can be seen from the comparison table that the results have increased during the calculation and have slight differences compared to the leakage current measurement results themselves. This is because from the calculation results, the cable temperature detection experienced a slight increase in the cable temperature as measured by thermovision to determine the thermal failure voltage. However, the cable is still suitable for operation because the temperature of the cable itself has a standard that does not exceed 15^{0}C for several measured cable phases.

Keywords: Gas Insulated Substation (GIS), Leakage Current, Thermal Failure Voltage

1. Introduction

At the main substation accommodated by PT. PLN (Persero) distributes electrical energy using a step-down power transformer from a 150 kV voltage system to a 20 kV [1], [2] medium voltage system using medium voltage cable lines because for distributing power to a 20 kV medium voltage system using air, it is sometimes difficult to implement because it reduces the aesthetic factor of the space. So the factor that needs to be considered when using ground cables is the insulation characteristics, because one of the obstacles to using ground cables is the failure of the insulation to carry out its function as a medium voltage insulation medium, which is caused during the installation process or installation of 20 kV cables which do not comply with standards and not supervised by someone who is competent in their field so that it can cause gaps in the isolation within a certain period [3],[4].

If the rate of heat generation at a point in the cable insulation material exceeds the rate of heat dissipation outward, an unstable condition will occur in the cable insulation material which is called thermal failure [5]-[8]. If this continues for a long time it will reduce the reliability of the cable which will cause insulation failure and reduce the life of the cable. Leakage current is a current that flows through or through the insulating surface. The insulation itself functions to separate two conductors that are close to each other so that no current leakage occurs in the 20 kV incoming cable. Leakage current is also caused by cavities in the cable and the occurrence of thermal failure stress [9]. The leakage current test on the 20 kV incoming cable is the current flowing from the 20 kV incoming cable from the secondary of the transformer. Leakage current itself is a current that flows from an insulating surface on the cable. Leakage current itself can also be caused by thermal failure voltage, tearing of the cable insulation [10].

Previous research on leakage currents in 20 kV cables has been carried out by several researchers. This research was conducted by Bayu Kusumo and Arif Rahman Hakim [11]. They used a 20 kV ground cable with a single aluminum core and monitored the leakage current for two weeks after the fault occurred. The research results show that the leakage current in the cable tends to be constant and does not show a significant increase, so the cable is still suitable for operation. Other research was conducted by A. Sofwan and S. Angga Kusuma [12], they designed a grounding-based 20 kV ground cable leakage current monitoring tool to overcome disturbances that caused load outages of 1350A, 35 MW, and 5 MVar on the 150/20 kV transformer at Jatirangon GI. This tool uses thermal failure theory to determine the value of insulation resistance.

According to Fortes [13], there is still little research evaluating the effectiveness of thermography as a long-term predictive tool for preventive maintenance, especially in GIS environments. Most thermography studies on transformers have been conducted in GIS with different configurations or in locations that are not 150/20 kV GIS [14]. The lack of field data from the GIS Simpang in Surabaya using thermography to detect thermal failures and leakage currents represents a gap that could be the focus of research. Many thermography studies on transformers have been conducted in regions with temperate climates [15]. Research highlighting the challenges of using thermography in tropical environments with high humidity, such as Surabaya, is still limited. High humidity can affect temperature readings and detection accuracy.

Table 1. Research Gap of the Thermovision Method

Advantages	Disadvantages
The thermography method provides a visualization of temperature in the form of thermal images, which facilitates the identification of hotspot locations that could potentially cause failures [16].	The results of thermography measurements can be influenced by environmental factors such as humidity, dust, and light reflections, which can affect the accuracy of temperature readings [19].
The use of thermography enables rapid temperature detection and can be performed in a short time, thus improving maintenance efficiency [17].	This method often does not utilize historical data that could assist in trend analysis and long-term predictions [20].
This method is capable of identifying issues early, such as insulation degradation, which can prevent more serious failures [18].	It requires specialized equipment and complex analysis, and it often cannot provide a thermal image of the entire transformer [21].

In this research, the emphasis is on analyzing leakage currents in special transformers in the GIS (Gas-Insulated Substation) Simpang environment, Surabaya, providing unique insights adapted to local conditions. These specifications can reveal location-based challenges and solutions. Then, incorporating the thermal failure stress in the leakage current calculation is an innovative approach. This method may offer more accurate data or better reveal transformer health conditions and potential failures, which could be a breakthrough in transformer diagnostics. Thus, the findings of this study could have significant implications for high-voltage transformer maintenance strategies, potentially leading to more effective predictive maintenance protocols and improving the reliability of power supply systems.

2. Methods

The method used in this research is by monitoring and carrying out calculations as well as measuring leakage currents which are measured on voltage cables or incoming 20 kV cables in R, S and T phases on 150/20 kV transformers at GIS Simpang. This research also aims to find out the value of the leakage current on the 20 kV power cable or incoming cable is by using a clamp meter (Ammeter) to determine the leakage current data on the cable being measured, and can determine and calculate the leakage current due to thermal failure. This research method also uses quantitative methods or what is called quantitative research. In research on calculating leakage current through thermal failure voltage in transformers. In the research flowchart below, the researcher will explain the sequence or steps in analyzing data according to the flowchart above by collecting data which is analyzed by adjusting the results researched by the PT. PLN (Persero).

In the explanation of the research procedure in analyzing data, it starts from pre-research by searching for related literature studies, after carrying out the literature study, then collecting data that will be analyzed further. The data that will be analyzed includes:

a. Leakage current measurement data
b. Data on leakage current due to thermal failure
c. Cable type specification data

After carrying out some data collection, several analyzes were then carried out by researchers to determine the characteristics of leakage current through thermal stress. The analysis that will be carried out includes:

a. Analysis of resistivity calculations
b. Analysis of thermal failure stress calculations
c. Analysis of leakage current calculations

After carrying out some data collection and data analysis, the results of the research carried out will draw conclusions regarding the detection of leakage current through thermal failure voltage.

2.1 Leakage Current

Leakage current is the current that flows in an electrical installation through electrical insulation or due to line capacitance for alternating voltage and conductor losses. The effect of capacitance on the conductor for low voltage systems can be ignored, this is taken into account when analyzing systems with a fairly high working voltage and long enough lines or conductors [22].

Meanwhile, power loss due to conductor losses in alternating current (AC) depends on the rms current and the conductor's effective AC resistance. AC resistance is greater than DC resistance because of the skin effect on AC current so that the loss of conductor power in AC current is greater than in DC current. Carry out a leakage current test on the 20kV power cable on the 150/20kV transformer that will be measured [23].

2.2 Leakage Current Measurement

The initial step in conducting a leakage current test on a 20 kV power cable on a 150/20 kV transformer is to measure the leakage current and carry out a calculation analysis of the leakage current due to thermal failure. Data collection was carried out during the leakage current measurement process on several cables in the 150/20 kV transformer. Researchers measured each phase, namely phase R, phase S, and phase T, and divided the measurements into several cable sections contained in each phase R, S, and T. The part of each phase is explained as follows:

a. Phase R has 3 cables, specifically: core 1, core 2, core 3
b. Phase S has 3 cables, specifically: core 1, core 2, core 3
c. Phase T has 3 cables, specifically: core 1, core 2, core 3

The total number of cables measured from the R phase, S phase and T phase is 9 cables from each core or core of each cable. Measurements are carried out using a clamp meter. In Figure 1 and Figure 2 is a picture of the clamp meter measuring tool used to detect leakage current.

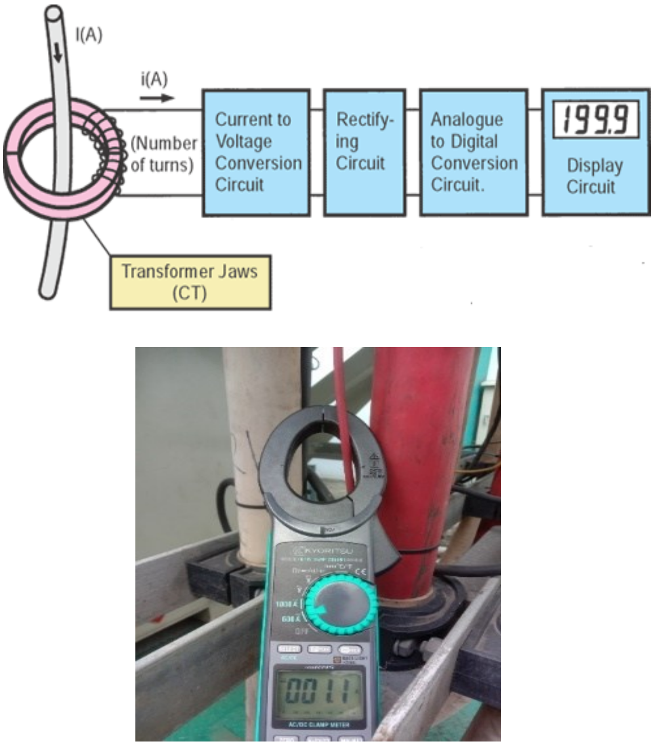

Figure 1. Leakage Current Measurement with Clamp Meter [24]

2.3 Operational Temperature Measurement

In this procedure the researcher carried out an analysis by detecting the temperature on each 20 kV cable in the transformer using thermovision. In collecting this data, researchers also looked for standard specification data for leakage currents on the cables being measured.

Leakage current due to thermal failure voltage can be determined with a thermovision measuring instrument which functions to detect temperature and determine hot point temperatures. This instrument provides a visual representation of temperature distribution, allowing for precise identification of potential thermal failures in electrical systems. Figure 2 is a thermovision measuring instrument.

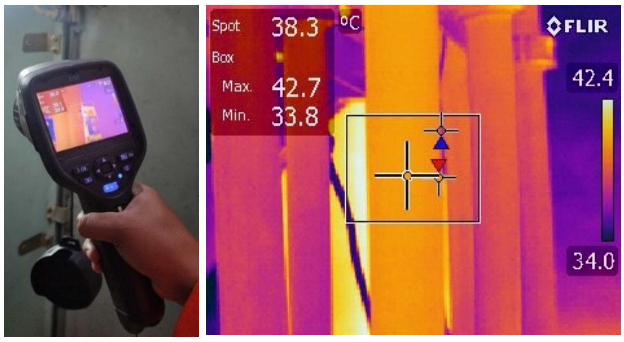

Figure 2. Cable Temperature Measurement with Thermovision

2.4 Cable Specifications for GIS 150 kV Simpang

The cable used in GIS 150 kV Simpang is XLPE type cable. XLPE cable is the best cable for transmission and distribution lines because of its excellent electrical and physical properties. XLPE itself is formed from polyethylene polymer which undergoes a cross-linking process. The type of cable measured in the leakage current measurement process is XLPE cable or Supreme 20 kV cable. The cables used are the N2XSY Cable, which is a copper core cable with XLPE insulation and a PVC cover sheath, and the NA2XSY Cable, which is a single aluminum core cable with XLPE insulation and a PVC outer sheath. More complete specifications regarding the type of cable used for leakage current measurements are explained in Table 1.

Figure 3. N2XSY or NA2XSY Wire [25]

Table 2. Cable Specifications

Information	Specifications	
Bay Name	Transformer 1	
	Transformer 2	
Status	Transformer 1	Operate
	Transformer 2	
Voltage	Transformer 1	150/22 kV
	Transformer 2	150/20 kV
Phase	Transformer 1	RST
	Transformer 2	
Manufacturer	Transformer 1	Indonesia
	Transformer 2	
Beginning of Operations	Transformer 1	2019
	Transformer 2	1996
Brand of Cable	Transformer 1	Supreme Cable
	Transformer 2	
Type of Cable	Transformer 1	N2XSY/NA2XSY
	Transformer 2	
Insulation of Cable	Transformer 1	XLPE
	Transformer 2	
Cross Sectional Area	Transformer 1	RST (3X3X800)
	Transformer 2	RST (3X3X400)
Age of Cable	Transformer 1	3%
	Transformer 2	26%
Cable Length (Meter)	Transformer 1	40% (40 Meter)
	Transformer 2	33% (33 Meter)
Number of Core (Per Phase)	Transformer 1	3 Core
	Transformer 2	3 Core
Installation	Transformer 1	Duck Cable
	Transformer 2	

The conductor wire used is copper or aluminum, and the type of conductor is determined by considering several things, namely current capability and price. The type of conductor that is often used on the secondary side of 150/20 kV transformers is XLPE, which is installed via underground channels to the 20 kV cubicle.

2.5 Transformer Specifications

Transformers are vital components in electric power systems which include the generation, transmission and distribution of electrical energy. The transformer specification data used when measuring leakage current is taken from the transformer template in GIS 150 kV Simpang. This specification data includes the operational capacity and voltage used. Transformer specification data at GIS 150 kV Simpang is explained in Table 3.

Table 3. Transformer Specifications

Information	Status	
Bay Name	Transformer 1	
	Transformer 2	
Brands of Transformer	Transformer 1	B & D
	Transformer 2	Hitachi
Voltage	Transformer 1	150/22 kV
	Transformer 2	150/20 kV
Rating	Transformer 1	60 MVA
	Transformer 2	50 VA

3. Resistivity Type of Conductor

Conductors are intended to conduct electricity both from low voltage, medium voltage and high voltage. The electrical conductivity of a material is expressed in conductivity, which is the inverse of the resistivity or resistance of the conductor which is formulated in the following equation (1) [26].

$$\rho = \frac{R \cdot A}{l} \tag{1}$$

Where,

A : Cross sectional area (m^2)
l : Length (m)
R : Resistivity (ohm)
ρ : Resistivity type (ohm.m)

In calculating the resistivity from equation (1), the first step is to find the resistivity value by determining the value of the conductor length and its cross-sectional area. This information is obtained from the cable specifications used. After the resistivity value is known, the calculation process continues to determine the conductor resistance value. In operation, it uses a 20 kV ground cable with a single aluminum core. Aluminum metal has an electrical conductivity of 3,8 × 10^7 $(ohm.m)^{-1}$, a thermal conductivity (k) of 200 J/m.s °C and a specific resistance of 2,65 x 10^{-8} Ωm.

4. Thermal Failure Voltage

In carrying out thermal failure voltage, specifically by detecting the temperature of the 20 kV incoming cable on the 150/20 kV transformer. This is done to determine the results of hot point temperatures when detected with thermovision. According to Whitehead, the minimum thermal failure voltage (V_m) is calculated using the following equation (2) [11]

$$\text{Vm} = \int_{Tm}^{To} \left|\frac{(8k)}{\sigma}\right| dt \tag{2}$$

Where,

Vm : Thermal Failure Voltage Minimum $[V]$
To : Temperature at the surface of the material [°C]
Tm : Critical temperature at which a material fails [°C]
σ : Electrical Conductivity $[ohm\ meter]^{-1}$

k : Thermal Conductivity $\left[\frac{J}{m}.s°C\right]$

The thermal failure voltage calculation is carried out by calculating from the formula above with the results of the data that has been calculated from the results of resistivity calculations and conductor resistance calculations to determine the value of the data that is calculated next, specifically calculating the leakage current.

5. Leakage Current through Thermal Failure Voltage

To calculate the leakage current in a 20 kV cable, the value can be calculated using the following equation [12].

$$I_{leak} = \frac{V_m}{R} \quad (3)$$

Where,

I_{leak} : Leakage current (A)

V_m : Thermal failure voltage minimum (V)

R : Resistance (Ω)

In calculating leakage current in voltage cables, we use data from previous calculations. This includes values from the thermal failure voltage formula and resistance data (R), which calculates the resistance of the conductor. This calculation process involves calculating resistivity, thermal failure voltage, and leakage current. Before carrying out calculations, the leakage current is measured and thermovision is used to measure the temperature of the cable to be calculated. Specification data such as cross-sectional area and conductor length are also used in the calculation process.

3. Results and Discussion

Leakage current measurements are carried out once a week on several transformers. There are two transformers used in leakage current research. Data is taken by measuring the leakage current on the 20 kV incoming cable, followed by detecting the cable temperature using thermovision. In addition, data is taken from cable and transformer specifications to be analyzed through calculations.

3.1 Leakage Current Measurement Result

Leakage current measurements were carried out in several locations, namely at Transformer 1 and Transformer 2 using a clamp meter. Table 4 is data from leakage current measurements on Transformer 1 and Transformer 2.

Table 4. Leakage Current Measurement Result

Bay Name	Phase	Core 1	Core 2	Core 3
		Current	Current	Current
Transformer 1	R	0,4 A	1,2 A	0,5 A
	S	0,6 A	0,5 A	0,5 A
	T	0,2 A	0,2 A	0,1 A
Transformer 2	R	0,9 A	0,9 A	0,9 A
	S	0,8 A	0,7 A	0,8 A
	T	1,3 A	1,2 A	1,2 A

In summary, Transformer 1 shows variable leakage currents across different phases and cores, with the highest current of 1,2 A observed in core 2 during phase R. Transformer 2 exhibits more consistent leakage currents, especially in phase R where all cores have the same leakage current of 0,9 A, and the highest leakage current of 1,3 A is noted in core 1 during phase T.

3.2 Cable Temperature Measurement Results

In the process of measuring and collecting data using FLIR E-Series Type E60 thermovision which is used in leakage current measurement research and as a temperature measurement on cables. In the process, measurements are carried out on several transformers:

1. Transformer 1 150/22 kV 60 MVA
2. Transformer 2 150/20 kV 50 MVA

Measurements are taken once a week during research or when data collection is carried out. This research includes measuring the temperature of the 20 kV cable on the incoming cable to transformer 1 and transformer 2 at GIS 150 kV Simpang.

Table 5. Cable Temperature Measurement Results

Bay Name	Phase	Core 1	Core 2	Core 3
		Temperature	Temperature	Temperature
Transformer 1	R	38,5 ^{0}C	39,6 ^{0}C	40,6 ^{0}C
	S	38,3 ^{0}C	39,5 ^{0}C	39,6 ^{0}C
	T	38,1 ^{0}C	38,2 ^{0}C	38,3 ^{0}C
Transformer 2	R	35,3 ^{0}C	35,6 ^{0}C	36,1 ^{0}C
	S	35,5 ^{0}C	37,1 ^{0}C	37,4 ^{0}C
	T	37,3 ^{0}C	38,2 ^{0}C	36,7 ^{0}C

The table shows the results of cable temperature measurements for two transformers, each measured on three phases (R, S, T) and three cores (Core 1, Core 2, Core 3). Temperature is recorded in degrees Celsius (°C). Transformer 1 exhibits higher temperatures than Transformer 2, with small temperature variations between cores for each phase. In Transformer 1, the R phase has the highest temperature (38,5°C to 40,6°C), followed by the S phase (38,3°C to 39,6°C), and the T phase (38,1°C up to 38,3°C) has the most consistent and lowest temperature. Meanwhile, in Transformer 2, the R phase shows the lowest temperature (35,3°C to 36,1°C), followed by the S phase which is slightly higher (35,5°C to 37,4°C), and the T has the highest temperature (36,7°C to 38,2°C). These results show higher temperature consistency and higher values in Transformer 1 compared to Transformer 2, which may indicate differences in load conditions or cooling efficiency between the two transformers. Further investigation is required to determine whether this temperature difference is within acceptable limits or indicates a potential problem with the transformer.

3.3 Total Leakage Current

The leakage current calculation is carried out using several formulas which are used and taken from data that has been processed by researchers as additional data for the leakage current calculation process.

1. Resistivity Value

In calculating resistivity, it can be calculated using the following equation:

$$\rho = \frac{R\,.\,A}{l}$$

$$\rho = \frac{0{,}0221\,.\,8x10^{-4}}{40}$$

$$\rho = 4{,}42\ x\ 10^{-7}\ \Omega\text{m}$$

2. Thermal Failure Voltage Value

In calculating the thermal failure stress, it can be calculated using the following equation:

$$V_m = \int_{Tm}^{To} \left|\frac{(8k)}{\rho}\right| dt$$

$$V_m = \int_{120}^{35{,}8} \left|\frac{(8x200)}{4{,}42\ x\ 10^{7}}\right| dt$$

$$V_m = \int_{120}^{35{,}8} |0{,}0000361| dt$$

$$V_m = |(0{,}0000361\,.\,35{,}8) - (0{,}0000361\,.\,120)|$$

$$V_m = 0{,}00129 - 0{,}004332$$

$$V_m = 0{,}003042\ \text{V}$$

3. Leakage Current Calculation

In the calculation, finding the leakage current value can be found from the calculation using the following equation:

$$I_{Leak} = \frac{Vm}{R}$$

$$I_{Leak} = \frac{0{,}002952}{0{,}0221}$$

$$I_{Leak} = 0{,}133\ A$$

The calculation above is the result of leakage current measurements from the R phase (core 1) of Bay Transformer 1 in the Second Week. The calculation results show the leakage current value is 0,133 A, calculated using a predetermined formula.

3.4 Analysis of Research Results

In measurements and calculations based on previously analyzed data, the results of the data and calculations are compared using comparison tables and trend graphs to evaluate the current values measured every week from the first to the fourth week. In addition, a comparison of the leakage current calculation results is carried out with the established method by entering the data into the same table and graph. The Table 6 shows a comparison between calculation and measurement results for leakage current and thermal failure voltage, while the Figure 4 and Figure 5 shows a comparison between weekly measurements and calculations carried out during research and analysis.

Table 6. Comparison Results of Calculations and Measurements

Wire Temperature (°C)	Thermal Failure Voltage (V)	Leakage Current (A)	Measurement Current (A)
38,5	0,002952	0,133	0,4
39,6	0,002912	0,131	1,2
40,6	0,002872	0,129	0,5
38,3	0,002952	0,133	0,6
39,5	0,002912	0,131	0,5
39,6	0,002912	0,131	0,5
38,1	0,002962	0,134	0,1
38,2	0,002962	0,134	0,1
38,3	0,002952	0,133	0,1
35,3	0,002382	0,050	0,9
35,6	0,003272	0,069	0,9
36,1	0,002362	0,050	0,9
35,5	0,002385	0,050	0,8
37,1	0,002332	0,049	0,7
37,4	0,002322	0,049	0,8
37,3	0,002332	0,049	1,3
38,2	0,002302	0,048	1,2
36,7	0,002342	0,049	1,2

The data table contains comparison results between calculation data and leakage current measurement results using a clamp meter. The data included in this table is data from the second week, which compares the results of measurements and calculations from transformer bay 1 and transformer bay 2. Table 6 shows a comparison of the calculation and measurement results related to wire temperature, thermal breakdown voltage, leakage current, and measurement current. At higher wire temperatures (e.g., 39.6°C), the leakage current tends to be slightly higher, while at lower temperatures (e.g., 35.5°C), the leakage current decreases. Next, these data will be included and graphed to find out the comparison results from the second week. This comparison graph consists of two graphs that are analyzed, namely the comparison graph of transformer bay 1 and transformer bay 2. The following is an analysis of the comparison graph between the results of measurements and calculations from transformer bay 1 and transformer 2 in the second week:

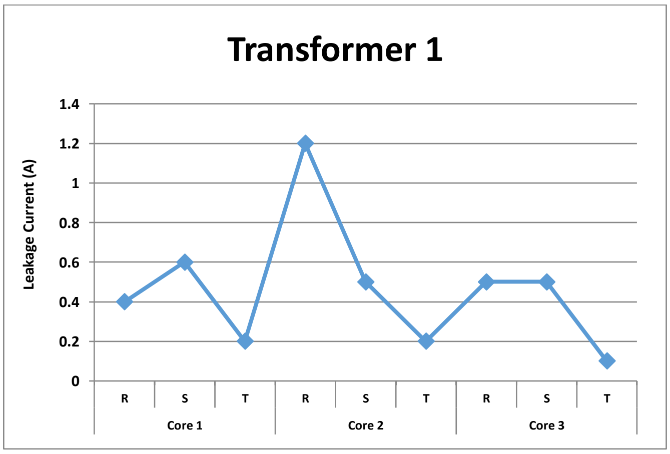

Figure 4. Leakage Current on Transformer 1

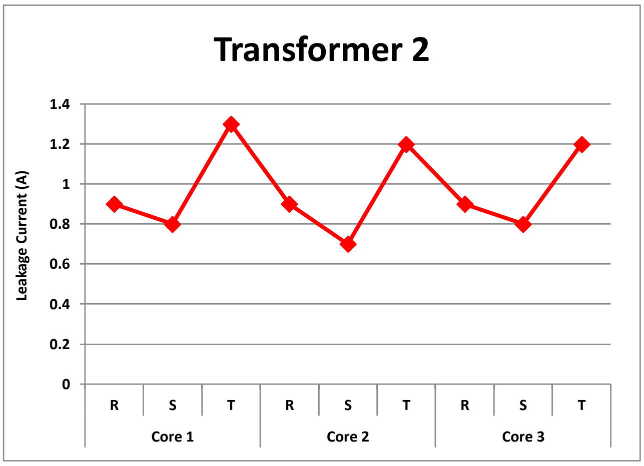

Figure 5. Leakage Current on Transformer 2

Thermal failure in transformers is mainly caused by overheating, which can result from several factors such as overload, insulation degradation, cooling system failure, and external environmental factors. When a transformer experiences a thermal failure, this can cause a localized hotspot that further damages the insulation, thereby causing leakage current. Several factors can affect leakage current in a transformer, such as temperature, humidity, aging, and contaminants. Higher operating temperatures can reduce insulation resistance, humidity can significantly reduce insulation resistance, aging of insulating materials can reduce their effectiveness, and contaminants such as dust can create conductive paths on the insulating surface.

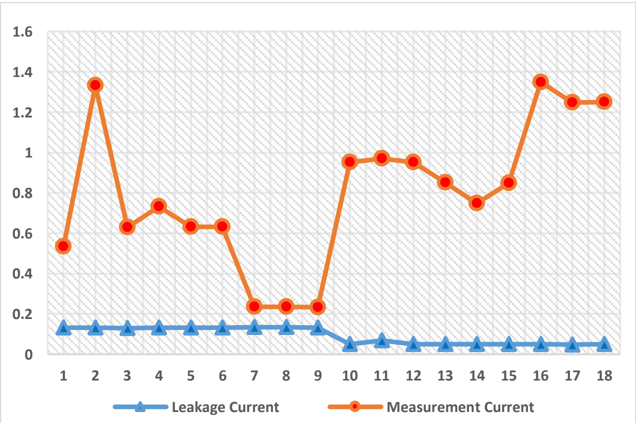

Figure 6. Comparison of leakage to measurement current

Figure 6 shows a comparison of the leakage current and measurement current data with 18 different temperature cases previously described in Table 6. The leakage current remains relatively stable, hovering around 0,2 A throughout all 18 data measurement, indicating minimal fluctuations. The measurement current experiences significant variations. Initially, it spikes to approximately 1,4 A at second measurement, then drops and fluctuates between 0,4 and 1,2 A. Around the 10th to 14th measurement, there is a noticeable dip where the measurement current decreases to around 0,4 A, followed by another rise, peaking again near 1,4 A.

This analysis suggests that while the leakage current remains consistent, the measurement current is much more variable, with significant peaks and valleys across the intervals measured. To reduce the risk of thermal failure and manage leakage current, several strategies can be implemented, including regular monitoring and testing of insulation resistance and leakage current, ensuring the cooling system is functioning properly, avoiding transformer overload by managing load distribution, and routine inspection and maintenance of the system isolation to detect and degradation. By understanding the factors that contribute to thermal failure and implementing routine monitoring and maintenance practices, transformer reliability and lifespan can be significantly improved.

4. Conclusion

From the evaluation of leakage current measurements on the GIS Simpang 150/20 kV transformer, it was found that the leakage current was stable at 1.3 A from phase point T of transformer 2 during the first and second weeks. However, in the third and fourth weeks, the leakage current increased to 2,2 A and 2,5 A from phase point T of transformer 1, indicating a peak in the fourth week. Meanwhile, the leakage current remained stable at around 0,2 A across all 18 measurements, while the measurement current showed significant fluctuations, initially spiking to approximately 1,4 A in the second measurement and then fluctuating between 0,4 A and 1,2 A. The use of thermography in thermal failure analysis is highly effective as it allows for the identification of hot spots and temperature deviations that may not be visible through conventional measurements. By detecting temperature differences in components, thermography can provide early insights into potential issues, including leakage currents and thermal instability.

References

[1] Widagdo, R. S., & Andriawan, A. H. (2023). Analysis of Losses Due to Load Unbalance in a 2000 kVA Transformer at Supermall Mansion 2 Tower Tanglin Surabaya. *Journal of Engineering and Scientific Research*, *5*(2), 78-84.

[2] Widagdo, R. S., & Andriawan, A. H. (2023). Prediction of Age Loss on 160 KVA Transformer PT. PLN ULP Kenjeran Surabaya using The Linear Regression Method. *Jurnal Riset Rekayasa Elektro*, *5*(2), 83-92.

[3] Zhuang, T., Ren, M., Gao, X., Dong, M., Huang, W., & Zhang, C. (2019). Insulation condition monitoring in distribution power grid via IoT-based sensing network. *IEEE Transactions on Power Delivery*, *34*(4), 1706-1714.

[4] O. Boler, Y. Sozer, A. D. Abreu-Garcia, and J. Lauletta, "Aging condition assessment for live XLPE-type cables through precise high frequency impedance phase detection," in Proc. IEEE Energy Convers. Congr. Expo., Oct. 2019, pp. 2021–2025.

[5] Wang, W., Sonoda, K., Yoshida, S., Takada, T., Tanaka, Y., & Kurihara, T. (2018). Current integrated technique for insulation diagnosis of water-tree degraded cable. *IEEE Transactions on Dielectrics and Electrical Insulation*, *25*(1), 94-101.

[6] Liu, Y., Wang, H., Zhang, H., & Du, B. (2022). Thermal Aging Evaluation of XLPE Power Cable by Using Multidimensional Characteristic Analysis of Leakage Current. *Polymers*, *14*(15), 3147.

[7] Villalobos, R. J., Moran, L. A., Huenupán, F., Vallejos, F., Moncada, R., & Pesce, C. (2022). A new current transducer for on-line monitoring of leakage current on HV insulator strings. *IEEE Access*, *10*, 78818-78826.

[8] Granizo, R., Platero, C. A., & Guerrero, J. M. (2020, June). HVDC Ground Fault Detection Method Based on the Shield Leakage Current Measurement for Long Cable Energization. In *2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)* (pp. 1-5). IEEE.

[9] Kemari, Y., Mekhaldi, A., Teyssèdre, G., & Teguar, M. (2019). Correlations between structural changes and dielectric behavior of thermally aged XLPE. *IEEE Transactions on Dielectrics and Electrical Insulation*, *26*(6), 1859-1866

[10] Ushakov, V. Y., Mytnikov, A. V., & Rakhmonov, I. U. (2023). Diagnostics of High-Voltage Cable Lines. In *High-Voltage Equipment of Power Systems: Design, Principles of Operation, Testing, Monitoring and Diagnostics* (pp. 263-272). Cham: Springer Nature Switzerland.

[11] Kusumo, B., & Hakim, A. R. (2022). Analisis Pendeteksian Dini Arus Bocor Kabel Power 20 kV Pada Transformator 1 150/20 kV di GIS Gandaria. *JURNAL ELEKTRO*, *10*(1), 53-62.

[12] Sofwan, A., & Kusuma, S. A. (2018). Pendeteksian Dini Terhadap Arus Bocor Kabel Tanah Tegangan Menengah Pada Transformator 150/20kV. *SINUSOIDA*, *20*(2).

[13] Fortes, R. R., Buzo, R. F., & de Oliveira, L. C. (2020). Harmonic distortion assessment in power distribution networks considering DC component injection from PV inverters. *Electric Power Systems Research*, *188*, 106521.

[14] Dang, D., Liu, Y., & Lee, S. K. (2024). State Evaluation of Electrical Equipment in Substations Based on Data Mining. *Applied Sciences*, *14*(16), 7348.

[15] Balakrishnan, G. K., Yaw, C. T., Koh, S. P., Abedin, T., Raj, A. A., Tiong, S. K., & Chen, C. P. (2022). A review of infrared thermography for condition-based monitoring in electrical energy: Applications and recommendations. *Energies*, *15*(16), 6000.

[16] Soni, R., & Mehta, B. (2021). Review on asset management of power transformer by diagnosing incipient faults and faults identification using various testing methodologies. *Engineering Failure Analysis*, *128*, 105634.

[17] Mahami, A., Bettahar, T., Rahmoune, C., Amrane, F., Touati, M., & Benazzouz, D. (2022, November). A New Transformer Condition Monitoring Based on Infrared Thermography Imaging and Machine Learning. In *International Conference on Artificial Intelligence in Renewable Energetic Systems* (pp. 408-418). Cham: Springer International Publishing.

[18] Zarco-Periñán, P. J., Martínez-Ramos, J. L., & Zarco-Soto, F. J. (2021). A novel method to correct temperature problems revealed by infrared thermography in electrical substations. *Infrared Physics & Technology*, *113*, 103623.

[19] Zarco-Periñán, P. J., Zarco-Soto, F. J., Zarco-Soto, I. M., & Martínez-Ramos, J. L. (2022). Conducting Thermographic Inspections in Electrical Substations: A Survey. *Applied Sciences*, *12*(20), 10381.

[20] Patil, A. J., Singh, A., & Jarial, R. K. (2020). Introduction to condition monitoring of electrical systems. *Soft Computing in Condition Monitoring and Diagnostics of Electrical and Mechanical Systems: Novel Methods for Condition Monitoring and Diagnostics*, 91-120.

[21] Asefi, S., Asad, B., Leinakse, M., Manninen, H., Kilter, J., Vaimann, T., ... & Landsberg, M. (2024). Review of High Voltage Instrument Transformer Condition Monitoring. *IEEE Transactions on Dielectrics and Electrical Insulation*.

[22] Wu, Y., Yang, Y., Wang, Z., & Zhang, P. (2021). Online monitoring for underground power cable insulation based on common-mode signal injection. *IEEE Transactions on Industrial Electronics*, *69*(7), 7360-7371.

[23] Kang, S. D., & Kim, J. H. (2020). Investigation on the insulation resistance characteristics of low voltage cable. *Energies*, *13*(14), 3611.

[24] Widagdo, R. S., Slamet, P., Andriawan, A. H., Hariadi, B., Wardah, I. A., & Hartono, E. D. (2024). Assessment of Power System Equipment to Enhance the Power Quality at Dr. Saiful Anwar General Hospital Malang. *BERNAS: Jurnal Pengabdian Kepada Masyarakat*, *5*(2), 1596-1604.

[25] Rozegnał, B., Albrechtowicz, P., Mamcarz, D., Rerak, M., & Skaza, M. (2021). The power losses in cable lines supplying nonlinear loads. *Energies*, *14*(5), 1374.

[26] Bragatto, T., Cresta, M., Gatta, F. M., Geri, A., Maccioni, M., & Paulucci, M. (2023). Assessing thermal behavior of medium voltage cable joints through simulations and measurements. *IEEE Transactions on Industry Applications*.