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Surge Voltage Distribution in a Transformer Winding Model for Fast Rising Double Exponential Switching Surges

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Abstract-*In power systems, 'Power Transformer is one of the very important components in the power system. Any failure of the power-transformer results in widespread and serious disturbances. Also at higher voltage levels, it is not practical to have stand-by units of large and very expensive transformers. Thus transformer failures cause a long duration power outage as well as large financial losses.*
In view of the above, transformer failures have been widely investigated but there are still many unexplained failures. Therefore in this paper an attempt is made to understand the behaviour of transformer for lightning and fast rising representative switching surges of double exponential nature waveforms. Different surges of 1kV magnitude are generated in the laboratory and are applied to a custom built transformer winding model having 160 turns which is partly interleaved. Studies are carried out for lightning impulses and fast rising switching impulsesmentioned above.

Keywords-*Fast risingSwitching Surge, Voltage distribution, Double exponential pulse, Power Transformer, Variable frequency source*

I. INTRODUCTION

With the constantly increasing growth of transmission system and their interconnection in to larger systems, supply of uninterrupted service is becoming more important. This has necessitated the great amount of study on the subject of increased reliability of all component parts making up the whole system. A power transformer is one of the very important and costly components in a power system. Power Transformer is 'the Link' that enables power flow. Any failure of the power-transformer results in widespread and serious disturbances. The operational security of transformers is of decisive importance for reliable power supply. At higher voltage levels, it is not practical to have stand-by units of large and very expensive transformers. Thus transformer failures cause a long duration power outage as well as large financial losses. An understanding of the behavior of this component under different voltage stresses in the field is a very important task, as a transformer failure could cause long interruptions and costly repairs. Therefore, it is very desirable to understand potential failures.
Further, almost always, failure of a power apparatus is due to failure of the electrical insulation system. Therefore, it is no wonder that great deal of emphasis is given to

a) Proper design of electrical insulation
b) Proper evaluation (in the manufacturing shop) by high voltage tests.
c) Great care in transportation and commissioning and
d) Periodic maintenance and often on-line diagnostics of electrical insulation of EHV transformers.

This has motivated the development of several studies in order to understand its performance, especially during switching transients and lightning, which can lead to different kinds of failures. In light of the above it is of great importance to study the causes of failure of Power transformers and prevent them to the best possible extent.
One of the major causes of transformer failures is occurrence of over voltages is thought to be the most severe. Analysis of failures has shown that in spite of thoroughness of investigation (of failures), a good percentage of failures have not been satisfactorily explained. Some of the failures could be overstressing of insulation during occurrence of fast switching surges. One of the peculiar aspects of switching surges is that they have widely varying wave shapes, which are almost always oscillatory with varying degree of damping due to the resistance of the system. The frequencies of oscillations also vary widely. The waves could also be asymmetrical due to travelling phenomena. There could be nonlinearities due to ferro-resonance kind of phenomena.
In spite of the above, failures of transformers do occur causing serious disturbances as well as financial losses.
It has been expressed that fast switching surges could be the cause of such transformer failures. However, there is only limited literature reporting studies of surge phenomena in transformers under switching over voltages. Therefore an attempt is made to study the effect of lightning as well as fast rising switching surges of double exponential waveform

applied to a custom built, partly interleaved, transformer winding model of varying frequency. The study also includes the response of the winding to Lightning Impulse waveform also for the sake of completeness. Therefore, the present study is confined to the following sources:

i) Lightning Impulse – 2.5/50µs and 5/50 µs

ii) Fast rising Switching Impulse of double exponential in nature - 10/100 µs, 20/100 µs, 50/100 µs and 100/500 µs.

III. LABORATORY GENERATED SOURCE DETAILS

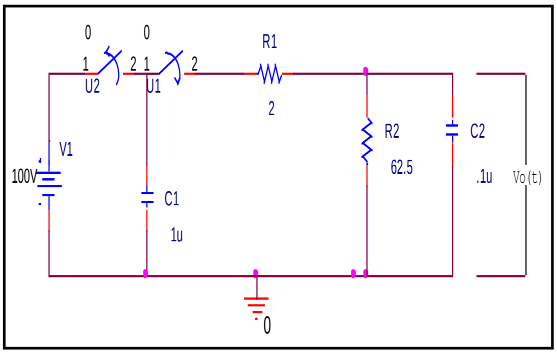

Figure 1 : Equivalent circuit for double exponential source generation

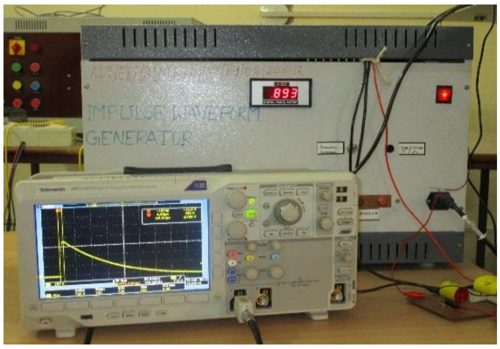

Figure 2 : Source Generator in the Laboratory

Figure 1 shows the equivalent electrical circuit for the generation of double exponential waveforms and Figure 2 showsthe actual waveform generator designed based on the electrical circuit shown in Figure1.The desired impulse wave shape of good voltage efficiency is obtained by choosing C_1 to C_2 ratio in the range of 5 to 10. The Generator capacitor C_1 previously charged to a particular D.C voltage is suddenly discharged in toa wave shaping network (R_1, R_2& C_2) by closing the switch S_2. The discharge voltage V(t) across C_2 gives thedesired exponential wave shape. The wave front and wave tail times can be independently controlled by changing R1 and R2 respectively.

This generator is used to generate double exponential waveforms by suitably varying the values of R and C in the circuit. Following double exponential sources with varying front and tail times of interest are generated:

A. Lightning Impulse waveforms

a) 2.5/50 µs b) 5/50µs

B. Fast rising representative Switching Impulse of double exponential in nature

a) 10/100µs b) 20/100µs c) 50/100µs and d) 100/500 µs

The generated Pulses for 2.5/50 µs impulse and 50/100µs representative double exponential switching surge is as shown in Figures 3 and 4 respectively.

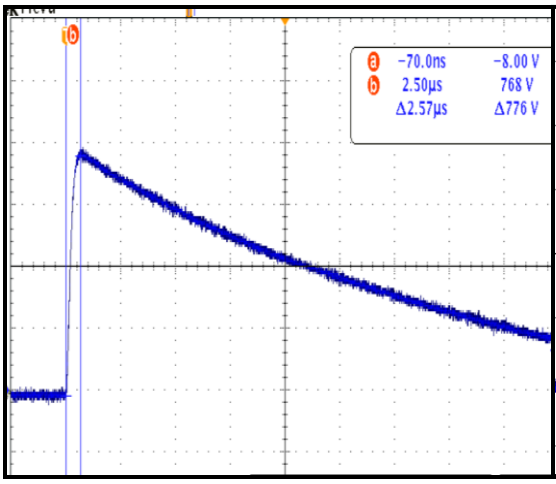

Figure 3 : Impulse Voltage 2.5/50 µs

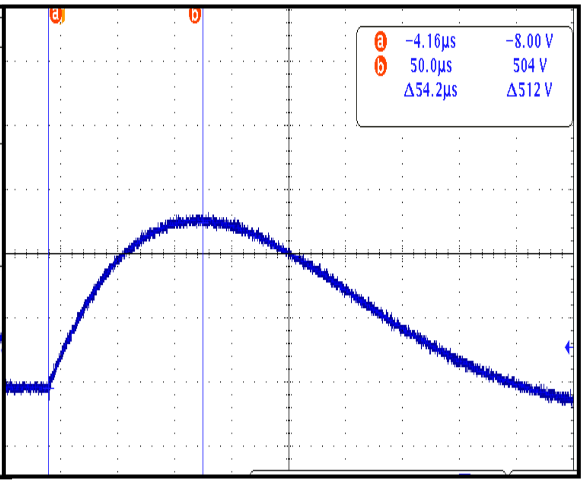

Figure 4 : Double exponential switching surge 50/100 µs

IV. DETAILS OF AIR CORED TRANSFORMER WINDING MODEL

Figure 5 shows the winding layout of the custom built transformer winding model. Figure 6 shows the custom built air cored, partly interleaved transformer winding having 20 discs containing 8 turns/disc. First ten discs (60 turns) from the line end are having interleaved connection and the remaining 10 discs are ordinary disc winding. Taps are provided at every disc for the purpose of measurements.
In this paper Node Voltage Distributions are studied by measuring the voltages at every disc with respect to ground. That is measurements are made for every 8 turns of the winding. Experiments are carried out for different types of double exponential sources mentioned earlier.

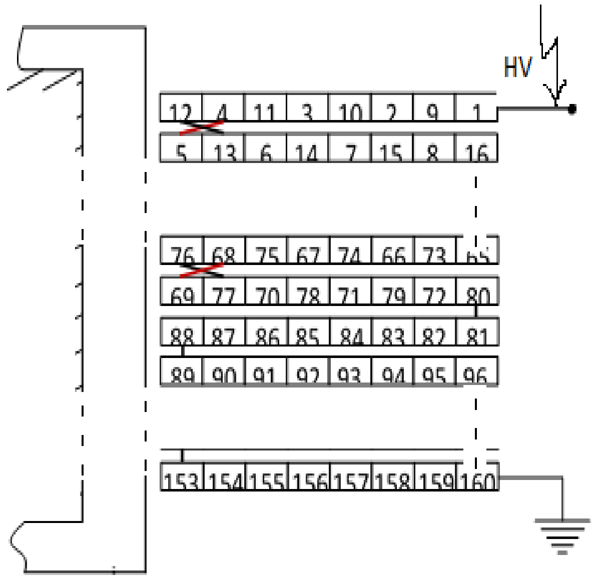

Figure 5 : Layout of Winding Turns

Figure 6 : Air cored Transformer winding Model

V. EXPERIMENTAL DETAILS

The above mentioned sources of double exponential in nature representing lightning impulse and fast rising switching impulse, are applied to the model transformer winding at the HV terminal as indicated in figure 5. Voltages with respect to ground at different nodes are recordedusing a 500MHz Digital Storage Oscilloscope.Experiments are carried out for the following winding patterns :

Winding 1 - Transformer winding pattern having 160 turns(80 turns from line end are interleaved and next 80 turns towards the groundare ordinary disk windings). Here disc numbers 1 to 20 i.e., complete winding is connected for the experimental study.

Winding 2 – Transformer winding patternhaving 80 turns (Ordinary disc winding). In this case, disc numbers 11 to 20 having ordinary disc winding structure is connected for the experimental study.

Winding 3 – Transformer winding pattern having 80 turns (fully interleaved winding). In this case, disc numbers 1 to 10 having interleaved structure of the winding is connected for the experimental study.
The results are recorded and analysed for different types of surges and thus for different frequencies. Only the peak values (occurring at different instants of time) are considered to study the node voltage distributions.

VI. RESULTS

A. Node Voltage Distribution for Lightning Impulse – 2.5/50 µS and 5/50 µS

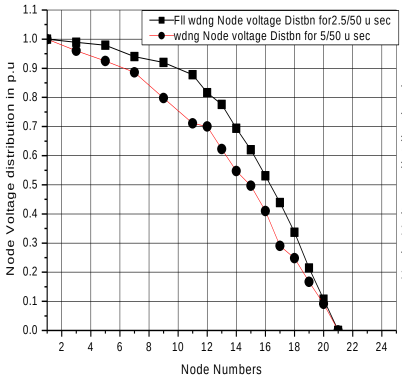

Figure 7 – Winding 1

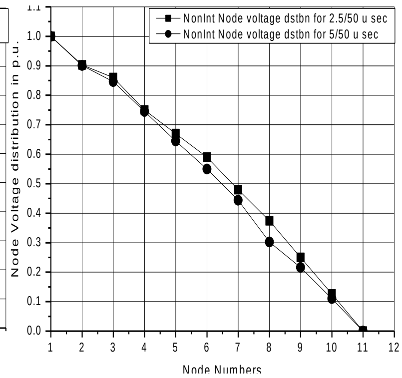

Figure 8 – Winding 2

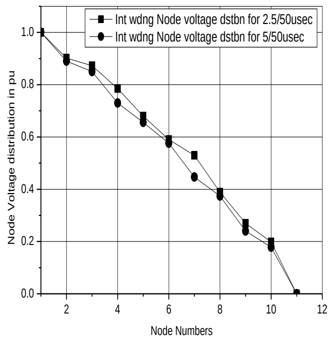

Figure 9 – Winding 3

B. Node Voltage Distribution for representative fast rising Double Exponential Switching surge of varying front time 10µS to 50µS with constant tail time of 100µS.

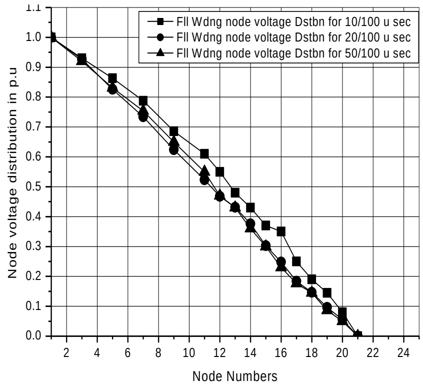

Figure 10 – Winding 1

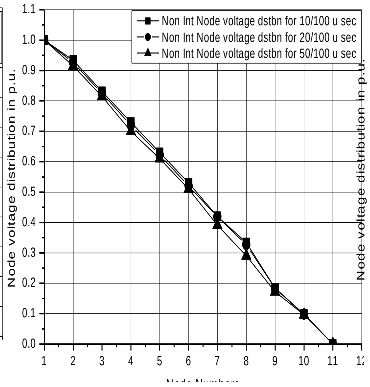

Figure 11 – Winding 2

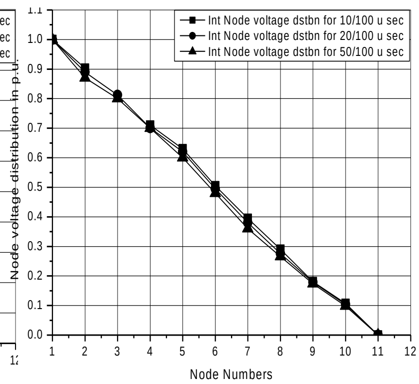

Figure 12 – Winding 3

C. Node Voltage Distribution for representative Double Exponential Switching surge - 100/500µS

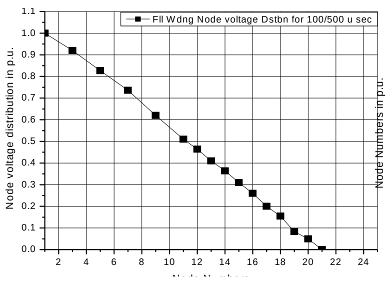

Figure 13 – Winding 1

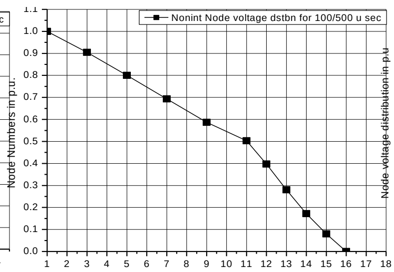

Figure 14 – Winding 2

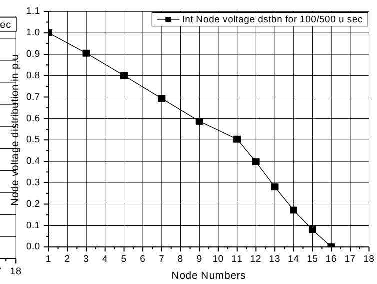

Figure 15 – Winding 3

VII CONCLUSIONS

The switching voltage response is studied on a model transformer winding for standard lightning impulses and representative double exponential switching surges of varying front and tail times. The surges are generated in the laboratory and are applied to the custom built transformer winding model for different winding configurations – partly interleaved (160 turns), fully interleaved(80 turns) and fully non-interleaved(80 turns).

The voltage distribution in all the three windings show a nonlinear voltage distribution. Non-linearity is more for lightning impulses as the frequency is high compared to other sources and is in good agreement with literature. The fast rising switching impulses also results in a non-linear voltage distribution. Winding 1 - Partly interleaved winding show highly non-linear voltage distribution, the reason being flattening of the curve at the line end because of the interleaved nature of the winding and thus the stress gets transferred to the ground end. However, the voltage distribution show almost a linear distribution in case of winding 2-completely non-interleaved winding. Also, the distribution is linear in case of winding 3 – completely interleaved winding. Similar trend is seen in case of fast rising representative switching pulses. The distribution becomes almost uniform for the source 100 µS/500 µS. This is due to the fact that the frequency is less and the length of the winding is too small, however, this may not the case in real power transformer.

Hence it is evident that the voltage distribution does not become linear because of partly interleaving rather, increases the stress in windings towards ground end. However, this may help in reducing the line end stresses. Also, the completely interleaved winding appears to be a better winding pattern. To understand this phenomena in a better way studies with reference to a real power transformer is necessary.

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