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# Failure Analysis of Transformers during Lightning Impulse Test

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**ABSTRACT:** In the Lightning Impulse Voltage test, many times electrical equipment fail to withstand the lightning impulse voltage due to various reasons. Impulsive rise or decline of voltage is not considered as a favourable condition for any dielectric medium and it is the main reason why this test is conducted on various electrical equipment. In this paper an analysis of the lightning impulse voltage generator as well as various reasons due to which equipment fail to withstand the lightning impulse voltage test has been done hence explaining the importance of such test.

**KEYWORDS:** Impulse test, insulation failure, doubling effect, impulse fault, wave- front time, wave- tail time, fault diagnosis.

## I. INTRODUCTION

Lightning Impulse Voltage test is one of the significant test in determining the withstand capability of any dielectric medium. Actual conditions of a lightning impulse voltage are simulated and applied on the electrical equipment to check it's voltage withstand capability. This test is very necessary as it is a check of whether the equipment can withstand the voltage surges or not which are a very regular phenomenon in our power system. In fact this criteria is one of the main deciding factor in the designing of insulation of a power system upto a certain voltage level and above certain voltage level switching impulse voltage withstand capability is the main deciding factor due to a phenomenon called doubling effect that occurs during the switching of any electrical equipment.

CPRI, Bhopal has two Lightning Impulse voltage generators which caters the testing needs of the power sector of India as well as other countries. Rating of these two generators are 800kV, 20kJ and 2400kV, 240kJ. Sudden transition of voltage is the main factor in lightning impulse voltage test which hampers the dielectric strength of any electric equipment. This transition of voltage is captured by three variable parameters which are denoted as front time, tail time and peak value of any voltage impulse, variation in these three parameters also affects the withstand capability of any dielectric medium.

## II. LIGHTNING IMPULSE VOLTAGE WAVEFORM

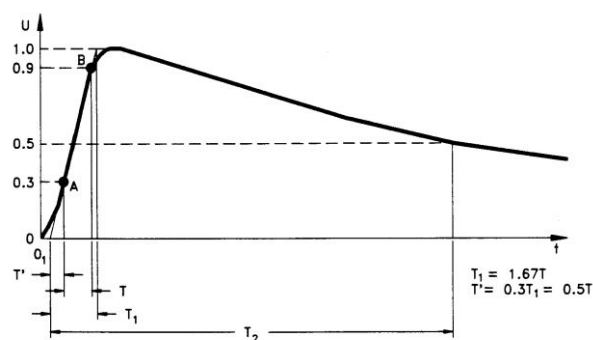


Figure no.-01: Full Wave Lightning Impulse

Above is the waveform of full wave lightning impulse voltage. The mentioned parameters from above waveform are front time ( $T_1$ ), tail time ( $T_2$ ) and peak value ( $P$ ).

**II.1 Front time ( $T_1$ ):** As per various standards, it has been defined as 1.67 times the interval between the instants when the impulse is 30% and 90% of the peak value.

**II.2 Tail time ( $T_2$ ):** As per various standards, it is defined as the time interval between the origin and the instant when the voltage has decreased to half the peak value.

**II.3 Peak Value ( $P$ ):** The peak value attained by any Lightning Impulse Voltage.

The dielectric stress of any equipment is very much affected by these parameters as well as the time interval for which the overvoltage is maintained over any equipment. However, since the application of voltage is in  $\mu s$ , hence the impulsive rise / decline of voltage usually dominates the other factor. According to various Indian and International standards the values of front time and tail time which is required to be taken while testing are  $1.2\mu s$  and  $50\mu s$ .

### III. ANALYSIS OF THE IMPULSE VOLTAGE GENERATOR CIRCUIT

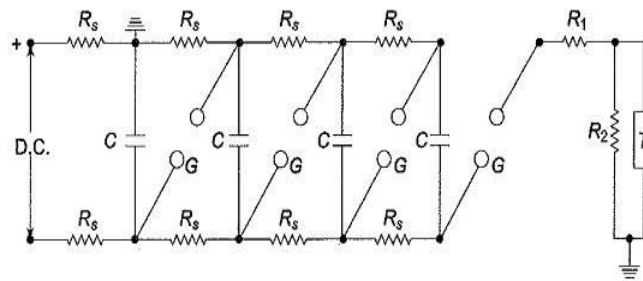


Figure no.-02: Impulse generator working on the principle of voltage multiplication based on the Marx circuit.

The lightning impulse voltage generator works on the principle of multistage Marx circuit as shown above. The basic principle of Marx circuit is that the capacitors are charged initially in a parallel manner and then discharged through wave shaping resistors ( $R_1, R_2$ ) once the required voltage is attained using the sphere gaps in a series manner. The charging resistance  $R_s$  in each stage determines the charging time up to the required voltage, usually the charging time is kept under one minute and it also limits the charging current for the protection of generator capacitances.

Circuit of Lightning Impulse Voltage Generator that is slightly modified version of basic multistage Marx circuit in which wave shaping resistors are divided into the number of stages or the number of charging capacitors in each stage as shown in the below image.

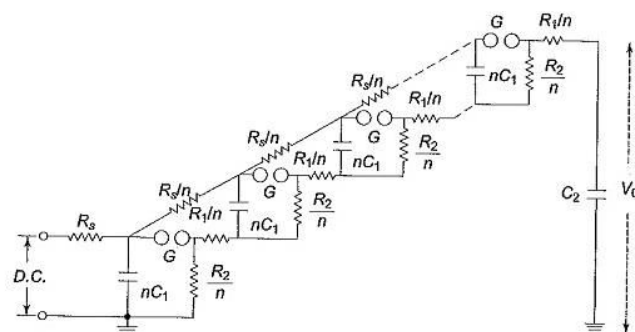
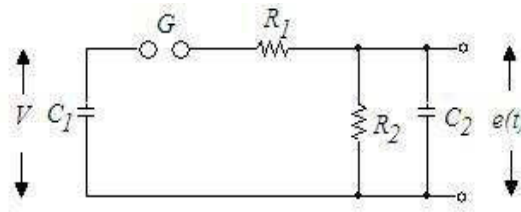


Figure no.-03: Multistage Marx circuit incorporating wave shaping resistors in each stage

In the above circuit the front time and tail time can easily be controlled by varying the wave shaping resistances  $R_1$  and  $R_2$ . The effect of  $R_1$  and  $R_2$  on the output voltage can be easily seen by finding out the equation for output voltage. To find out the equation for output voltage the equivalent circuit of multistage Marx circuit is as given below which represents the discharging of generator capacitances in series.

**Figure no.-04: Equivalent circuit of Multistage Marx circuit**

In the above circuit, the generator capacitance  $C_1$  represents all the generator capacitances connected in series, output capacitance represents all the load capacitances, capacitance due to voltage divider and stray capacitances due to other reasons connected in parallel, there is a sphere gap in the circuit which helps in connecting all the generator capacitances in series when they are charged upto the desired voltage level and  $R_1$  (front resistors) and  $R_2$  (tail resistors) are the wave shaping resistors. There is also some inductance present in the circuit which causes some oscillations in the output voltage of the circuit. These oscillations are denoted by another parameter called overshoot ( $\beta$ ), also low value of beta ( $<5\%$ ) is a desirable condition according to various Indian and International standards and for that reason the inductance of the circuit is kept as low as possible. Special wire wound resistors in the circuit ( $R_1$  &  $R_2$ ) are used which offers negligible inductance in the circuit and it is also tried to keep the test object near the lightning impulse voltage generator to minimize the inductive effects of the connecting leads and wires in the circuit hence we have neglected the inductance in the circuit for the derivation of the equation of output voltage. The equation for output voltage can be derived using Laplace equations as shown below:

$$e(t) = (V)(a/2c)((b/2 + c)e^{-(b/2 + c)t} - (b/2 - c)e^{-(b/2 - c)t})$$

$e(t)$  = Output voltage

$V$  = Input DC voltage

$a = 1/(R_1 C_2)$

$b = (R_1 C_1 + R_2 C_2 + R_2 C_1)/(R_1 R_2 C_1 C_2)$

$c = \sqrt{(b^2/4) - 1}$

Clearly we can see the impact of  $R_1$  and  $R_2$  on the output voltage which is being applied to the test object and discharged through the front resistors and tail resistors. We can also find out to observe that front time ( $T_1$ ) is mainly controlled by varying resistor  $R_1$  and the tail time ( $T_2$ ) is mainly controlled by varying resistor  $R_2$ .

In case of transformers the capacitive current is directly proportional to the rate of change of voltage and hence such stress increases with the decrease in wave time.

$$I(c) = C (dV/dt)$$

The capacitance distribution and hence the voltage distribution is non – uniform along the transformer windings in case of this test because the effect of capacitance increases due to very high rate of change of voltage in case of lightning impulse voltage test. Also such effects are relatively higher in case of voltage rising during front time in comparison to voltage falling during tail time because the value of tail time is much higher than rise time.

#### IV. EXAMPLES OF IMPULSE TESTING ON TRANSFORMERS:

Lightning impulse test on transformer is very different from that on any other sample. Few examples of Lightning Impulse tests on transformers which have been conducted in general accordance with IEC: 60076 – 3, 2013 are shown below by few case studies:

**Case I:** Single limb of 33/11kV, 10/14MVA, 3 – phase Transformer as per Clause 13.3.2 of IEC : 60076-3,2013 is shown in figure 5.

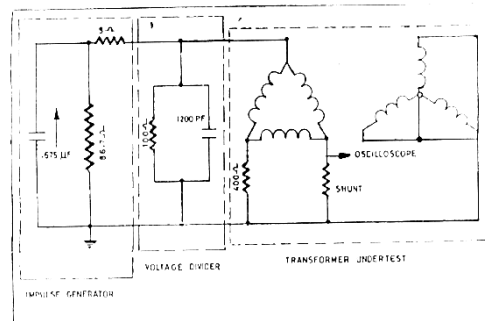


Figure no.-05: Connection Diagram

Osc No.	Impulse Application (1W): (Negative Polarity)		
	Test Sequence	kVp	Remarks
01	Reduced full wave	101	Passed
02	100% full wave	170	Passed
03	110% chopped wave	186	Passed
04	110% chopped wave	186	Passed
05	100% full wave	170	Passed
06	100% full wave	170	Passed

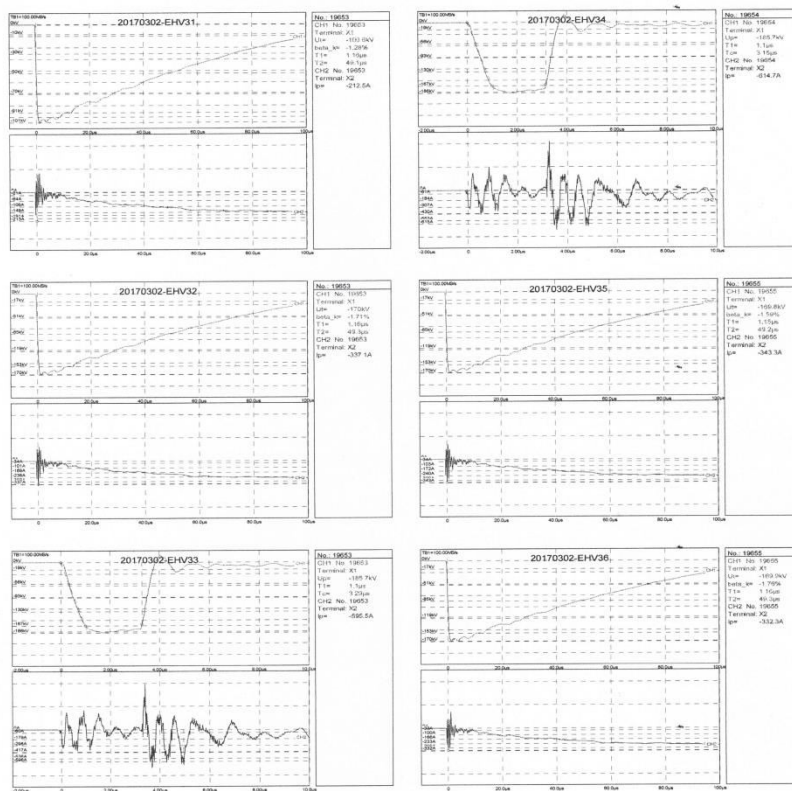


Figure no.-06: (Oscillogram Nos. 01 to 06)

By comparing the neutral current osc nos. 03 and 04 it is observed that the tail chopping has occurred between 3 & 6 $\mu$ s, as required. Comparison of osc nos. 01 to 06 shows a similar behaviour between all neutral current oscillograms and all voltage wave oscillograms. The transformer is said to have withstood all the lightning impulse voltage applications.

### Case II: Impulse Test on 630kVA, 33/0.433kV 3-Phase Distribution Transformer

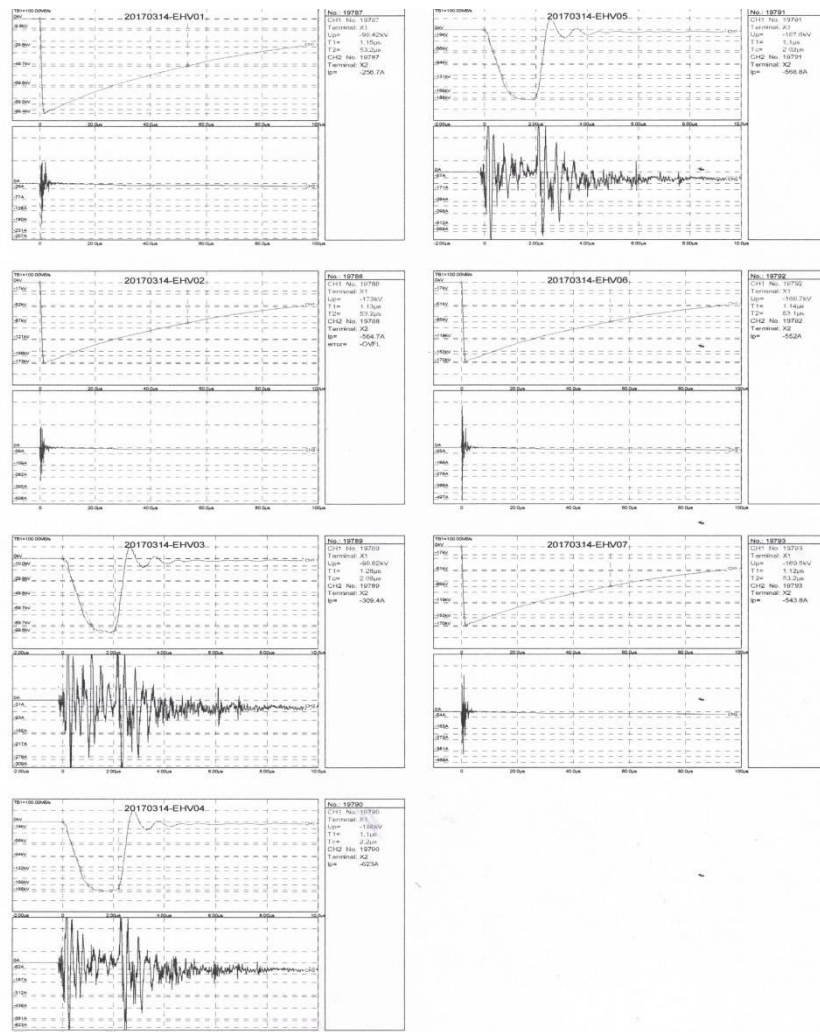


Figure no.- 07: (1U limb, Oscillogram Nos. 01 to 07)

Osc No.	Impulse Application (1V) : (Negative Polarity)		
	Test Sequence	kVp	Remarks
01	Reduced full wave	100	Passed
02	100% full wave	170	Passed
03	Reduced Chopped wave	100	Passed
04	110% chopped wave	187	Passed
05	110% chopped wave	187	Passed
06	100% full wave	170	Passed
07	100% full wave	170	Passed

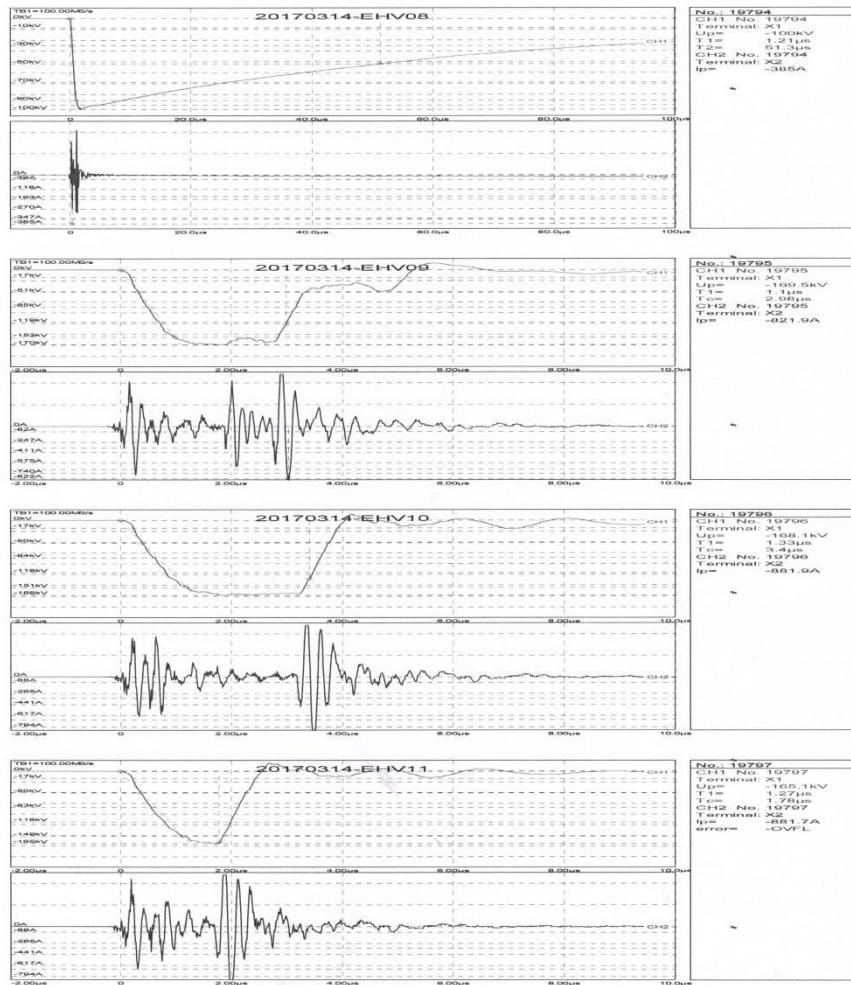


Figure no.-08: (1V limb, Oscillogram Nos. 08 to 11)

Osc No.	Impulse Application (1V) : (Negative Polarity)		
	Test Sequence	kVp	Remarks
08	Reduced full wave	100	Passed
09	100% full wave	170	Failed
10	100% full wave	170	Failed
11	100% full wave	170	Failed

After the successful application of impulses on 1U limb, when test was conducted on 1V limb, it was observed by comparison of reduced & full wave oscillograms 08 & 09 that full voltage wave oscillogram has collapsed and in the corresponding waveform of neutral current there are high frequency oscillations. This is an indication of arc across the major portion of the transformer winding thus resulting in the failure of transformer insulation.

### Case III: Impulse test on 11/0.433kV, 25kVA, 3phase Distribution Transformer

This test was conducted on all the three phases as per Clause13 of IS:2026 – 3,2009. Results are presented only for one phase.

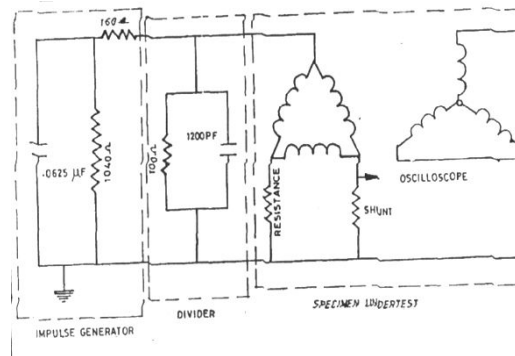


Figure no.-09: Connection Diagram

Osc No.	Impulse Application (1U) : (Negative Polarity)		
	Test Sequence	kVp	Remarks
01	Reduced full wave	43 kVp	Passed
02	100% full wave	75 kVp	Passed
03	100% full wave	75 kVp	Failed

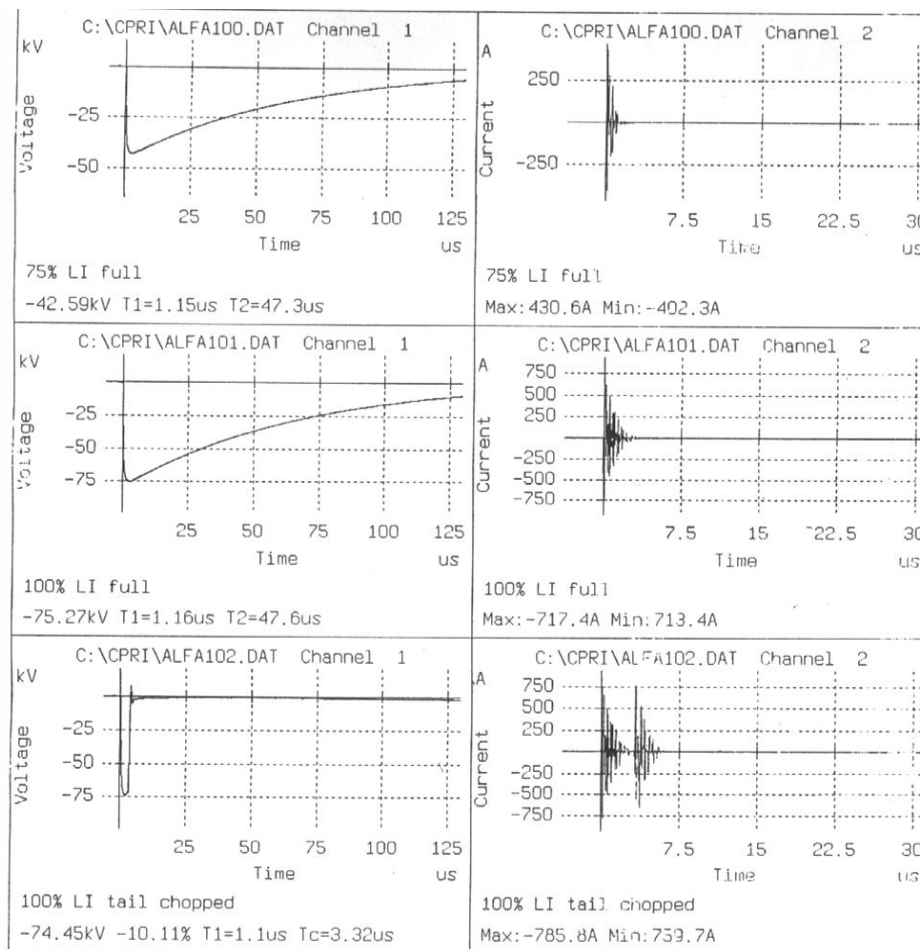


Figure no.-10: (Oscillogram nos. 01 to 03)

By observing oscillograms 01 to 03 it is found that the second full voltage wave oscillogram 03 has collapsed and in the corresponding waveform of the neutral current there are high frequency oscillations. This is an indication of failure of transformer insulation.

#### Case IV:

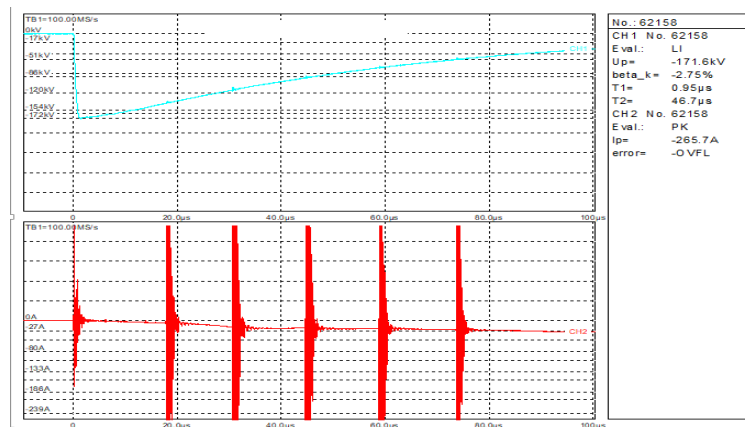


Figure no. – 11: (Oscillogram nos. 01 to 02)

Here is the fourth case of Lightning Impulse voltage test on the Transformer. In this test, we can clearly observe that there is no noticeable spike in the voltage waveform of the equipment but there are so many repeated spikes in the waveform of current. Transformer did not comply with the required standard, initially it was slightly difficult to know the cause of such failure in impulse test. Later on it was found by the manufacturer that paper insulation of winding was damaged at many points due to which winding turns were getting short – circuited at high voltage as well as quality of oil was also not good. It caused the winding to withstand the high impulse voltage with little invisible spikes but high discharge current got noticed.

#### Case V:

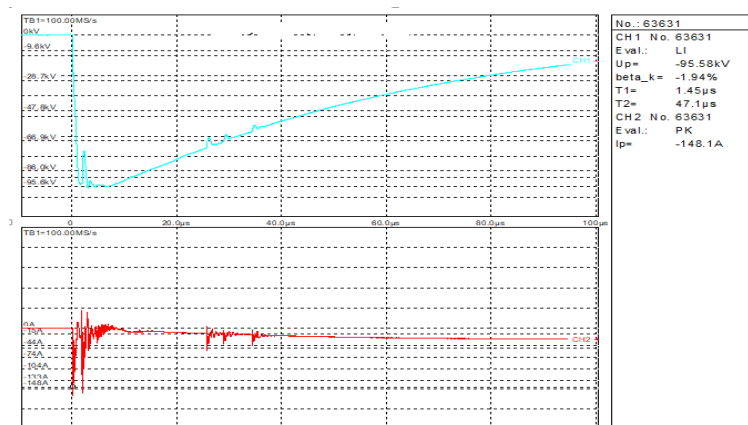


Figure no. – 12: (Oscillogram nos. 01 to 02)

This is the fifth case of transformer failure in impulse test in which there are few noticeable small spikes in the voltage waveform as well as current waveform. Interestingly, the reason for this failure was that there was an air trapped inside the transformer along with the oil. Oil obviously has a greater dielectric strength than air. So the air inside the transformer lowered down the overall dielectric strength.

## V. RESULTS

In all the above cases of transformers not being able to withstand the lightning impulse voltage tests, various possible reasons of dielectric breakdown has been explained after an analysis of these samples for their failure. Reasons may vary for different electrical equipment and especially in case of transformer multiple reasons are involved due to its complex construction and involvement of all kinds of dielectrics i.e. solid (bushings), liquid (transformer oil) & gaseous (air). Noticeably, the test of transformer bushing is a separate test altogether and hence in most of the cases we conduct the transformer test only for negative polarity because test on positive polarity may cause some erratic flashovers.

## VI. ANALYSIS OF FAILED TRANSFORMERS

Lightning impulse test is usually done on variety of samples like transformers, insulators, panels, isolators, AB switch, etc. Testing methods of Lightning Impulse voltage test is different for different equipment. For normal insulators and other equipment in which dielectric strength is based on insulators, we don't need to measure the current because there is very minimal discharge through the insulators, in fact discharge through these insulators means collapse of voltage and it means that the said sample did not withstand the applied voltage and hence we only need to measure the voltage in this case but on the other hand in case of transformers the dielectric media is a liquid and there is a flow of some discharge current between the windings due to capacitances, impurity of dielectric oil, etc. Many times, there is no complete collapse of voltage in case of transformer and we take the decision based on the discharge current waveform only. Usually there is a comparison by superimposition of the waveforms at reduced voltage level (50% to 70% of full voltage) and at full voltage level to take any conclusive decision about the test.

## VII. CONCLUSION

By observing all the above mentioned case studies, anyone can clearly realize the importance of Lightning Impulse Voltage test as one of the most important Dielectric test of a Transformer in our power system network. The various factors which affects the dielectric strength of any system should be taken care.

Clearance and creepage distance, impurity of dielectric media being the main controlling factors. If these measures are not taken care of properly then our entire system will always be at risk. The dielectric breakdown due to various voltage surges such as Lightning impulse voltages as well as switching impulse voltage surges which are a very regular phenomenon in our power system. So these dielectric tests acts as a measure of checks in our power system to get assured of the dielectric strength in fact the insulation of our power system is designed by keeping these voltage impulses in mind.

## ACKNOWLEDGEMENT

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