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Voltage and Current Analysis of Oil Immersed Power Transformer due to Lightning Impulse with Different Insulation Conditions

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Abstract: Insulation breakdown is a common cause of transformer failure. Insulation is used to prevent current from flowing between points in an electrical system with varying potentials. Lightning strikes are a natural cause of transient overvoltage in the power system. A lightning strike is an impulsive transient variation with a polarity that is unidirectional (positive or negative). This research aims to determine waveform of voltage and current with its peak and RMS value for oil immersed power transformer with lightning impulse. Specifically, it analyses the data obtained for a good and poor insulation of the transformer. A comprehensive lightning impulse test was conducted on the transformer. Both high voltage and low voltage winding was subjected to a test voltage ranging from 50% to 75% integrity of the entire test voltage. Following that, three consecutive full-wave lightning impulses at 100% of the test voltage are applied. The result showed a significant disparity value for both conditions especially for current peak and RMS value which are 215.8 A and 156.7 A respectively due to shorten tail time which obtained from poor insulation is 20.1 µs. This results in a significant rise in the current value, as the tail time is supposed to be between 40 µs and 60 µs. Although the difference between voltage peak and RMS value is minuscule which are 2.4 kV and 1.7 kV respectively, the voltage waveform for poor insulation is unstable. As a result, a lightning impulse will affect a huge number of apparatuses or electrical equipment when it strikes a transformer with an insulation fault. Preventive maintenance is necessary for the safe and reliable operation of transformers. Maintenance identifies issues early and helps avert future deterioration.

Keywords: Oil immersed power transformer, lightning impulse, good and poor insulation

1. Introduction

Lightning strikes are a common cause of transient overvoltage in the power system [1]. Lightning strike is a polarized unidirectional impulsive transient variation (positive or negative). The majority of overhead transmission lines are affected by lightning. Induced voltage through insulators and phase lines is caused by lightning current that strike into shield wires or the tower body. Shield wires protect transmission lines from direct lightning strikes. 500kV, 275kV, and 132kV are the transmission voltage networks, while 33kV, 11kV, and 400/230 volts are the distribution voltage networks [2]. The distribution voltages in some parts of Johor and Perak, however, may be as high as 22kV and 6.6kV. The frequency of the supply is 50Hz + 1%.

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Power transformers are often rated over 200 MVA and are utilized in transmission networks with higher voltages for step-up and step-down applications (400 kV, 200 kV, 110 kV, 66 kV, 33 kV) [3]. Power transformers are critical components of power grids and their reliability has a direct impact on the power system's safety [4]. It is utilized for transmission purposes when the load is large, the voltage is greater than 33 kV and the efficiency is 100%. It is likewise larger in size than distribution transformers and it is utilized in power generation and transmission substations. Additionally, it features an excellent amount of insulation. Meanwhile, distribution transformers are used to connect low-voltage distribution networks (11 kV, 6.6 kV, 3.3 kV, 440 V, 230 V) and are typically rated less than 200 MVA. Distribution transformers are used to distribute electrical energy at low voltages of less than 30kV in industrial applications and 440V-220V in residential applications. It operates at a low efficiency level of 50–70% is compact, simple to install, has low magnetic losses and it is not always completely loaded.

Electrical transformers are critical components of the process of power transmission and distribution [5]. Transformers are the most expensive component of the power system and their proper operation is critical to system operation. A transformer is a passive electrical device that uses electromagnetic induction to transmit electrical energy from one circuit to another [6]. Faults are a significant factor in the operation of all electrical devices. A transformer defect can result in catastrophic failure, causing considerable property damage and significant business interruption. A simple distribution problem might result in the complete loss of electricity in a region. While transformers require significantly less maintenance than other electrical equipment, determining the reason of failure and the genesis of a flaw is not straightforward. Failures can be attributed to a variety of factors. However, these are frequently the result of a number of variables. Among these variables are design and environmental imperfections.

Insulation breakdown is a common cause of transformer failure. Insulator is a term that refers to a material that does not conduct electricity [7]. Insulators are a critical component of a transmission system's electrical components [8]. In a power system network, insulators are required to isolate line conductors from the ground and to provide necessary mechanical support [9]. Insulation is used to prevent current from flowing between locations of varying potential in an electrical circuit. Insulation failure is one of the most prevalent types of equipment failure. Degraded insulators can result in flashover or power outages on transmission lines due to the mechanism and insulation level of the insulator strings degrading over time [10]. Insulating fluids, conductor insulation, and solid insulator are the most often utilised insulations in transformers. When one of these insulating mediums fails, the transformer suffers catastrophic damage.

2. Methodology

This chapter described the methodology utilized to get the findings. Testing was used to test the oil immersed power transformer with lightning impulse. The lightning impulse test for the transformer was conducted with a good and poor insulation.

2.1 Project and Testing Flow

The projects begin with research and literature reviews to get a deeper knowledge of the subject. The methodology used to complete the project is shown in Figure 2.1. To begin, research distribution transformer to get a better understanding of the idea. Insulation are the primary subjects to be explored. Following that, the literature review on lightning impulse is primarily focused on gathering as much information as possible on faults. The testing was then performed with lightning impulse for both good and poor insulation circumstances.

The flow chart shown in Figure 2.2 illustrates the testing process. The first step is to connect distribution transformer with earth point. After that, LV windings is shorted and connected to the tank. Following that, tank to be earthed through shunt resistor. Then, phase which are not being tested have to be earthen during the test. If the terminal has neutral line, the neutral line has to be tested. Additionally, external resistor can be put between shorted terminals to earth. Maximum external resistance value is 400 ohms. Next, select the correct front and tail resistor at the circuit test in order to get correct waveform. Front and tail resistor is determine based on trial-and-error method to get correct curve (waveform). Finally, the data collection process takes place.

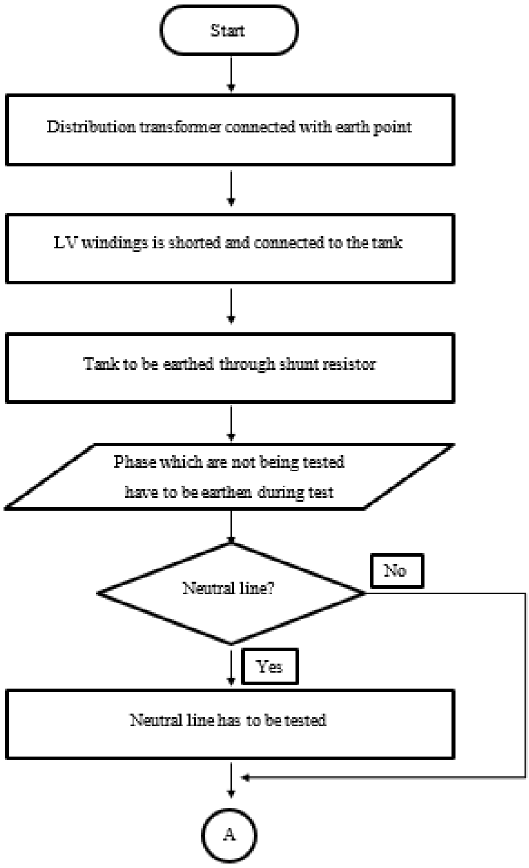

Fig. 2.1 - Project flow chart

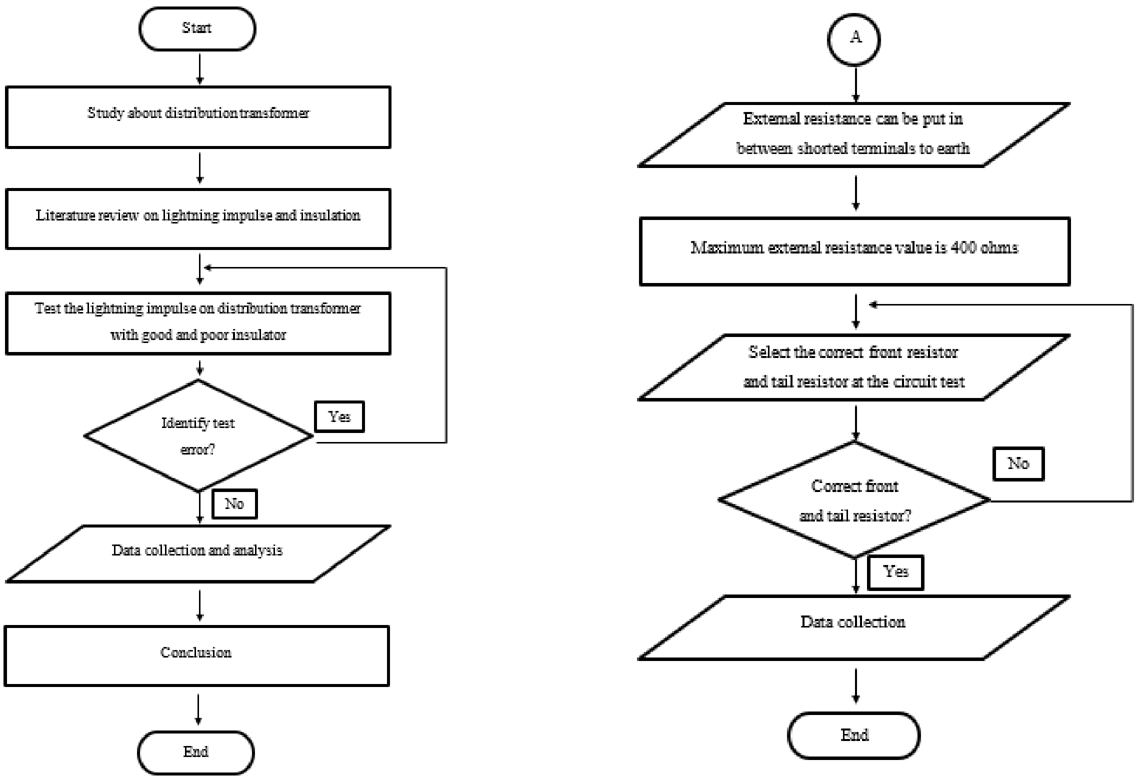

Fig. 2.2 - Testing flow chart

2.2 Rated Characteristics of the Test Transformer

The rated characteristics of the test transformer is depicted in Table 2.1. The type and vector of the test transformer are oil immersed power transformer and Dyn11. The characteristics for rated voltage, frequency and power of the test transformer are 33000/11000 V, 50 Hz and 5000/6250 kVA respectively.

Table 2.1 - Rated characteristics of the test transformer

Type	Oil Immersed Power Transformer
Vector	Dyn11
Rated Voltage	33000/11000 V
Rated Frequency	50 Hz
Rated Power	5000/6250 kVA

2.3 Test Methodology Applied

The test was performed according to IEC 60076-3 (2013-01) – Power transformers - Part 3: Insulation levels, dielectric tests and external clearances in air.

2.4 Description of the Test

The transformer was subjected to full lightning impulse test. The test voltage, 50% to 75% of full test voltage was applied to every high voltage winding and low voltage winding. The test is then followed with the application of three consecutive full-wave lightning impulse at 100% full test voltage. The test was conducted at principal tapping for high voltage.

2.5 Electrical Diagram

The connection between the test transformer and the test system is illustrated in figure 2.3. To avoid inducing excessive over voltages in the windings that are not being tested, they are shorted through shunt resistor and linked to ground. However, short circuiting affects the transformer's impedance, posing difficulties in altering the impulse generators' typical waveshape. Additionally, it lowers detection sensitivity.

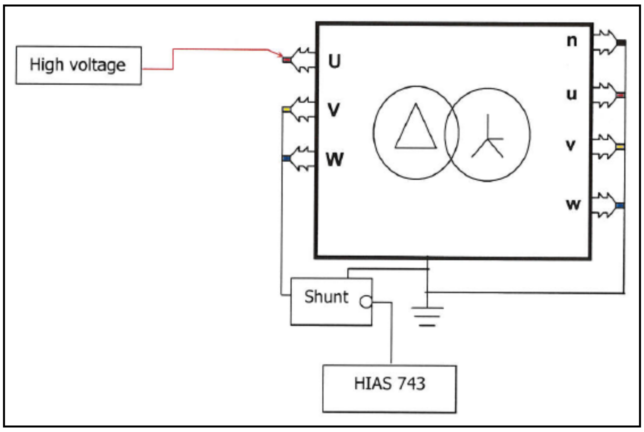

Fig. 2.3 - Connection between test transformer and test system

2.6 Testing Configuration

The panoramic view and testing configuration of setup for lightning impulse test and installation of shunt for current measurement are shown in Figure 2.4 and 2.5 respectively.

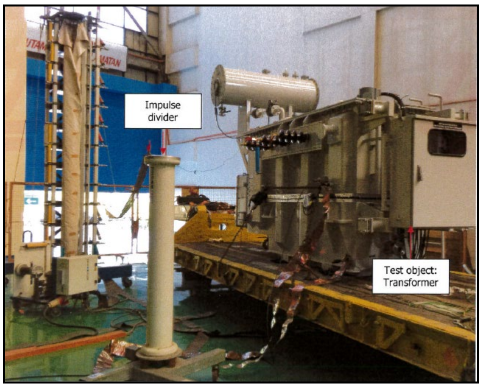

Fig. 2.4 - Setup for lightning impulse test

Fig. 2.5 - Installation of shunt for current measurement

2.7 Test Equipment Schematic Diagram

The impulse test set schematic diagram is illustrated in Figure 2.6. The circuit configuration is depicted in Table 2.2. The number of stages for the circuit configuration is 3 stages for HV side and 2 stages for LV side. The generator capacitance of the circuit is 25000 pF. The tail resistor is 1150Ω for HV side and 1.5kΩ for LV side and the front resistor is 56Ω for HV side and 91Ω for LV side. Next, the voltage divider ratio is 356.6. The termination and shunt resistance are 75 Ω and 0.997 Ω respectively.

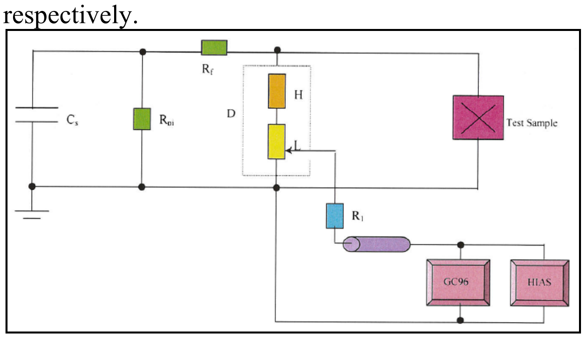

Fig. 2.6 - Impulse test set schematic diagram

Table 2.2 - Circuit configuration

Circuit Configuration	
Number of Stage	3 stages for HV side, 2 stages for LV side
Generator Capacitance (CS)	25000 pF
Tail Resistor (Rpi)	1150 Ω for HV side, 1.5k Ω for LV side
Front Resistor (Rf)	56 Ω for HV side, 91 Ω for LV side
Voltage Divider Ratio	356.6
Termination (R1)	75 Ω
Shunt	0.997 Ω

2.8 Poor Insulation

Figure 2.7 shown two points of damages or punctures of a coil between HV and LV coil barrier sheet.

Fig. 2.7 - Points of punctures of a coil between HV and LV coil barrier sheet

3. Result and Discussion

This chapter discussed about testing result. The voltage and current for peak and its RMS value from the testing have been discuss here for good and poor insulation. There are some major different values from both conditions.

3.1 Good Insulation

3.1.2 Voltage Waveform

The output is the same for the red, yellow and blue phase, therefore just the yellow stage result is shown. The peak voltage for reduce lightning impulse voltage waveform of Figure 3.1 is equivalent to 87.0 kV. Some calculations have to be made to obtain the RMS value. The formula for converting maximum voltage to RMS:

$$V_{rms} = \frac{V_{peak}}{\sqrt{2}} \tag{3.1}$$

The RMS value for phase voltage is 61.5 kV based on the conversion using formula 3.1. The front and tail time are 1.2 µs and 41.8 µs. The waveform in Figure 3.2, 3.3 and 3.4 depicts full lightning impulse voltage waveform. The test result of lightning impulse voltage for yellow phase in negative polarity is shown in Table 3.1. The peak voltages are 172.6 kV, 172.9 kV and 172.6 kV respectively, which corresponds to an RMS value of 122.0 kV, 122.3 kV and 122.0 kV respectively. The average for peak voltage and RMS value are 172.7 kV and 122.1 kV. The front and tail time are 1.2 µs and 42.0 µs for the three full lightning impulse voltage waveforms.

Reduce lightning impulse voltage waveform is shown in Figure 3.1. The peak voltage and RMS value are 87.0 kV and 61.5 kV respectively. The front and tail time are 1.2 µs and 41.8 µs.

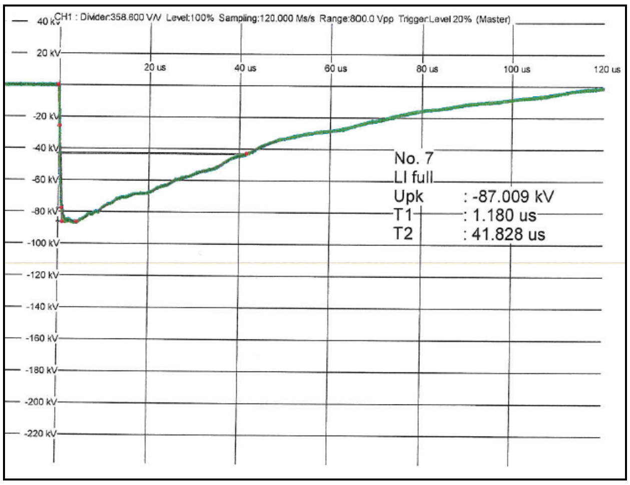

Fig. 3.1 - Reduce lightning impulse voltage waveform

Full lightning impulse voltage waveform is depicted in Figure 3.2. The peak voltage and RMS value are 172.6 kV and 122.3 kV respectively. The front and tail time are 1.2 µs and 42.0 µs.

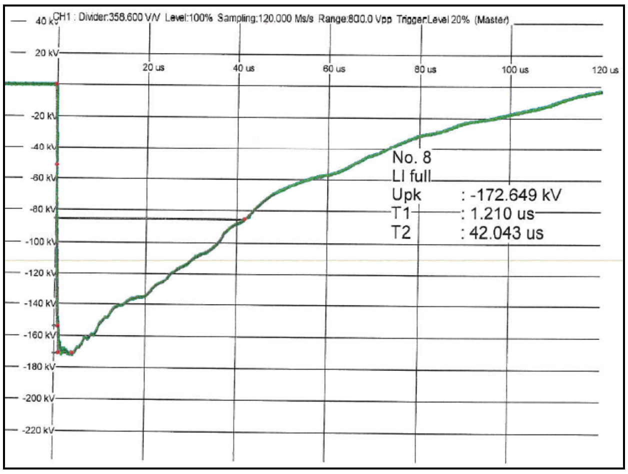

Fig. 3.2 - Full lightning impulse voltage waveform test 1

Full lightning impulse voltage waveform is depicted in Figure 3.3. The peak voltage and RMS value are 172.9 kV and 122.0 kV respectively. The front and tail time are 1.2 μs and 42.0 μs.

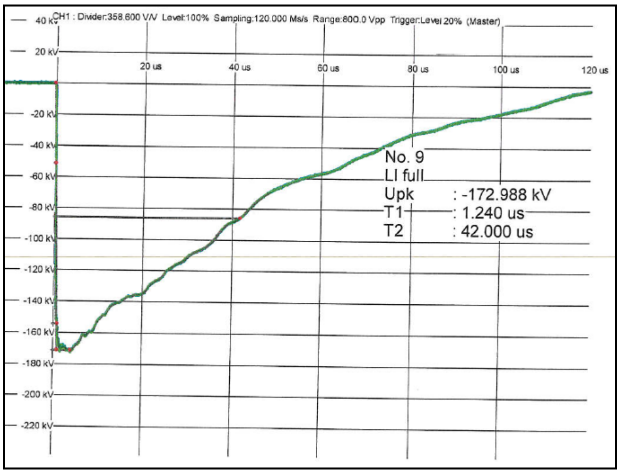

Fig. 3.3 - Full lightning impulse voltage waveform test 2

Full lightning impulse voltage waveform is depicted in Figure 3.4. The peak voltage and RMS value are 172.6 kV and 122.0 kV respectively. The front and tail time are 1.2 μs and 42.0 μs.

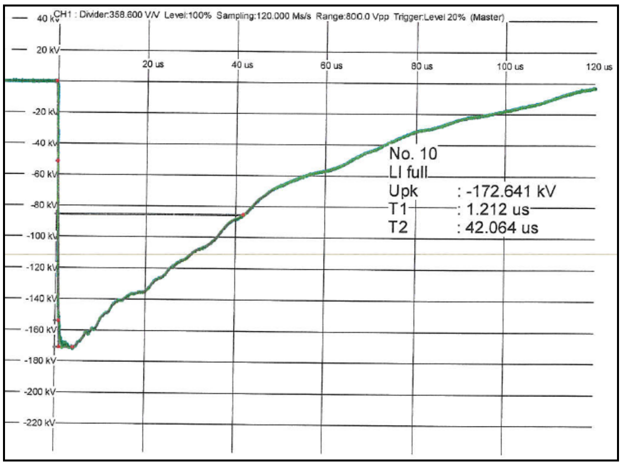

Fig. 3.4 - Full lightning impulse voltage waveform test 3

Table 3.1 - Test result of lightning impulse voltage for yellow phase in negative polarity

Figure	Test Type	Percentage applied %	Charging Voltage (kV)	Required Peak Voltage (kV)	Test Peak Voltage (kV)
4.1	Reduce	50	94.0	85.0	87.0
4.2	Full	100	188.0	170.0	172.6
4.3	Full	100	188.0	170.0	172.9
4.4	Full	100	188.0	170.0	172.6

3.1.2 Current Waveform

The maximum and minimum of peak current for reduce lightning impulse current waveform of Figure 3.5 is equivalent to 24.3 A and 18.5 A. Some calculations have to be made to obtain the RMS value. The formula for converting maximum and minimum current to RMS:

$$I_{rms} = \frac{I_{peak}}{\sqrt{2}} \tag{3.2}$$

The RMS value for maximum and minimum of peak current are 17.2 A and 13.1 A based on the conversion using formula 4.2. The waveform in Figure 3.6, 3.7 and 3.8 depicts full lightning impulse current waveform. The test result of lightning impulse current for yellow phase in negative polarity is shown in Table 4.2. The maximum of peak current is 43.4 A, 50.5 A and 30.5 A and the minimum of peak current is 24.0 A, 16.9 A and 29.5 A. It corresponds to RMS value for maximum of peak current of 30.7 A, 35.7 A and 21.6 A and RMS value for minimum of peak current of 17.0 A, 12.0 A and 20.9 A. The average for maximum and minimum of peak current are 41.5 A and 23.5 A respectively and the average for RMS value for maximum and minimum of peak current are 29.3 A and 16.6 A respectively.

Reduce lightning impulse current waveform is depicted in Figure 4.5. The maximum and minimum of peak current are 24.3 A and 18.5 A respectively. The RMS value for maximum and minimum of peak current are 17.2 A and 13.1 A.

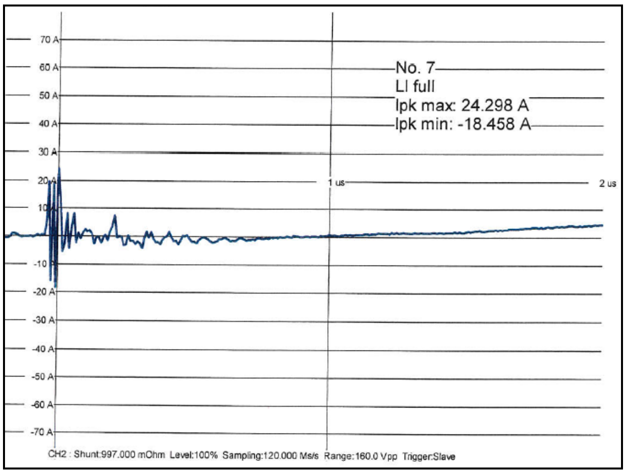

Fig. 3.5 - Reduce lightning impulse current waveform

Full lightning impulse current waveform is depicted in Figure 3.6. The maximum and minimum of peak current are 43.4 A and 24.0 A respectively. The RMS value for maximum and minimum of peak current are 30.7 A and 17.0 A.

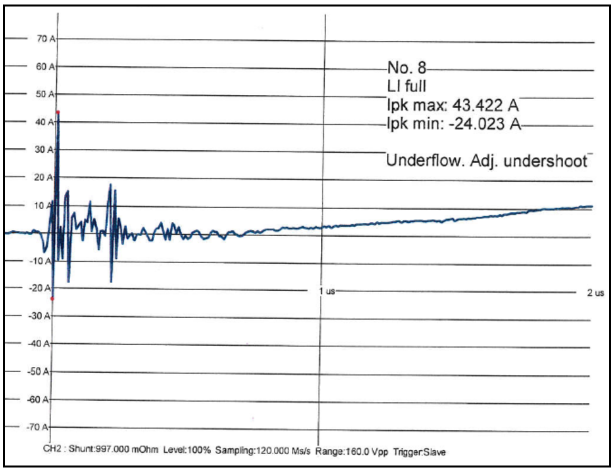

Fig. 3.6 - Full lightning impulse current waveform test 1

Full lightning impulse current waveform is depicted in Figure 3.7. The maximum and minimum of peak current are 50.5 A and 16.9 A respectively. The RMS value for maximum and minimum of peak current are 35.7 A and 12.0 A.

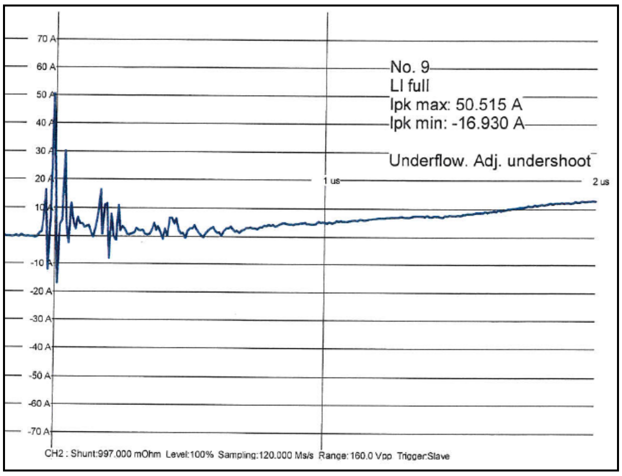

Fig. 3.7 - Full lightning impulse current waveform test 2

Full lightning impulse current waveform is depicted in figure 3.8. The maximum and minimum of peak current are 30.5 A and 29.5 A respectively. The RMS value for maximum and minimum of peak current are 21.6 A and 20.9 A.

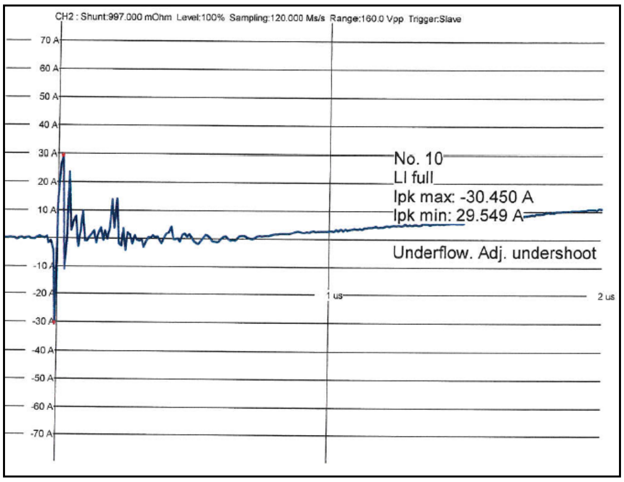

Fig. 3.8 - Full lightning impulse current waveform test 3

Table 4.2 - Test result of lightning impulse current for yellow phase in negative polarity

Figure	Test Type	Percentage applied %	Charging Voltage (kV)	Current Peak	
				Maximum (A)	Minimum (A)
4.5	Reduce	50	94.0	24.3	18.5
4.6	Full	100	188.0	43.4	24.0
4.7	Full	100	188.0	50.5	16.9
4.8	Full	100	188.0	30.5	29.5

3.2 Poor Insulation

3.2.2 Voltage Waveform

Lightning impulse voltage waveform is depicted in figure 3.9. The voltage waveform is unstable due to its poor insulation. The peak voltage is 170.3kV and the RMS value is 120.4 V. The front and tail time are 1.2 μs and 20.1 μs.

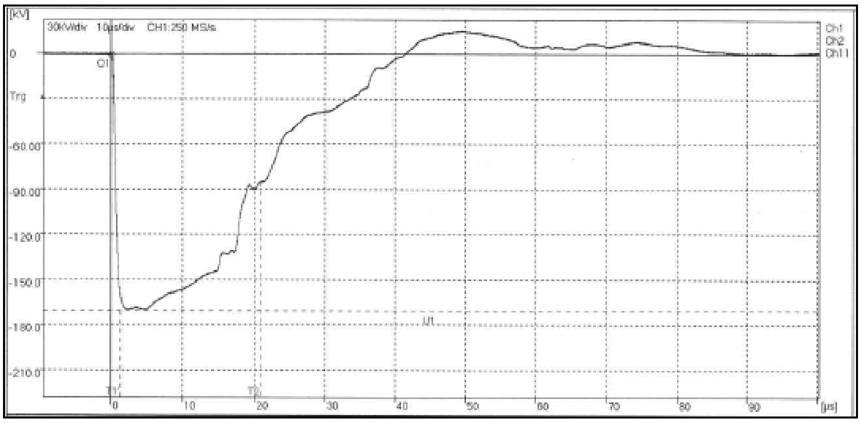

Fig. 3.9 - Poor insulation lightning impulse voltage waveform

3.2.2 Current Waveform

Lightning impulse current waveform is depicted in figure 3.10. The current waveform is unstable due to its poor insulation. The peak current is 245.1 A and the RMS value is 173.3 A.

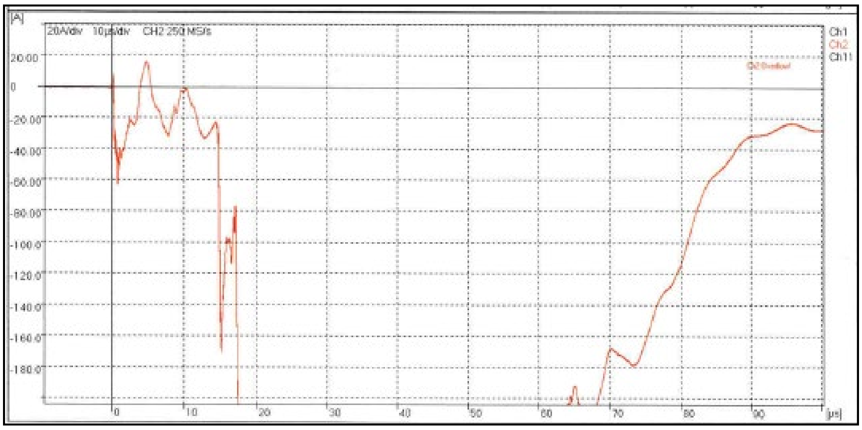

Fig. 3.10 - Poor insulation lightning impulse current waveform

3.3 Comparison between Good and Poor Insulation

Comparison value between good insulation and poor insulation is depicted in Table 3.3. The difference value between both condition for Vpeak, Vrms, Ipeak, Irms, front and tail time are 2.4 kV, 1.7 kV, 215.8 A, 156.7 A, 0 µs and 21.9 µs as depicted in Table 3.4. It is a major difference for the Ipeak and Irms which are 215.8 A and 156.7 A due to the shorten tail time which is 20.1 µs. It causes the current value increases significantly because the tail time is supposed to be between 40 µs and 60 µs. The shorten tail time is caused by a poor insulation of the transformer. The voltage waveform for the poor insulation is unstable even though the difference is minor for the Vpeak and Vrms which are 2.4 kV and 1.7 kV. It is caused by flashover due to weak internal resistance.

Table 3.3 - Test result of lightning impulse current for yellow phase in negative polarity

Insulation	Voltage (kV)		Current (A)		Time (µs)	
	Peak	RMS	Peak	RMS	Front	Tail
Good	172.7	122.1	29.3	16.6	1.2	42.0
Poor	170.3	120.4	245.1	173.3	1.2	20.1

Table 3.4 - Difference value for both conditions

Voltage (kV)		Current (A)		Time (µs)	
Peak	RMS	Peak	Peak	Front	Tail
2.4	1.7	215.8	156.7	0	21.9

4. Conclusion

The testing was conducted for analysing both conditions. Both conditions have a major difference value especially for Ipeak and Irms because of the tail time. This prove that when the insulation is weak or frail, voltage and current value will be different. The tail time is shortened due to the poor insulation of the transformer. Additionally, the voltage waveform for poor insulation is unstable despite the fact that the difference between Vpeak and Vrms are minimal. Thus, a lightning impulse will impact a large number of apparatuses or electrical devices when it strikes a transformer with an insulation fault.

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