Non Linear Voltage Distribution in Windings of Power Transformer

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Abstract

High voltage impulse tests allow us to analyze the dielectric behaviour of power equipments. The test is performed using standard waveforms and procedures. But the transient overvoltages seldom have the standard waveshape, so there is a need to evaluate the response of equipments with actual high voltage impulses. In this contribution, different impulse waveforms (full wave and chopped waves), the non linear voltage distribution and stress oscillation in transformer windings has been investigated for peak voltage, time of its occurrence along with the coil sections. An attempt has been made to compare the peak values of the voltage distributed across the windings with different waveforms, different tappings and different inter coil separations. This analysis will help in knowing the stress condition across the major and minor insulation of the transformer when subjected to transients and thereby help in developing reliable insulation designs.

Keywords- Chopped impulses, Insulation, Impulse, Modelling, Standard and Non-standard waves, Transients

I. INTRODUCTION

Transformer life expectancy depends on the insulation condition. It is evident from Figure I, that the rate of failure of power transformer increases exponentially with poor insulation [1]. The dielectric system of high voltage power apparatus is stressed and damaged by transient voltages of wide varieties of waveshapes, caused by lightning as well as by switching operations [2].

Over voltages caused by lightning surges propagates unequal voltage stress distribution along the insulation and may lead to breakdown of the insulation system. The breakdown of insulation depends generally on the maximum voltage and the time duration [3].

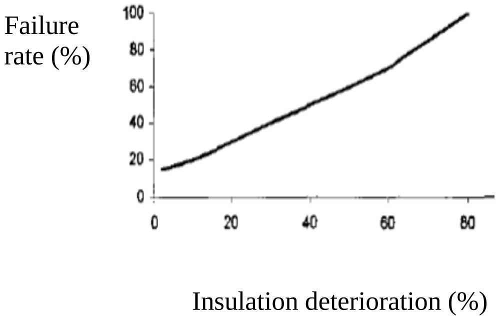

Figure. I Poor insulation and failure rates [1]

For the specification of winding insulation of transformers, it is important to know the electrical stresses to which the winding can be exposed during fast transient oscillations, the voltage appearing across the insulation (as a function of time) and the strength of insulation against the particular voltage wave [4]. The accurate measurement of fast transient voltages is important in the assessment of their effects on electrical power equipment and insulation. If proper information about the voltage distribution and impulse response is available at the design stage, it will allow the designer to apply a sufficient insulation in the areas of high stress, and at the same time reduce an excessive insulation in order to make savings on an optimized insulation. Also proper choice of winding arrangement, clearances and insulation structure can be made with high quality and low cost production. So, to design correctly the winding insulation, a designer needs to know the transient voltage difference across each turn or at least each section of the winding, and also between each point on one winding and the closest point on the adjacent winding [5].

II. TRANSFORMER SURGE MODEL

In order to investigate the distribution of voltage stress and amplifications in the windings with the application of a transient voltage, a surge model of a transformer using MATLAB SIMULINK has been constructed using the design data of a 3 MVA, 33/11 kV, 3-phase, 50 Hz, Dyn 11 Transformer [4]. The main winding constitutes of 80 coils and 8 extra coils are used as tap coils [6]. In order to accurately simulate performance of winding to high-frequency transient voltages the present investigation is done with special reference to the tap windings during open end condition (0% tappings) and when the tap windings are in series with the actual winding (10% tappings) and with inter coil separation of 0.3 mm and 6 mm. Also the inter coil. In a previous work, surge modelling of the transformer has been done using the design data [4].

This arrangement is shown in Figure. II.

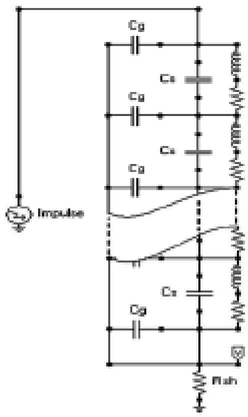

Figure. II Lumped parameter of a 3MVA Transformer [4]

The design data of the 3 MVA, 33/11 kV three phase transformer used in the modelling is summarized below:
Outer diameter of 33 kV winding =524 mm
Inner diameter of 33 kV winding = 424 mm
Axial height of 33 kV disc = 6.6 mm
Average number of turns per disc, N_1 = 19
Inductance of each coil, M_0 = 3.234 X 10 $^{-4}$H
Resistance of each coil, R= 0.151 Ω

III. DETAILS OF INVESTIGATION

Generally, the insulation of various power equipments are tested using the standard waveshape 1.2/50µs for lightning impulse and 250/2500µs for switching impulse in accordance with IEC60060-1 and -2 [7, 8]. Due to non linear effects such as corona, soil ionisation, tower surge response, switching operations and other reflections in the power substation, the transient stresses on a transformer significantly differ from the response obtained with standard lightning impulse voltage. So, there is a need to evaluate the dielectric strength under standard lightning as well as non-standard impulse voltages [7, 9-11].

Parameters like peak magnitude, front time, tail time and chopping time characterises the impulse waveforms [9]. It is important to investigate whether any variation in wave front and tail time alter the spectrum of frequencies contained in a wave. Present investigation has been done with applied full voltage, impulses with tail chopped at 3µs, 8µs and 15µs waveforms.

Impulse waveshape to a great extent determines the voltage distribution in different sections of the winding. For instance, a faster front impulse produces a higher disc to disc voltage and the chopped impulse due to its extended frequency spectrum excite high frequency oscillations in the transformer windings [12, 13].

During the investigation, Specific winding sections namely the line-end section, mid winding and earth-end section coils are subjected to impulses of standard full waveshape (1.2/50 µs), impulse waves with tails chopped at 3 µs, 8 µs and 15 µs. The potential to ground along with time of occurrence for the coils and potential across the coils with time of occurrence is observed and noted at different parts of the winding. This is done for tappings in open ended condition and tappings in series with main winding and also with inter coil separation of 0.3 mm and 6 mm [6].

IV. OBSERVATION

The transient voltage distribution induced in the winding sections by the standard lightning impulse and tail chopped impulses is plotted on a three-dimensional graph as given in Figure III. The three dimensional surface plot gives a preview of impulse penetration when windings are subjected to different impulse waveforms. The maximum voltage to ground and maximum voltage across the coils along with the time of their occurrences against different winding sections, and inter coil gaps of 0.3 mm and 6 mm for 0% tapping and 10% tapping respectively is recorded in Table I and Table II respectively.

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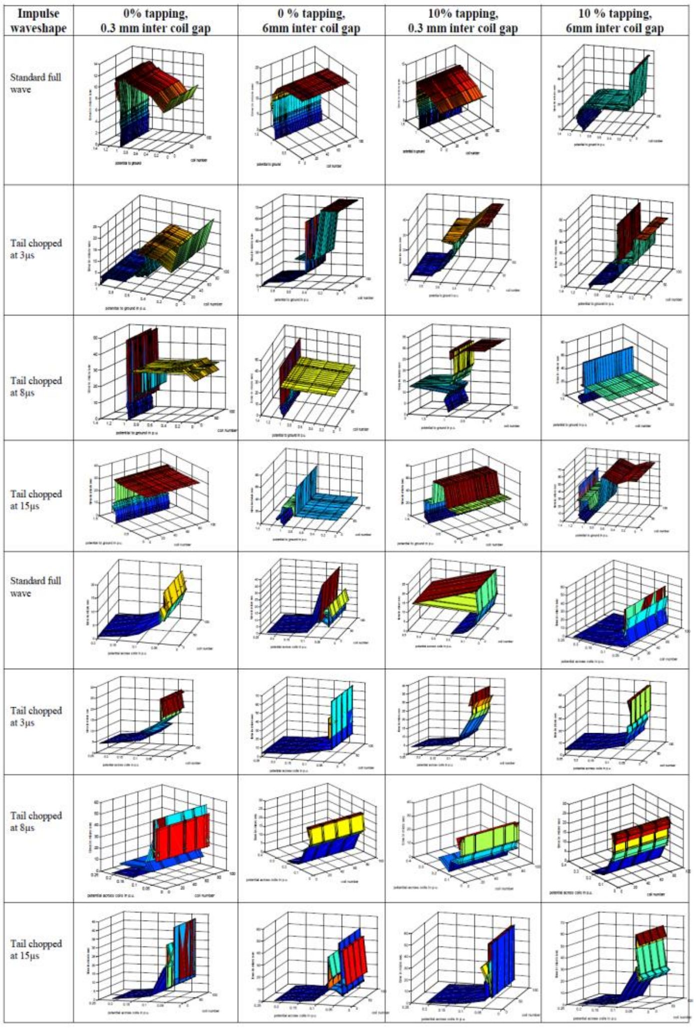

Figure III 3D Surface plot of transient response of the winding coils during 0% and 10% tapping and coils separated by 0.3 mm and 6mm when subjected to the standard lightning impulse and tail chopped impulses at 3μs, 8 μs and 15 μs.

Table I Impulse voltage distribution at 0% tapping and peak voltages at various winding sections.

Type of Impulse	Winding section	Max. Pot. To ground in p.u.		Time of occur. in μs		Max. Pot. Across the coil in p.u.		Time of occur. in μs	
		0.3 mm inter coil gap	6 mm inter coil gap	0.3 mm inter coil gap	6 mm inter coil gap	0.3 mm inter coil gap	6 mm inter coil gap	0.3 mm inter coil gap	6 mm inter coil gap
Standard Full wave Impulse	Line end	1.11	1.17	11.00	11.00	0.20	0.23	0.70	0.90
	Mid	1.09	1.10	11.40	11.80	0.03	0.03	12.2	10.40
	Earth end	0.93	0.88	12.00	17.20	0.47	0.05	13.2	18.40
Tail chopped at 3 μs	Line end	1.00	1.00	2.98	3.00	0.24	0.25	4.30	4.10
	Mid	0.50	0.54	6.50	9.60	.08	0.04	10.90	42.40
	Earth end	0.57	0.60	16.80	25.50	.04	0.05	26.00	23.80
Tail chopped at 8 μs	Line end	1.06	1.08	49.60	44.80	0.21	0.22	0.80	0.90
	Mid	0.94	0.99	49.40	11.00	0.04	0.04	49.20	15.50
	Earth end	1.04	1.06	29.80	27.20	0.06	0.06	29.40	26.10
Tail chopped at 15 μs	Line end	1.15	1.12	12.50	10.60	0.21	0.22	0.80	0.90
	Mid	1.09	1.16	15.00	29.40	0.03	0.04	9.80	8.20
	Earth end	0.95	0.96	33.00	30.80	0.05	0.05	33.00	19.50

Table II Impulse voltage distribution at 10% tapping and peak voltages at various winding sections.

Type of Impulse	Winding section	Max. Pot. To ground in p.u.		Time of occur. in μs		Max. Pot. Across the coil in p.u.		Time of occur. in μs	
		0.3 mm inter coil gap	6 mm inter coil gap	0.3 mm inter coil gap	6 mm inter coil gap	0.3 mm inter coil gap	6 mm inter coil gap	0.3 mm inter coil gap	6 mm inter coil gap
Standard Full wave Impulse	Line end	1.12	1.14	8.65	9.80	0.21	0.23	0.75	0.90
	Mid	1.12	1.13	11.60	11.00	0.04	0.05	24.70	26.10
	Earth end	1.02	1.02	11.80	17.60	0.47	0.05	14.70	19.40
Tail chopped at 3 μs	Line end	1.00	1.01	2.9	3.60	0.24	0.25	4.20	4.60
	Mid	0.56	0.59	11.1	9.00	0.05	0.05	20.10	27.40
	Earth end	0.60	0.62	27.2	24.80	0.05	0.05	29.40	48.40
Tail chopped at 8 μs	Line end	1.10	1.12	7.20	7.20	0.21	0.22	8.50	1.00
	Mid	1.00	1.03	11.30	11.80	0.05	0.05	15.50	14.00
	Earth end	0.95	1.03	25.60	27.20	0.07	0.07	29.00	27.40
Tail chopped at 15 μs	Line end	1.11	1.13	11.60	9.60	0.21	0.22	0.80	0.80
	Mid	1.29	1.16	33.40	29.40	0.04	0.05	29.80	21.00
	Earth end	1.12	0.96	33.80	30.80	0.06	0.05	34.40	50.60

V. ANALYSIS OF THE OBSERVATIONS

From the tables I and II, it can be understood that occurrence of peaks are not systematic and regular. There is under stressing and overstressing of various sections of the impulsed winding with different applied impulses waveforms, tappings and inter coil separations. An arbitrarily chosen time-to-chop in chopped impulse application enforces different stress situations in different coils along the winding. An attempt has been made to compare the peak value of the coil to coil voltage and coil to ground voltage. When the winding is subjected to a full wave standard impulse waveform and other waveforms with chopped tails at 3 µs, 8 µs and 15 µs with tap winding in open end condition maximum, potential to ground was found at the line end section. Maximum potential to ground was 1.11p.u. and 1.17 p.u. for inter coil separation of 0.3 mm and 6 mm respectively with applied standard full waveshape, 1.0 p.u. each for inter coil separation of 0.3 mm and 6 mm respectively with applied chopped waveform at 3 µs and 1.06 p.u. and 1.08 p.u. for 0.3 mm and 6 mm respectively with applied waveform tail chopped at 8 µs, 1.15 p.u. and 1.12 p.u. for inter coil separation of 0.3 mm and 6 mm respectively with waveform tail chopped at 15 µs. When the tap windings are in series with the actual winding and upon subjected to standard impulse wave, the maximum voltage to ground is obtained in the line end section with 1.12 pu and 1.14 p.u. for inter coil separation of 0.3 mm and 6 mm respectively. For impulses chopped at 3 µs maximum voltage to ground was found in the line end sections with 1.00 p.u and 1.01 p.u for inter coil gaps of 0.3 mm and 6 mm respectively. Similarly for tail chopped waveform at 8 µs, 1.10 p.u and 1.12 p.u was the maximum values of potential to ground for 0.3 mm and 6 mm inter coil gaps. Exception is 15 µs chopped impulse where maximum voltage to ground was found in the mid winding section at 1.29 p.u and 1.16 p.u for 0.3 mm and 6 mm intercoil gaps respectively. For inter coil gap of 0.3 mm for both open ended tap windings and tapings in series with actual winding, maximum potential across coils are found in the line end sections of the winding for all the chopped impulses, and for standard full waveshape, it is found in the earth end section of the winding. For both 0% and 10% tappings, the maximum voltage across the coils is found with standard full wave impulse at the earth end section. With 6 mm inter coil gap, the maximum potential across coils is 0.25 p.u. at line end section for both 0% tapping and 10% tapping with applied tail chopped impulse of 3µs.

It is seen from the 3D surface plots that the 10% tapping condition maintains a higher voltage profile than in the 0% tapping conditions (Maximum is 1.29 p.u in the mid winding section with 0.3 mm intercoil gap and 1.16 in the line end winding section for 6 mm inter coil gap).

Variation in waveform of the applied impulse results in modification to the voltage distribution developed both for potential to ground and potential between turns and coils. Chopping of the impulse on the wavetail results in differences in inter-turn and inter-coil stress.

Earlier research also proved that the short duration, fast rising front of the voltage wave, or the sudden chopping of the wave produces a nonlinear voltage distribution inside the windings, and results in a high voltage difference between adjacent turns and layers [15]. For steep front impulses the breakdown voltage is lower than for impulse waveforms of longer wavefronts and the tail time does not seem to be critical in determining the breakdown voltage [16]. It was found that shorter wavetails increase the breakdown voltage level of a given air gap. Long time delays of breakdown for the fast-front and short time delays for the slow-front waves were also observed [1]. It was also established that the potential distribution in the winding is not linear in the high frequency range [17]. The full wave because of its relatively long duration causes major oscillations and develops high voltages across the windings and between the winding and ground.

The breakdown voltages reduce with increase in voltage application duration [18]. The patterns of stress oscillation in corresponding line-end and earth-end coils are almost alike [19].

VI. CONCLUSION

In the present paper extensive observational studies on non linear voltage distribution with standard full-wave and tail chopped impulses have been made on surge model of a 3 MVA, 33/11 kV, 3-phase, 50 Hz, Dyn 11 Transformer. The studies cover winding responses to full standard waveshape, tail chopped standard impulses at 3 µs, 8 µs and 15 µs with tap winding in open end condition (0 % tapping) and with tap windings in series with actual winding (10% tapping) and with inter coil gap separation of 0.3 mm and 6 mm. For designers it is very important to analyse the effect of transients on the voltage distribution in the windings of power transformers to develop reliable insulation designs at low cost. The results of our tests have led us to conclude that there is non linear distribution of voltages in the windings due to the applied surge waveforms. Different stress conditions are aroused in the winding sections by different waveshapes (full and chopped waveforms).

A possible direction for extension of this research is to analyse a large number of waveforms which comply with the actual HV impulses, identify relevant features in them, simulate the lightning strike properly and use it for testing different transformers and other power equipment models for surge analysis and enhancement in insulation design.

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