

Improving the Basic Insulation Level (BIL) of Distribution Transformers

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Abstract - Distribution transformer is one of the critical parts of the electrical distribution network to ensure reliable supply of electricity to homes and industries. During the life cycle, distribution transformer experience several electrical stresses due to lightning strikes. This results in the reduction of dielectric strength of the transformer and lifespan may reduce. For the worst case transformer will face a complete breakdown. Therefore it is important to design the transformer to meet the required insulation levels as specified in IEC based on rated voltage of the transformer or as per customer specification. A project was conducted to design, manufacture and test 33 kV rated distribution transformers with BIL of 250 kV. Two methods were adopted, the first by introducing extra layer insulation in HV winding and the other by inserting an electrostatic shield inside the HV winding of the transformer. Both types of transformers were subjected to impulse withstand voltage test relevant to 250 kV BIL. The two methods were analyzed against each other by comparing the impulse test results, temperature rise test results and their material cost. In this way the most effective method was identified which has more advantage in respect to performance and material cost.

Keywords—Distribution Transformer; Electrostatic Shield; Impulse; Dielectric Stress

I. INTRODUCTION

According to IEC60076-3 standard the rated lightning impulse withstand voltages for the 33 kV transformers are 170 kV and 200 kV [1]. However mostly used basic insulation level (BIL) is 170 kV and based on the common practice in some parts of the world, distribution transformers with BIL of 200 kV are also available. For the local utility Ceylon Electricity Board (CEB) LTL Transformers (Pvt) Limited (LTL) is designing 33 kV transformers to withstand lightning impulse test at 200 kV.

One of the reasons of distribution transformer failures is identified as the insulation failures that occurs with the lightning surges coming from the MV side [2]. Therefore based on the lightning level of different parts of the world, some countries have specified even higher values for the required BIL of distribution transformers than mentioned in the standard.

This paper discuss on a research and development project carried out to manufacture 33 kV distribution transformers with an improved BIL level of 250 kV. The requirement came from a foreign customer who wanted to purchase 33 kV distribution transformers of two capacities 200 kVA and 315 kVA with BIL of 250 kV.

Under the project four transformers were manufactured by adopting two methods to meet the specified higher BIL. Two transformers from each capacity (200 kVA and 315 kVA) were manufactured, one with extra layer insulation thickness between winding layers and the other by inserting two electrostatic shields between first two layers and final two layers. All four transformers were exposed to routine tests and sent to International accredited transformer test laboratory in India for chopped wave lightning impulse withstand test. Test results shows that both proposed methods are capable to withstand lightning impulse test at 250 kV. Therefore most economical transformer was selected based on the temperature rise test results and material cost.

II. CASE STUDIES

This section explains two different modifications done for the transformers to improve its BIL to 250 kV. These two cases are explained under case studies 1 and 2. Transformer specifications are given in Table I.

TABLE I. TRANSFORMER SPECIFICATIONS

Capacity	200 kVA		315 kVA	
Serial Number	T102R783	T028R783	T100R784	T034R784
Modification	Extra Insulation	With Shield	Extra Insulation	With Shield
Voltage / kV	LV		HV	
	0.4		33	
Number of Phases	3			
Vector Group	Dyn11			
Type	Hermetically Sealed			

A. Case Study 1 : Increasing Layer Insulation

The first case study was carried out to improve the BIL of the transformer by introducing extra insulation between layers of the HV winding. When designing a transformer to withstand a particular BIL level, it is important to use the correct insulation thickness between layers of the winding. This is mainly decided by the possible maximum inter layer potential difference. Based on the factors such as design BIL, number of layers and vector group the empirical equations have been derived and available with LTL to determine the required layer insulation thickness up to BIL of 200 kV and by using this data, the insulation thickness to be used in this case was calculated. Accordingly, two transformers were designed and manufactured with extra layer insulation with the capacities of 200 kVA and 315 kVA whose primary voltage is 33 kV. Below table shows

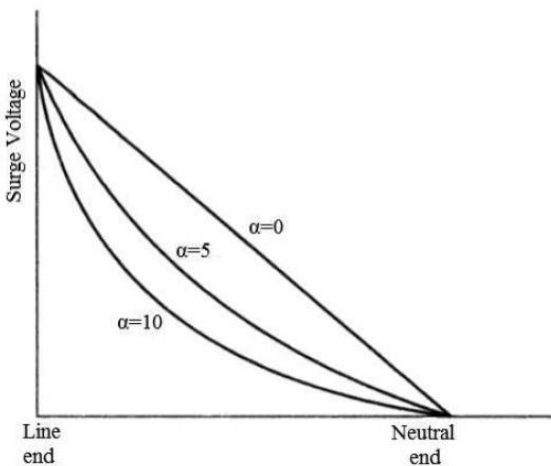
the layer insulation thicknesses that were utilized for these transformers.

TABLE II. THICKNESS OF LAYER INSULATION

BIL (kV)	Vector Group of High Voltage Side	Number of Layers	Layer Insulation Thickness (mm)	Insulation between layers 1-2 and last and next to last layers (mm)
200 kVA 33kV / 415 V				
250	Delta	20	2x0.25	4x0.25
315 kVA 33kV / 415 V				
250	Delta	16	3x0.25	5x0.25

B. Case Study 2 : Inserting an Electro Static Shield

When lightning strikes on a transformer, voltage distribution along the transformer HV winding will be as in Fig. 1. As can be seen from Fig. 1, the voltage distribution is governed by α . Factor α is known as the capacitance index. It is determined by the ratio of parallel capacitance, C_p and the series capacitance, C_s of the transformer. The equation for α is given in (1) [3]. As per this equation, α is governed by the ratio between parallel to series capacitance

Fig. 1. Surge voltage distribution of HV winding for different α values

$$\alpha = \sqrt{\frac{C_p}{C_s}} \dots (1)$$

When α becomes higher voltage distribution difference between the line end layers will become higher. This will create an extra stress on adjacent layers near the line end as their potential difference becomes higher. As the vector group of transformer of interest is Dyn11 the HV winding is in Delta configuration. Therefore starting point of one of the phases of the primary winding is connected to the end point of another phase. Thus if a lightning strike hit either one of the bushings, it will be crucial to consider the potential difference between the first two layers and the outermost layers of each of the three phases of HV windings in the transformer. This area tends to fail dielectric strength of the transformer.

Therefore in order to increase the transformer BIL, it is important to introduce a mechanism that could reduce the magnitude of α , in other words either to decrease parallel capacitance or to increase the series capacitance of the transformer. This will result in more uniform impulse voltage distribution similar to curve 1 in Fig. 1.

An electrostatic shield is a way to protect transformers on the inside of the transformer. More specifically inside the windings on the HV side of the transformer. Applying an electrostatic shield between two layers of windings will create several more series capacitances. The shield will reduce the major stress on the outermost layers of windings and create a more uniform voltage distribution under the lightning impulse withstand test.

In this case study two transformers of capacity 200 kVA and 315 kVA were designed to accommodate a shield and thereby improve the BIL. The material for the shield can be both copper and aluminum, but copper will be exceedingly expensive compared to aluminum. Therefore aluminum foil of 0.19 mm thickness was used in between first two layers and last two layers of both transformers as shown below in Fig 2. Foil width was selected equal to the HV winding conductor mechanical length.



Fig. 2. Applied aluminium shield between first two layers

The four transformers that were designed and manufactured under case studies 1 and 2 were first subjected to routine tests and then to Impulse withstand voltage test at 250 kV (including Chopped wave) as per the IEC60076 standard. Corresponding test results are given in the next section.

III. ROUTINE TEST RESULTS AND IMPULSE TEST RESULTS

After conducting routine tests at LTL test laboratory the four transformers were sent to an international accredited transformer test laboratory in India for chopped wave lightning impulse test and temperature rise test. The test results for full load test and no load test are given below in Table III.

In order to validate the lightning impulse with standability of transformers with the design improvement discussed under case studies 1 and 2, Chopped wave lightning impulse test was performed on HV winding. Test sequence with applied voltages and number of shots for the four transformers are shown in below in Table IV.

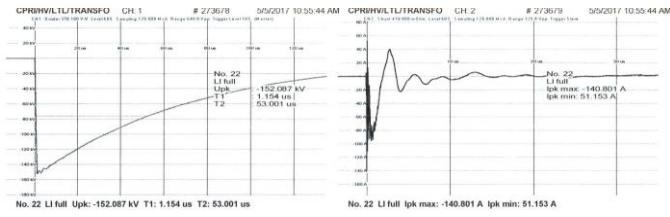
TABLE III. FULL LOAD TEST AND NO LOAD TEST RESULTS

Capacity/ kVA	Serial Number	Modification	Full Load Loss/Watt	No Load Loss/Watt
200	T102R783	Extra Insulation	2198	360
200	T028R783	With Shiled	2320	362
315	T100R784	Extra Insulation	3347	464
315	T034R784	With Shiled	3401	468

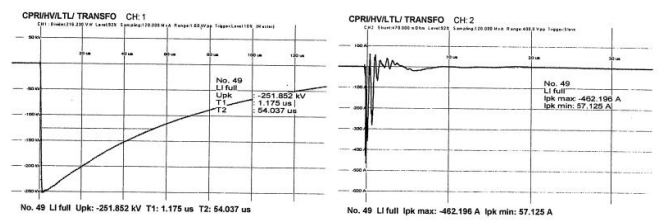
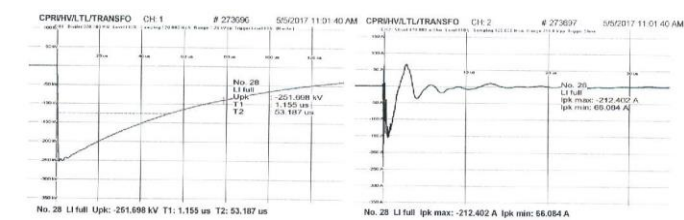
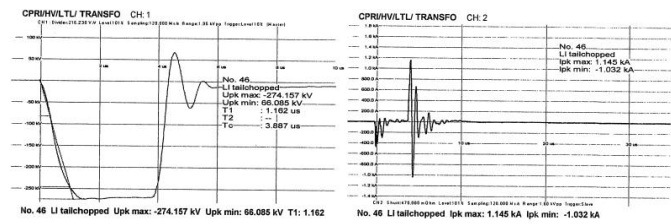
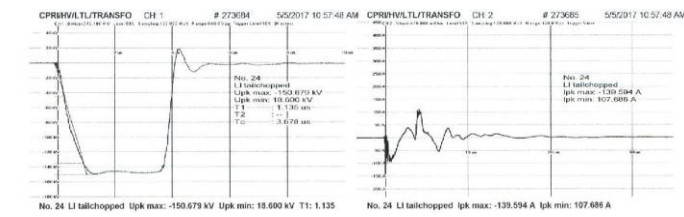
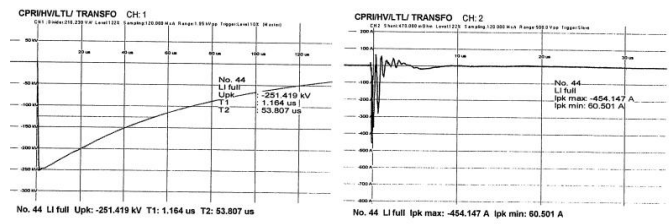
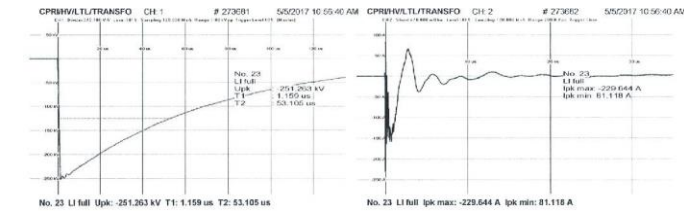
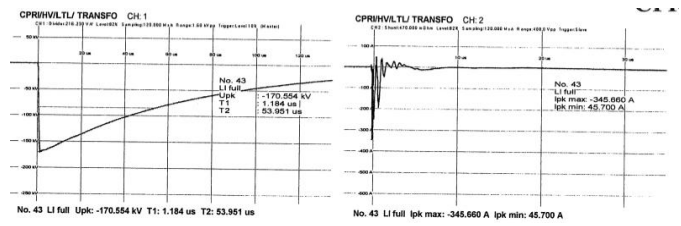
TABLE IV. TEST ORDER AND APPLIED WAVE TYPES

Source connected to (Tap Position)	Earth Connected to	Shot No.	Negative Polarity				
			Wave type	Test Voltage (kV Peak)			
				T102R783	T028R783	T100R784	T034R784
Terminal A (Tap No. 1) Maximum	Terminal B through shunt. Terminal C through resistor. All LV terminals along with frame.	1	Reduced Full Wave	152	171	153	172
		2	Full Wave	251	251	253	253
		3	Chopped Wave	274	274	273	274
		4	Chopped Wave	275	275	279	278
		5	Full Wave	250	253	251	252
		6	Full Wave	252	252	250	251
Terminal B (Tap No. 3) Nominal	Terminal C through shunt. Terminal A through resistor. All LV terminals along with frame.	1	Reduced Full Wave	149	171	150	172
		2	Full Wave	250	252	250	250
		3	Chopped Wave	276	275	273	274
		4	Chopped Wave	276	275	274	276
		5	Full Wave	249	253	250	251
		6	Full Wave	250	253	251	251
Terminal C (Tap No. 5) Minimum	Terminal A through shunt. Terminal B through resistor. All LV terminals along with frame.	1	Reduced Full Wave	149	170	153	169
		2	Full Wave	249	252	250	251
		3	Chopped Wave	275	276	274	274
		4	Chopped Wave	277	275	275	276
		5	Full Wave	250	252	250	252
		6	Full Wave	252	254	251	251

200 kVA 33kV/400V T102R783
Extra Insulation



200 kVA 33kV/400V T028R783
With Shield



315 kVA 33kV/400V T100R784 Extra Insulation

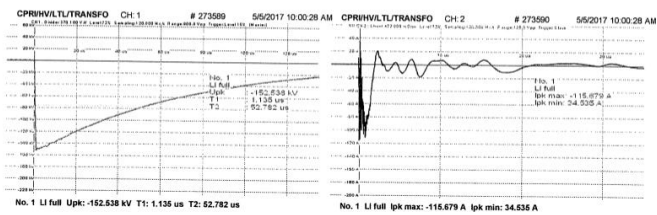


Fig. 11. Voltage and Current waveforms for shot No. 1

315 kVA 33kV/400V T034R784 With Shield

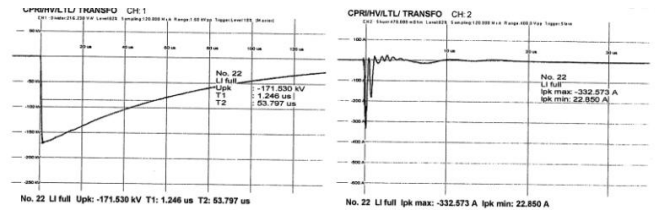


Fig. 12. Voltage and Current waveforms for shot No. 1

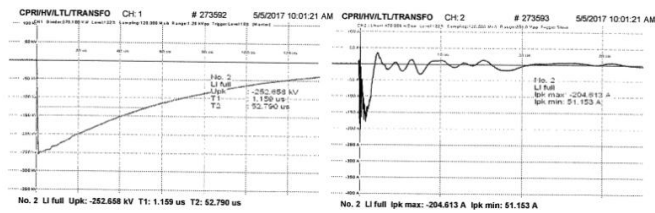


Fig. 13. Voltage and Current waveform for shot No. 2

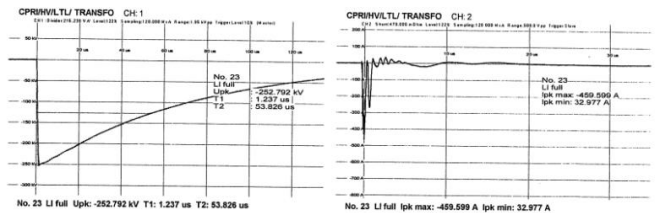


Fig. 14. Voltage and Current waveform for shot No. 2

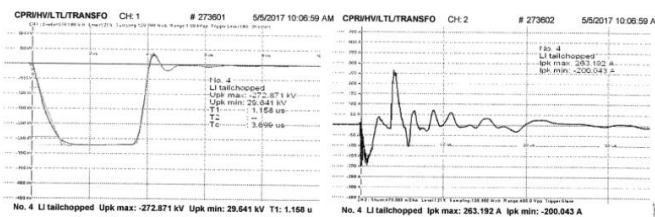


Fig. 15. Voltage and Current waveform for shot No. 3

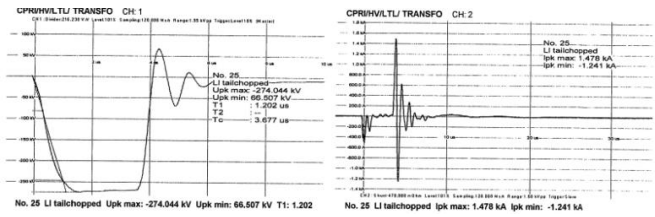


Fig. 16. Voltage and Current waveform for shot No. 3

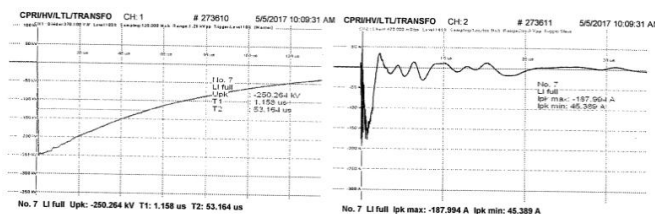


Fig. 17. Voltage and Current waveform for shot No. 6

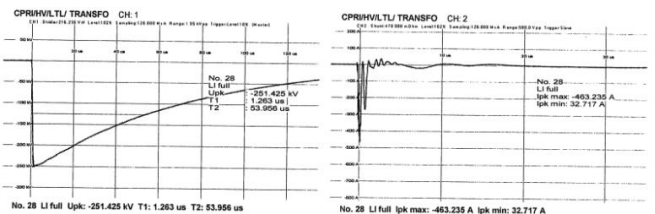


Fig. 18. Voltage and Current waveform for shot No. 6

During the testing no collapse of voltage waveforms were occurred in any of the terminals of four transformers hence fulfilled the basic pass criteria of the test. The corresponding voltage and current waveforms for shots 1, 2, 3 and 6 when the source is connected to terminal A are given in Fig. 3 to Fig. 18 for four transformers. Similar waveforms were obtained for balance shots with chopped wave and full wave voltages. As per IEC standard the waveform of shot 1 is kept as the reference wave shape and waveforms obtained in shots 2 and 6 are compared with the reference wave shape to conclude the test withstandability of the transformer. This test was repeated for the other two terminals of all transformers as given in Table IV.

By analyzing the results obtained for the transformers, it was found that all four transformers are capable to withstand the BIL of 250 kV. By comparing the material cost of two designs the most economical design can be selected.

The temperature rise of the transformer windings plays a vital role during operation to increase or decrease the life time of the transformer. Since the insulation design and the structure of the transformer windings was changed to achieve higher BIL it was decided to conduct the Temperature rise test for the transformers and find out the impact of the changes done under case studies 1 and 2.

IV. TEMPERATURE RISE TEST AND COST ANALYSIS

A. Temperature Rise Test

Temperature rise test was performed as per IEC 60076 standard. The measured temperature rise values for windings and oil against guaranteed temperature rise values are given below in Table V. It was found that the temperature rise values are always less in shield design than when introducing extra insulation.

TABLE V. TEMPERATURE RISE TEST RESULTS

	Temperature rise (K)			
	200 kVA		315 kVA	
	Extra Insulation	With Shield	Extra Insulation	With Shield
Serial Number	T102R783	T028R783	T100R784	T034R784
Top Oil	30.75	26.54	31.71	30.75
HV Winding	41.26	39.21	42.53	41.26
LV Winding	39.50	38.66	38.19	37.50

B. Cost Analysis

Cost for the four transformers with the two designs were calculated based on cost of major material, insulation material, other items and electrostatic shield for the transformers under case studies 1 and 2. Cost increment of designs with extra insulation was found below 1% from the transformer of same capacity with the shield design.

When comparing temperature rise results and material cost of transformers the transformer with electrostatic shield is economical to manufacture than the design with extra insulation.

V. CONCLUSION

This paper explains two methods to improve the BIL of distribution transformers. The first method is by accommodating extra insulation between winding layers and the second method is by introducing an electrostatic shield in the HV winding. Two case studies were conducted with four transformers to analyze the behavior of the two methods. All four transformers were tested for chopped wave lightning impulse test at an international accredited transformer test laboratory in India and proved its ability to withstand lightning impulse test at 250 kV.

In order to compare the performance of the two approaches temperature rise test data were analyzed along with a calculation of material cost. It was found that the performance under temperature rise test is better in the transformers with the electrostatic shield than in the design with extra insulation. Also the material cost is comparatively less in the shield design.

Further based on the obtained results through comparison of above two methods to improve the BIL, it is evident that the distribution transformers manufactured by LTL can be further improved by introducing an electrostatic shield. At present the distribution transformers are designed for BIL of 200 kV and after introduction of the shield the performance under lightning strikes will be much better.

Studies will be carried out to introduce the electrostatic shield in distribution transformers manufactured for local market.

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