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Failure Analysis of Transformers under Impulse Test

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Abstract

Transformers are the most critical and costly components in AC power systems. Insulation is the weakest link in transformers, and the design and quality of a transformer's insulation system shall be confirmed by performingdielectric tests according to National or International standards. The impulse test is more critical among the dielectric tests, as it verifies the integrity of the whole insulation system of the transformer. However, concluding the impulse test result is difficult when minor discrepancies exist in the earth's current waveforms. This paper presents two such case studieswith distribution class transformers.

Keywords: Insulation Failure, Impulse Testing, Minute Fault Analysis, Transformer

1. Introduction

Transformers are generally used in the power system to change the voltage levels for efficient power transmission and distribution. Hence, transformers are vital and costly equipment in the power system. The premature failure of the transformers may lead to an unreliable power supply. The insulation is the weakest link in the transformer. Insulation of the transformer is complex and comprises solid, liquid and gas insulating materials. Hence, the material quality, design and manufacturing process plays a significant role in the transformer's quality. Several dielectric tests are stipulated in the IEC standards to verify the transformer design and quality against expected overvoltages in the system.

The lightning impulse test is the most important of dielectric tests as it verifies the integrity of the whole insulation system in the transformer. It also verifies the smoothness of the conductor material. If there is a major fault in the insulation system, it is easy to conclude the failure under the impulse test. On the other hand, whenever there are minor faults in the insulation system during the impulse test, it requires proper experience to conclude the test result[1].

This paper discusses the surge phenomenon in winding using step response, which equivalently represents the impulse stress with sharp rise and slow fall. This paper also presents the failure analysis of two transformers under impulse test with minute faults as case studies. The impulse tests on 2.5MVA and 1MVA rated distribution transformers were carried out at High Voltage Division, CPRI-Bengaluru. Both transformers failed, and the failure analysis using the transfer function and their coherence is presented in this paper. The transformer's High Voltage (HV) terminals were subjected to impulse test by using HAEFELY make impulse voltage generator.The voltage and earth current signals were measured with Resistive Capacitive Resistive (RCR) voltage divider and HiAS743 digitizer of HAEFELY make.

2. Surge Phenomenon in Winding

The adventof computer technology in handling bulk data allowed design engineers to use numerical methods for evaluating voltage stresses across transformer winding. The numerical methods avoid many assumptions in the analytical standing wave and travelling wave theory. The analytical method available in the literature applies to uniformly insulated windings only and lacking in accuracy due to the presence of assumptions. Nevertheless, the analytical method of step response of the winding can illustrate the surge phenomenon in winding[1-3].

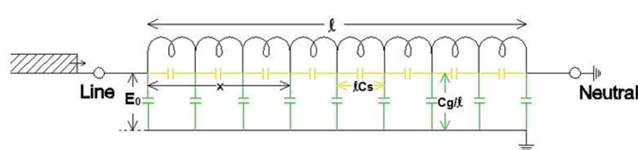

Figure 1. Representation of winding with distributed inductances and capacitances.

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$$\frac{d^2e}{dx^2} - \frac{1}{l^2}\frac{C_g}{C_s}e = 0 \qquad (1)$$

$$e = E_0 \frac{\sin\left(\alpha \frac{l-x}{l}\right)}{\sinh(\alpha)} \qquad (2)$$

$$\alpha = \sqrt{\frac{C_g}{C_s}} \qquad (3)$$

Uniformly insulated winding can be represented by distributed capacitances and inductances network as shown in Figure 1. In Figure 1, "*l*"- total length of the winding, "*x*"- distance from the line end to the point of observation on the winding, "*lCs*"- capacitance between portions of winding unit distance apart, "Cg/l"- capacitance to ground per unit length of the winding. At the time instant of step voltage application (t=0+), the distributed network's capacitances alone determine the voltage distribution across the winding as the inductances act as open circuits for that instant. The initial voltage distribution is found by solving the governing equation mentioned in "(1)"[1-3].

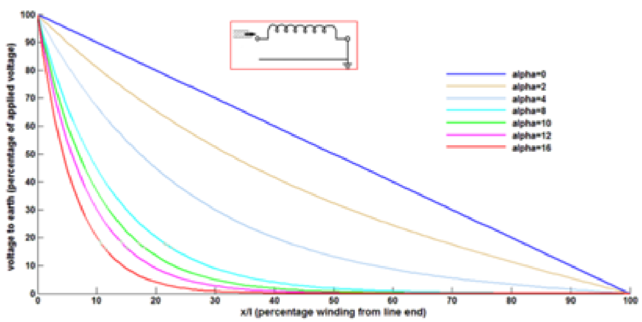

Figure 2. Initial voltage distribution across the winding for different **α** values.

The voltage at the neutral point is zero, and the voltage at the line end point is equal to the applied voltage (E_0). With these terminal conditions, the solution of the governing Equation at (1) gives (2). Where "C_g" is the capacitance between winding and ground, "C_s" is the capacitance between the line end and neutral end of the coil, and "*e*" is the voltage with respect to earth at "*x*" distance from the line end. The initial voltage distribution is plotted in Figure 2 for different values of "**α**".The initial voltage distribution in the winding becomes non-uniform with the increase in the "v" value.

$$\frac{d^4e}{dx^4} - \frac{L\,C_S}{l^2}\frac{d^4e}{dx^2dt^2} + \frac{L\,C_g}{l^4}\frac{d^2e}{dt^2} = 0 \qquad (4)$$

$$e = E_0\left(\frac{x}{l}\right) - E_n \sin\left(\frac{2\pi n x}{l}\right)\cos\omega_n t \qquad (5)$$

After a certain time interval, the voltage distribution in the winding will be determined by the capacitances and inductances of the distributed network. The voltage distribution in the winding will be governed by "(4)". For the existing terminal conditions of the winding, the voltage value at "*x*" distance from the line end will be given by "(5)". Where "L" is the leakage inductance, "n" is the order of space harmonic, and "ω_n" is the angular frequency of n^{th} order harmonic. Equation (4) and (5) shows that the voltage distribution in the winding is a function of space and time. The voltage distribution in the winding at different time instants is plotted in Figure 3 for "**α**=10".

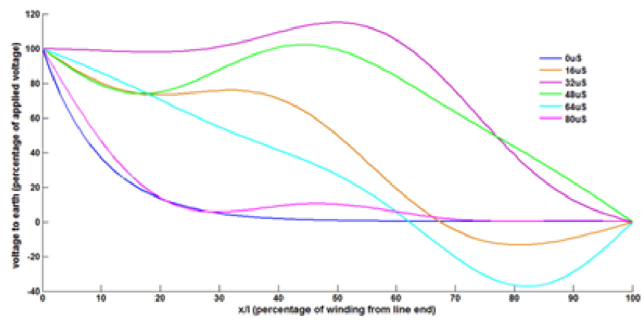

Figure 3. Voltage distribution in the winding at different instants for "**α** = 10".

Figures 2 and 3 show that the surge voltage distribution in the winding is non-uniform and depends on **α** value and varies with time and space. The impulse stress with sharp rise and slow fall on the winding can be equivalently represented by this surge phenomenon study with step response[2,3].

3. Chopped Impulse Test on 1MVA Transformer

The rating plate details of the transformer are mentioned in Table 1. The transformer was subjected to a chopped impulse test as per IEC 60076-3 standard. As per standard procedure, each HV terminal of the transformer was subjected to seven impulses individually in the following sequence: one reduced full wave at 50 to 70 % of BIL, one full wave at 100% of BIL, one reduced chopped wave at 50 to 70 % of BIL, two chopped waves at 110% of BIL, two full waves at 100% of BIL[4-6]. All Low Voltage (LV) terminals and the tank were earthed during the test.

Table 1. Name plate details of 1MVA transformer

Parameter	Rating details
Power (kVA)	1000
HV winding voltage (Volts)	33000
LV winding voltage (Volts)	433
Number of phases	3
Frequency (Hz)	50
Winding Connection	Dyn11
Type of cooling	ONAN
Tapping range	Tap switch position 1 to 6
% tap variation	105% to 80% with each tap step 5%
Tap voltage (Volts)	34650 to 26400 with each tap step 1650
Insulation level (HV winding)	LI-170 kV, AC-70 kV
Insulation level (LV winding)	AC-3 kV
Core material	CRGO
Conductor material	Copper

3.1 Impulse Test on R phase HV terminal

The impulse source is connected to the “R” terminal, and “Y” and “B” terminals were earthed through a shunt for monitoring earth currents. The tap switch is kept at position 1 (highest). Normalised voltage and earth current waveforms of the first reduced full wave (or reference wave) and the last full wave are plotted in Figures 4 and 5. As there were no discrepancies in the voltage and current waveforms comparison shown in Figures 4 and 5, the R terminal passed the test.

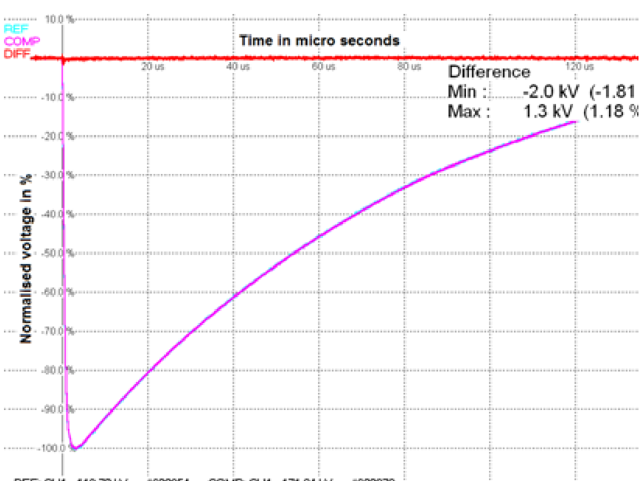

Figure 4. Impulse voltage waveforms of R phase terminal.

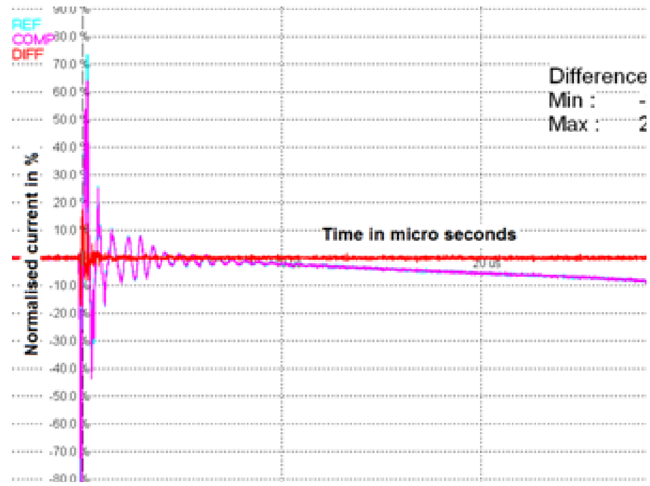

Figure 5. Earth current waveforms of R terminal under impulse excitation.

3.2 Impulse Test on Y phase HV terminal

The impulse source is connected to the "Y" terminal, “R” and “B” terminals were earthed through a shunt for monitoring earth currents. The tap switch is kept at position 2 (principal). Normalised voltage and earth current waveforms of the first reduced full wave (or reference wave) and the last full wave are plotted in Figures 6 and 7. Though there were no discrepancies in voltage waveforms shown in Figure 6, there are considerable minor changes in the earth current waveforms as shown in Figure 7.

There was an ambiguity due to minor deviations in the earth’s current waveforms alone. The transfer function and coherence function of respective waveforms were plotted up to 2MHz, as shown in Figure 8. There was a significant mismatch in the transfer function, and coherence reached zeronear 400 kHz. Hence, the Y terminal of the transformer failed the test.

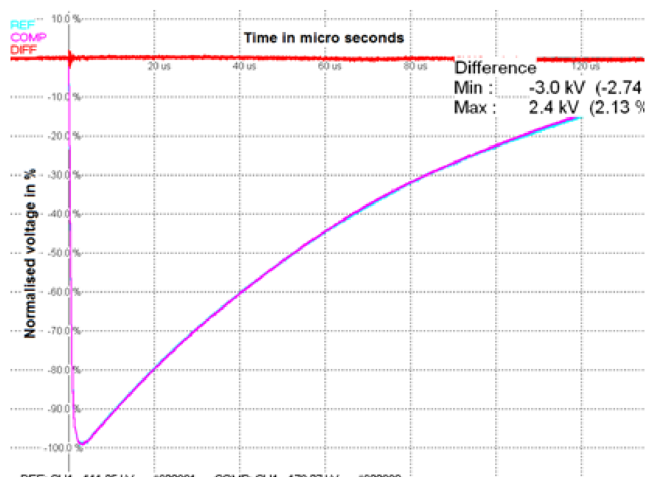

Figure 6. Impulse voltage waveforms of Y terminal.

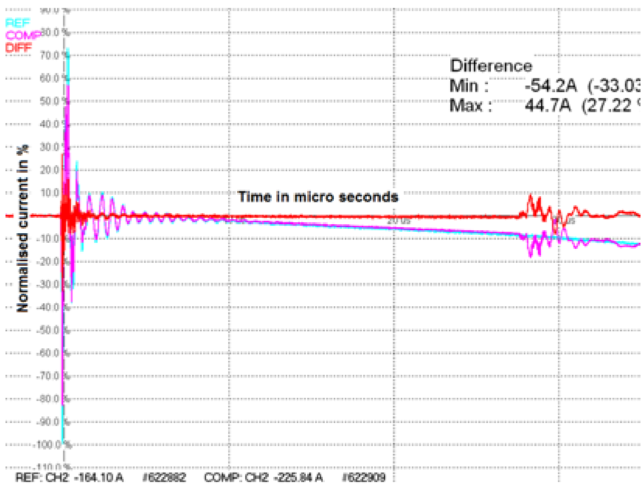

Figure 7. Earth current waveforms of Y terminal under impulse excitation.

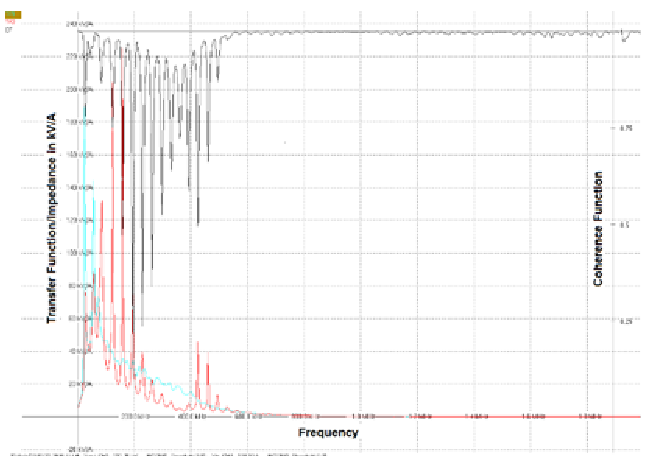

Figure 8. Transfer and coherence functions of Y terminal.

3.3 Impulse Test on B phase HV terminal

The impulse source is connected to the "B" terminal, "R" and "Y" terminals were earthed through a shunt for monitoring earth currents. The tap switch is kept at position 6 (lowest). Normalised voltage and earth current waveforms of the first reduced full wave (or reference wave) and the last full wave are plotted in Figures 9 and 10. As there were no discrepancies in the voltage and current waveforms comparison shown inFigures 9 and 10, the B terminal passed the test.

After the impulse test, the transformer was successfully subjected to all routine tests, including the induced voltage test. After untanking thetransformer, the windings were subjected to keen observation, and Figure 11 shows winding photographs of the Y phase or central limb of the transformer. From 1st photograph, it is observed that there was an opening in the LV winding insulation. From

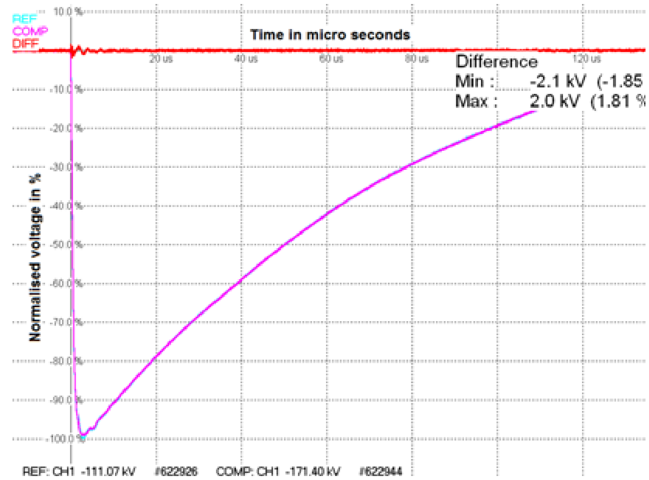

Figure 9. Impulse voltage waveforms of B terminal.

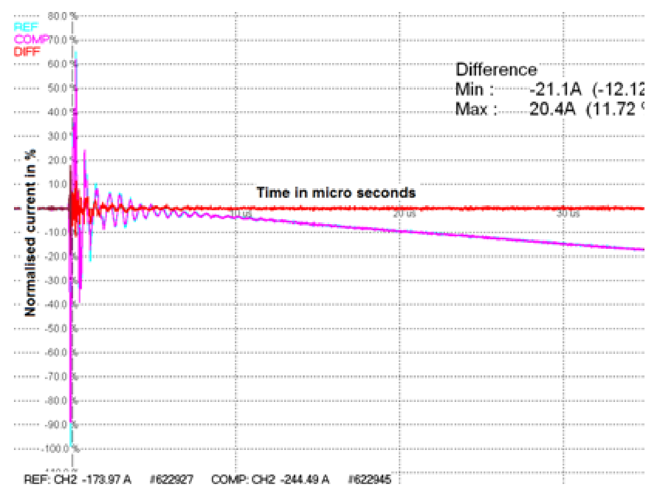

Figure 10. Earth current waveforms of B terminal under impulse excitation.

Figure 11. Photographs of the fault in Y phase LV winding with insulation puncture and carbon particles due to discharge.

2nd photograph, it is observed that there was an insulation puncture and the presence of carbon particles on LV winding. Hence, Impulse voltage applications on the HV side lead to bridging a few turns on LV winding due to the presence of the defect. The fault at LV winding does not reflect any change in the voltage waveforms but reflects minor deviations in the earth currents waveforms.

4. Full wave Impulse test on 2.5 MVA transformer

The rating plate details of the transformer are mentioned in Table 2. The transformer was subjected to a full wave impulse test as per IEC 60076-3 standard. As per standard procedure, each HV terminal of the transformer was subjected to four impulses individually in the following sequence: one reduced full wave at 50 to 70 % of BIL, three full waves at 100% of BIL[4-6]. All Low Voltage (LV) terminals and tank was earthed during the test.

4.1 Impulse Test on R Phase HV Terminal

The impulse source is connected to the "R" terminal, and “Y” and “B” terminals were earthed through a shunt for monitoring earth currents. The tap switch is kept at position 1 (highest). Normalised voltage and earth current waveforms of the first reduced full wave (or reference wave) and last full wave are plotted in Figures 12 and 13. As there were minor discrepancies in the voltage and earth current waves, transfer function and its coherence are shown in Figure 14. There were changes in the peak magnitudes of transfer functions of the winding without any shift, which indicates the presence of partial discharge1. The transfer functions not showing any mismatch up to 1MHz frequency, with the coherence dropping to 0.95 near 700 kHz due to partial discharge. Hence, the R terminal passed the test.

Table 2. Name plate details of 2.5MVA transformer

Parameter	Rating details
Power (kVA)	2500
HV winding voltage (Volts)	11000
LV winding voltage (Volts)	433
Number of phases	3
Frequency (Hz)	50
Winding Connection	Dyn11
Type of cooling	ONAN
Tapping range	Tap switch position 1 to 7
% tap variation	105% to 90% with each tap step 2.5%
Tap voltage (Volts)	11550 to 9900 with each tap step 275
Insulation level (HV winding)	LI-75 kV,AC-28 kV
Insulation level (LV winding)	AC-3 kV
Core material	CRGO
Conductor material	Copper

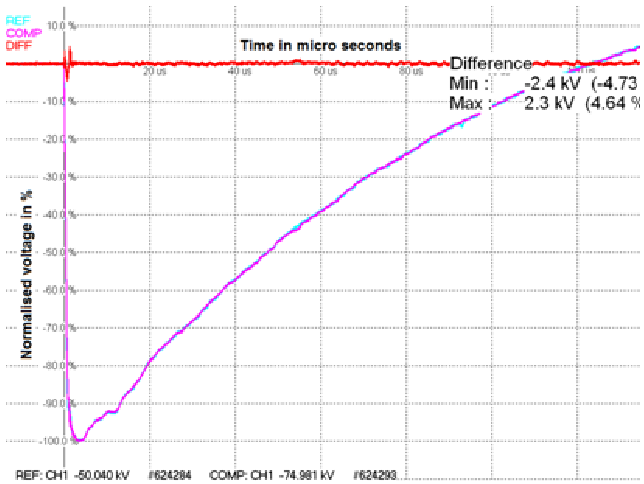

Figure 12. Impulse voltage waveforms of R phase terminal.

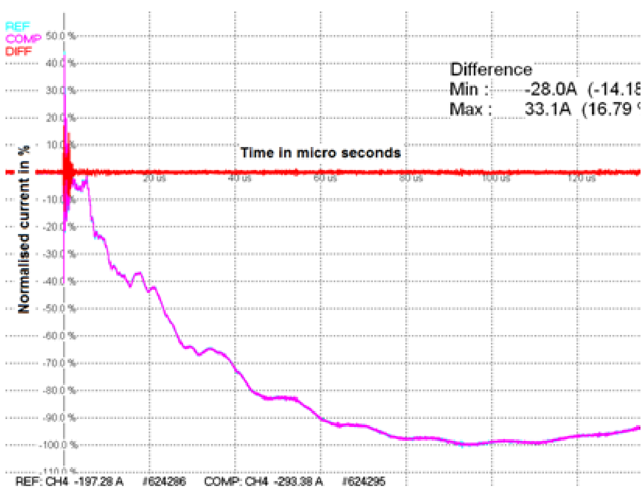

Figure 13. Earth current waveforms of R terminal under impulse excitation.

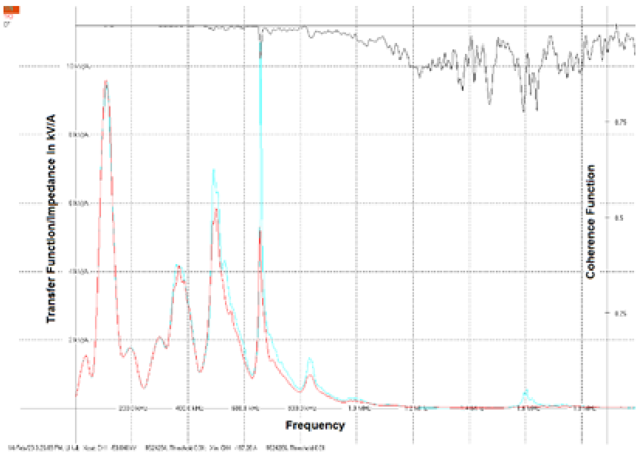

Figure 14. Transfer and Coherence functions of R terminal.

4.2 Impulse Test on Y Phase HV Terminal

The impulse source is connected to the “Y” terminal, “R” and “B” terminals were earthed through a shunt for monitoring earth currents. The tap switch is kept at position 3 (principal). Normalised voltage and earth current waveforms of the first reduced full wave (or reference wave) and last full wave are plotted in Figures 15 and 16. As there were minor discrepancies in the voltage and earth current waves, transfer function and it’s coherence is shown in Figure 17. There were changes in the peak magnitudes of transfer functions of the winding without any shift, which indicates the presence of partial discharge1. The transfer functions not showing any mismatch up to 1MHz frequency, with the coherence dropping to 0.85 near 650 kHz due to partial discharge. Hence, the Y terminal passed the test.

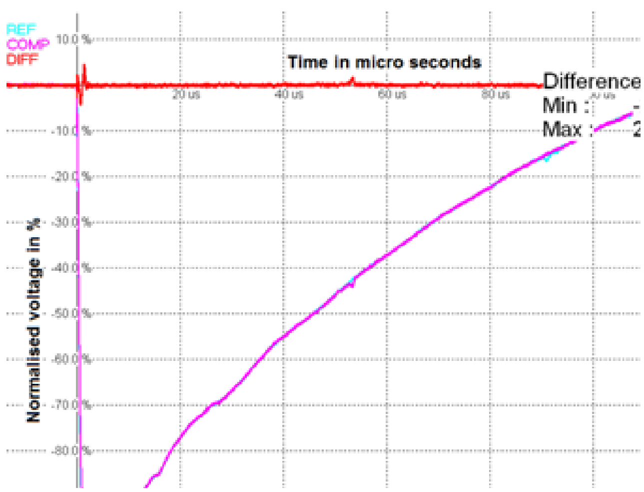

Figure 15. Impulse voltage waveforms of Y terminal.

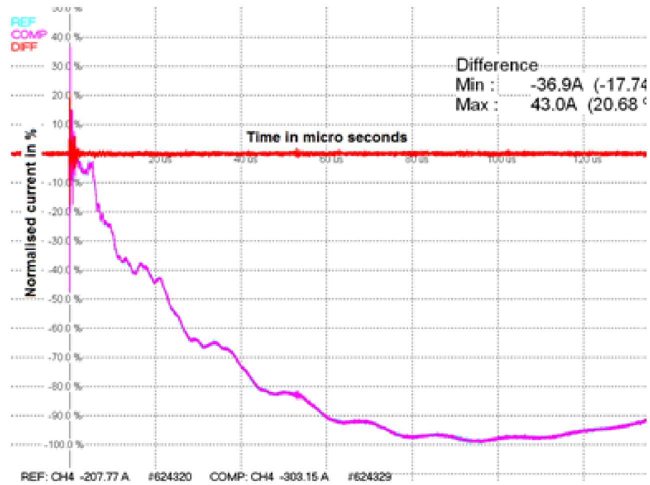

Figure 16. Earth current waveforms of Y terminal under impulse excitation.

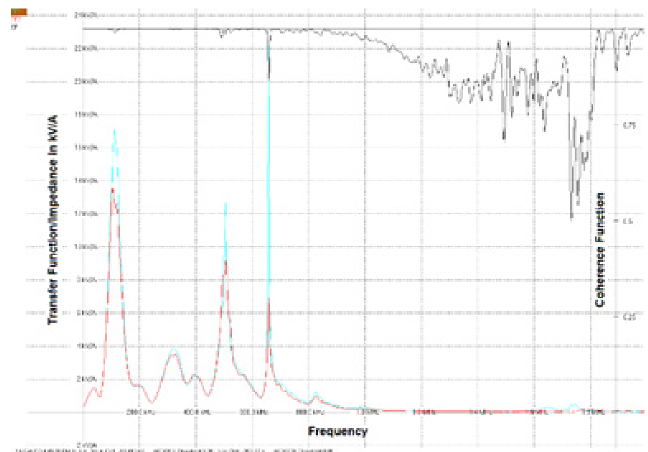

Figure 17. Transfer and coherence functions of Y terminal.

4.3 Impulse Test on B Phase HV Terminal

The impulse source is connected to the "B" terminal, "R" and "Y" terminals were earthed through a shunt for monitoring earth currents. The tap switch is kept at position 7 (lowest). Normalised voltage and earth current waveforms of the first reduced full wave (or reference wave) and last full wave are plotted in Figures18 and 19. As there were minor discrepancies in the voltage and earth current waves, transfer function and it’s coherence is shown in Figure 20. There were changes in the peak magnitudes as well as slight shifts in the peaks near 100 kHz, 300 kHz and 470 kHzwith the coherence dropping to 0.35. Hence, the B terminal failed the test.

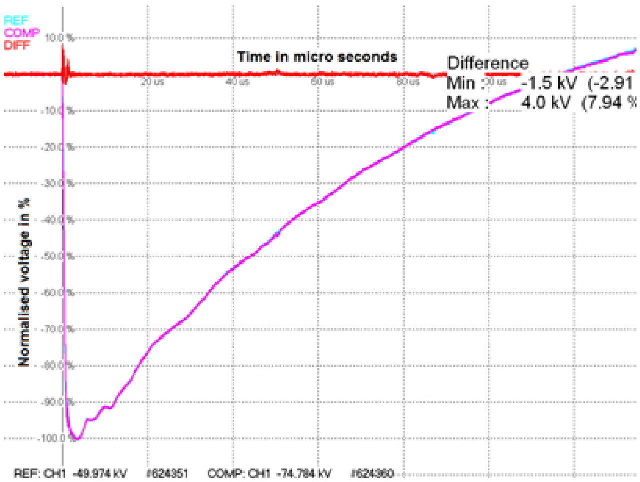

Figure 18. Impulse voltage waveforms of B terminal.

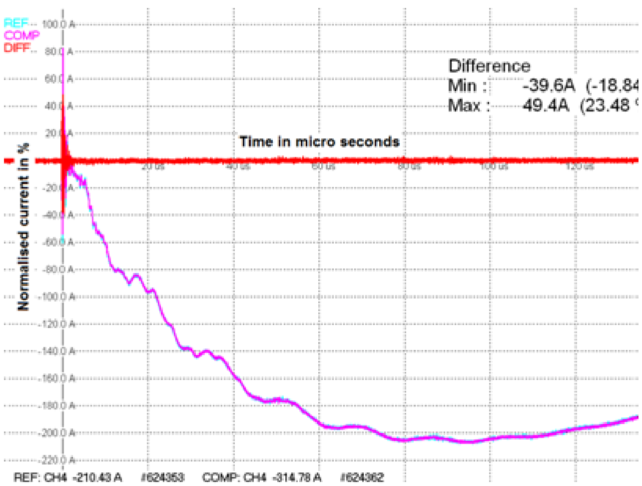

Figure 19. Earth current waveforms of B terminal under impulse excitation.

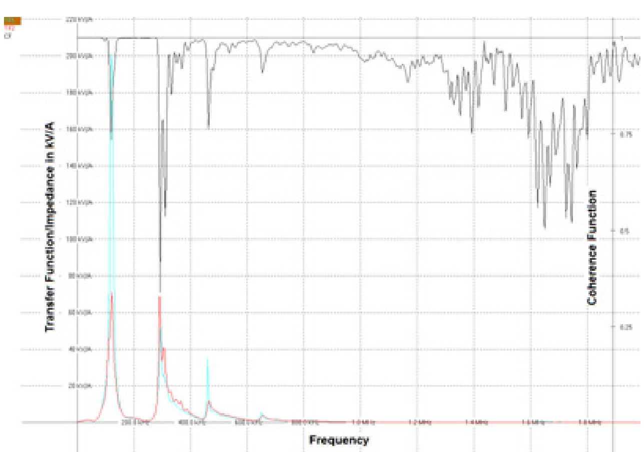

Figure 20. Transfer and coherence functions of B terminal.

After untanking the transformer, the windings were subjected to keen observation, and there were no signs of any puncture on winding, but as shown in Figure 21, the tap switch has ash/carbon marking on the B phase portion.

Figure 21. Photograph of the fault in B phase winding.

5. Summary

Transformers are the most vital and costly equipmentin the power system. Insulation is the weakest link in the transformers. Using impulse test the design and quality of the transformer's insulation system can be evaluated as per IS/IEC standards. From the surge phenomenon study, it is evident that the voltage distribution in the winding is non-uniform and is temporal under impulse excitation. It is tough to judge the minor discrepancies in voltage and earth current waveforms are due to partial discharges or minute faults.

The case study on a 1MVA transformer with a chopped wave impulse test showed a change in the earth current wave alone in the B phase due to a minor fault in the LV winding. In this case, the transfer functions of reference and last impulses and their coherence gave a clear-cut conclusion about the presence of a fault. The case study on a 2.5MVA transformer with a full wave lightning impulse test showed that there were minor deviations in voltage and current waveforms in all phase terminals. Nevertheless, the deviations in R and Y phases are due to partial discharges,and it is allowed as per standard.

The deviation in the B phase pertains to a minor fault at the taping portion. Despite the availability of the transfer function and coherence methods for analysing impulse test results, it still requires experience to derive a conclusion, as these methods may lead to wrong interpretations in the presence of induced earth signal disturbances.

6. Acknowledgement

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