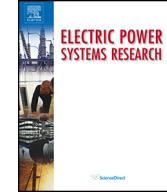




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Electric stresses on transformer winding insulation under standard and non-standard impulse voltages

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ABSTRACT

This work presents an extension of our previous work on voltage stress analysis of a 3 MVA, 33/11 kV, 3-phase, 50 Hz, Dyn 11 transformer against the application of standard and non-standard impulse voltages. A preliminary comparative study on the variation of maximum voltage to ground and voltage across the coils under different impulse voltages indicated that non-standard impulse voltage waveforms develop higher voltage stress in the windings. They pose high risk and are critical to transformer insulation system. The obtained test results provide the basis for further study of non-standard impulse voltage waveforms and make necessary correction in the existing impulse testing standards. However, to take care of the stringent effect of actual lightning and other impulse voltages occurring in practical field a more detailed study considering a wide variety of non-standard impulse voltage waveforms is aimed to be done in future.

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1. Introduction

Power equipment is exposed to a variety of impulse voltages during their life time. Impulse voltages originate as a result of lightning strokes, switching operations or system generated transients in the power system network.

These impulses contain high frequency overvoltages ranging from several kilo Hertz to several mega Hertz. Thus, during transient phenomenon, the power equipment experience high frequency overvoltages for very short duration of time. Also, they are excited with high current and voltage peaks compared to their normal system rating. This change in voltage and current amplitude though for very short time has high impact on the insulation system of the equipment.

Transformers are an integral part of transmission and distribution networks. Wagner [1] investigated surge phenomena in transformers and reported the effects of transients on transformer windings in 1915. When transformer windings are excited by impulse voltages, high amplitude oscillatory voltage stresses the transformer insulation between the winding and ground and across the windings. This degrades the insulation system [2]. The insulation degrades more on repeated exposure to impulses [3,4]. The

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severity of insulation degradation depends on steepness of the wave, instant of chopping, time to collapse, frequency of oscillations, overshoot near the peak, etc. [1,3,5]. Aschlimann [6] and Sirotnitski [7] showed that voltage stresses due to chopped waveforms were higher than those due to full wave of the same steepness. Heller and Veverka [8] also observed higher inter-turn and inter-disk insulation stresses for a chopped wave. Mitra et al. [9] did computational studies on winding response of transformer to oscillatory voltages. They reported that the effect of oscillatory voltages is worse than under full lightning impulse, chopped lightning impulse or steep front long tailed switching surge. The positive and negative polarity of oscillating waveforms affects the insulation breakdown in power equipment [10]. Overhead line-transformer and cable-transformer interfaces impose oscillatory switching overvoltages in the transformer and lead to insulation failure [11–13]. High frequency overvoltages are often produced by the re-strokes and pre-strokes during the opening or closing of a switching device like the circuit breakers. Popov et al. [14] investigated the phenomenon that can produce high overvoltages internally in large shell-type transformer windings. They also investigated the effect of fast voltage transients, which occur due to circuit breaker pre-strike on transformer insulation [2,15,16]. The importance of considering frequency-dependent behavior of transformer during overvoltage analysis has been reported in many studies [17–19]. Vector fitting method was proposed by Gustavsen and Semlyen and is the most popular method for frequency-dependent modeling [20–22]. This method offers the possibility to

Table 1
Few international standards used during impulse testing.

| Standards | Description |
|--------------------------|---|
| IEEE Std. 4 (2013) | This standard summarizes standard methods and basic techniques for high-voltage testing applicable to all types of apparatus for alternating voltages, direct voltages, lightning impulse voltages, switching impulse voltages, and impulse currents [34]. |
| IEEE Std. 1122 (1998) | This standard defines the requirements for digital recorders for measurements in high voltage impulse tests [35]. |
| IEEE Std. C57.138 (1998) | This standard describes the recommended practice for routine impulse test for liquid-immersed, single and three-phase distribution transformers [36]. |
| IEEE Std. C57.98 (2011) | This standard applies to impulse tests of power transformer. Test connections, methods, circuit configurations, failure analysis of lightning impulse, and switching impulse testing of power transformers are addressed [37]. |
| IEEE Std. 82 (2002) | This standard specifies test procedure for the impulse testing of insulated conductors (cables) and cables with accessories installed (cable systems). This procedure can be used as a design or qualification test for cables or for cable systems [38]. |
| IEC 61211 (2004) | This standard deals with impulse puncture testing in air of ceramic and glass insulator units of class B: cap and pin, pin type (including pin-post type) and class B long rod insulators with nominal voltage greater than 1000 V [39]. |
| IEC 60060-1 (2010) | This part of the standard describes the test techniques, general definitions and requirements for high voltage test of equipment above 1 kV. It applies to dielectric tests with alternating voltage, dielectric tests with direct voltage, dielectric tests with impulse voltage and dielectric tests with combinations of the above [24]. |
| IEC 62475 (2010) | This standard covers fault detection during lightning impulse testing. This standard also applies to high-current testing and measurements on both high voltage and low voltage equipment [40]. |

fit the admittance matrix, the parameters of which are within broad frequency range, and perform accurate transient simulation of linear power systems by fitting of measured or calculated frequency domain responses with rational approximation [17,23].

Investigation of the voltage stresses in the insulation system of power transformer due to transient overvoltages is essential for minimization of insulation failures and maintaining high reliability. Impulse voltage testing is generally done in high voltage laboratory for assessing the insulation strength of power equipment. Specific high voltage test requirements, voltage levels, procedures, etc. are specified and written in international standards by IEC and ANSI/IEEE. During impulse tests, voltage sequences of standard waveshape are generated in the laboratory and applied to the equipment as per testing standards. The lightning impulse test is done according to IEC 60076-4 using standard impulse voltage waveform having front time and a time to half-value of 1.2/50 μ s [24] and switching impulse test is done using voltage waveform having front time and a time to half-value of 250/2500 μ s [24]. The standard lightning impulse waveform of 1.2/50 μ s was first introduced by IEC in 1962 [25]. The standards are regularly revised to suit the current needs of the modern power system. In 2010, the test standards for electrical equipment up to 800 kV were revised and now process for revising standards for ultra high voltage (UHV) is in progress [26]. Few international standards used for impulse testing of high voltage equipment are given in Table 1. Meanwhile, there are certain conditions in practical life under which the power equipment encounters non-standard impulse voltages. Recently, a joint working group A2/C4.52 within CIGRE (Conseil

International des Grands Réseaux Électriques) Transformer Committee (SC A2) has been formed to deal with transformer modeling and simulation of high-frequency transient overvoltages that can occur in actual service (<http://www.cigre.org/>). For example, during impulse test performed in laboratory, the impulse generator often fails to generate the standard waveshape within tolerance limits due to disagreement in circuit parameters, etc. In such case, windings are exposed to non-standard voltages of both unidirectional and bi-directional oscillating waves [27]. Another important observation is that the naturally occurring transients do not always have the standard waveshape [28]. The actual lightning or switching surges consist of wide variety of complex waveforms differing in amplitude and waveshape. Therefore, it becomes very essential to test the insulation integrity of power equipment under standard as well as non-standard impulse voltage waveforms.

The main objective of our work is to investigate the effect of standard and non-standard impulse voltages on power transformer windings by computational as well as experimental method. This work is an extension of the investigation undertaken by the authors on surge response of a 3 MVA, 33/11 kV, 3-phase, 50 Hz, Dyn 11 power transformer [29–31]. In our previous works, validation of the developed transformer model and comparative study of transient response using few standard and non-standard impulse waveforms were done. We observed that there are considerable differences in the characteristics of the impulse voltages that are important to take into account to properly evaluate the insulation strength of the power transformer. In this work special attention is given to improve the test signals by taking into account, the stringent effect of actual lightning and other impulse voltages occurring in practical field. Standard and non-standard impulse voltage waveforms (full, chopped, oscillating and non-oscillating impulses) varying in steepness, instant of chopping, time to collapse, frequency of oscillations, etc. have been used for surge analysis. The applied non-standard impulse voltages are generated based on actual impulse voltage waveforms observed in field as reported in [32,33]. This study will provide relevant information for improving the inter-turn and inter-coil insulation design and minimizing the number of insulation failures. Also, the test results will contribute to further study of non-standard impulse voltage which may identify the need for modifying existing test standards or introducing new standards for impulse testing of power equipment.

2. Determination of impulse voltage distribution in winding of power transformer

Experimental and computational investigation was carried out on a 3 MVA, 33/11 kV, 3-phase, 50 Hz, Dyn 11 transformer under standard and non-standard lightning impulse voltages. The behavior of impulse stressed winding has been analyzed by considering it as an isolated winding with grounded ends. The effect of iron core could be neglected for impulse response studies at high frequencies and therefore, an air core has been used for transformer modeling [29]. For impulse testing of the 3-phase, mesh connected winding, an impulse voltage is applied at one terminal. The other two terminals are shorted and grounded through a small resistance.

The sample transformer main winding is constituted of 80 coils and 8 extra coils are used as tap coils. The main winding is divided into three sections namely line end section (coil nos. 1–27), mid winding (28–54) and earth end section (coil nos. 55–80). The experimental studies were done in the high voltage laboratory, Jadavpur University, Kolkata, India [29]. The actual disk windings have been represented by coils in form of circular rings of rectangular cross-section in the analog model. The computational model is developed in MATLAB Simulink. The photograph of analog model and corresponding MATLAB Simulink based simulated model are shown in Fig. 1.



Fig. 1. Analog and simulated model of 3 MVA, 33/11 kV, 3-phase power transformer. (Courtesy: High voltage laboratory, Jadavpur University, India) [29].

The design data of the high frequency transformer are:

Power rating of transformer: 3 MVA

Number of coils in main winding: 80

Number of tap coils: 8

Average number of turns per disk: 19

Voltage rating of transformer: 33/11 kV

Axial height of 33 kV disk: 6.6 mm

Outer diameter of HV winding: 534 mm

Inner diameter of HV winding: 424 mm

Mean radius of the disk: 237 mm

2.1. Parameter determination for transformer modeling

2.1.1. Calculation of self inductance

The self inductance of a disk coil can be calculated from the following equation [29]:

$$L = 4.10^{-7} R N_1^2 (\ln 8R/R_1 - 2) \text{ H} \quad (1)$$

where

$$\begin{aligned} \ln R_1 &= \frac{1}{2} \ln(a^2 + b^2) - ((b^2/12a^2) \ln(1 + (a^2/12b^2)) \ln(1 + (b^2/a^2))) \\ &\quad + ((2b/3a) \tan^{-1}(a/b)) + ((2a/3b) \tan^{-1}(b/a) - 25/12) \end{aligned} \quad (2)$$

Fig. 2 shows the cross-sectional view of the coil.

Average number of turns per disk, $N_1 = 19$, mean radius of the disk, $R = 237 \times 10^{-3}$ m, $a = 6.6 \times 10^{-3}$ m and $b = 0.05$ m. Hence, self inductance, L of one disk is calculated to be 0.324 mH.

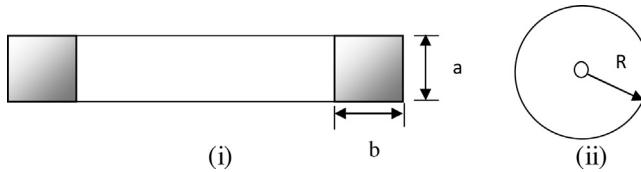


Fig. 2. (i) Disk coil with rectangular cross-section, (ii) circular inductive coil.

2.1.2. Calculation of capacitance to earth (C_g) and series capacitance (K)

These capacitances of the winding depend upon the winding geometry [41]. In this study, the capacitance between windings is calculated as the capacitance between coaxial cylindrical electrodes as presented in [1,29,42]. The capacitance between impulse side limb winding and the tank is computed by using the expression for capacitance between two co-axial cylinders with certain approximations. Methods of images have been utilized to calculate the capacitance between the impulse middle limb winding and the tank.

The parameters values are calculated as

$$C_{g1} = 1721.8 \text{ pF} \text{ (side limb)}$$

$$[43] C_{g2} = 1970.4 \text{ pF} \text{ (middle limb)}$$

$$K = 11.68 \text{ pF}$$

Since the actual winding is composed of 80 disk coils, it is necessary to construct the model with 80 coils each having self inductance same as that of the actual disk winding i.e. 0.324 mH. The series capacitance between each coil will be 80 times the equivalent series capacitance of actual winding. Shunt capacitance to earth for each coil will be 1/80 times the equivalent shunt capacitance to ground of the actual winding. The parameter values are:

Ground capacitance per coil capacitance to earth (C_g) = 24.63 pF for each coil

Series capacitance (K) = 934 pF between two consecutive coils.

2.1.3. Calculation of resistance of each coil

The resistance of each coil is given by:

$$R = \rho \frac{\pi d N}{A} \quad (3)$$

where d = mean diameter of each coil = 19.5×10^{-2} m, N = number of turns of each coil = 30, ρ = resistivity = $1.73 \times 10^{-8} \Omega \text{ m}$, A = area of cross-section of each conductor = $2.1 \times 10^{-6} \text{ m}^2$.

Hence, value of resistance for each coil is calculated to be 0.151 Ω.

2.2. Applied impulse voltage waveforms

In this study, the transformer winding sections are subjected to six different waveforms including standard (full and chopped) and non-standard (non-oscillating and oscillating) lightning impulse voltage waveforms. The single pulse and damped oscillating impulse voltage waveforms are used to represent realistic waveforms observed in actual field other than the typical standard waveforms. The applied impulse voltage waveforms are generated in MATLAB. Brief descriptions of the applied waveforms are given below:

2.2.1. Standard full lightning impulse voltage waveform

As per IEC 60060-1, a full standard lightning impulse voltage rises to its peak value in 1.2 μs and the tail of the wave decays to a level of 50 percent of the peak in 50 μs. The waveform is mathematically modeled by superposition of two exponential functions with different time constants as given in Eq. (4). The waveshape of a standard lightning impulse is shown in Fig. 3.

$$V = V_0 [\exp(-\alpha t) - \exp(-\beta t)] \quad (4)$$

where $\alpha = 0.0146$, $\beta = 2.467$, and $V_0 = 1.04$.

2.2.2. Chopped lightning impulse voltage waveform

A chopped wave is developed during flashover or puncture. The standard lightning impulse voltage waveform can be chopped on the tail, peak or front. The crest value of the standard tail chopped wave is 10% greater than that of full impulse wave and chopped at

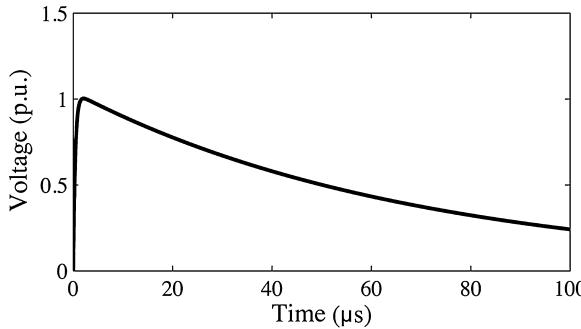


Fig. 3. Standard lightning impulse voltage waveform.

2–6 μ s [34]. Such impulses have a rapid voltage collapse on the tail with a small portion of negative overshoot. In this work, impulses with chopping time 3 μ s, 8 μ s, and 15 μ s on tails are used to investigate the voltage distribution on the winding. The tail chopped impulses at 8 μ s and 15 μ s represent the non-standard chopped impulses. The extreme value of undershoot of the chopped impulse is normally very small and so has been ignored in this work. The waveshapes of chopped lightning impulses are shown in Fig. 4.

2.2.3. Non-standard single pulse impulse voltage waveform

Single pulse non-standard impulse voltage waveform has been used in this work to study the winding response against non-standard lightning impulse waveforms without oscillations. These impulses have a steeper wavefront and short, non-oscillating tail compared to the standard lightning impulse waveform [32,33]. The waveshape of a typical single pulse impulse voltage waveform is shown in Fig. 5. The wavefront time of the impulse is 0.8 μ s and the tail of the wave decays to a level of 50 percent of the peak in 2.8 μ s.

2.2.4. Non-standard damped oscillating impulse voltage waveform

Oscillations can occur in impulse waveforms due to series and parallel resonance or disagreement in circuit parameters of impulse generator in the laboratory [32,33]. The waveshape of a typical damped oscillating impulse waveform is shown in Fig. 6. The voltage rise time is 1.9 μ s and the wavetail is characterized by a damped oscillation with frequency of 0.5 MHz.

2.3. Observations

The 33 kV mesh connected winding of the power transformer model is subjected to standard and non-standard lightning impulse voltage waveforms. The variation of maximum voltage to ground along with time of occurrence and voltage across the coils along with time of occurrence in the winding against the application of standard and non-standard impulse voltage waveforms are determined for both the analog and simulated models (Fig. 1). The characteristic curves showing the experimental and simulated values of variation of maximum voltage to ground against coil numbers are shown in Table 2. To compare simulated results with the experimental results, percentage error is calculated and placed in Table 3. The calculated percentage error is within $\pm 3\%$.

It is evident from Tables 2 and 3 that the response of the simulated model is reasonably in good conformity with the experimental results. The simulated model is used as the basis for further investigations involving non-standard, non-oscillating single pulse impulse voltage waveform and non-standard, oscillating damped impulse voltage waveform. The characteristic curves and maximum voltage to ground and voltage across the coils obtained against the application of standard and non-standard impulse

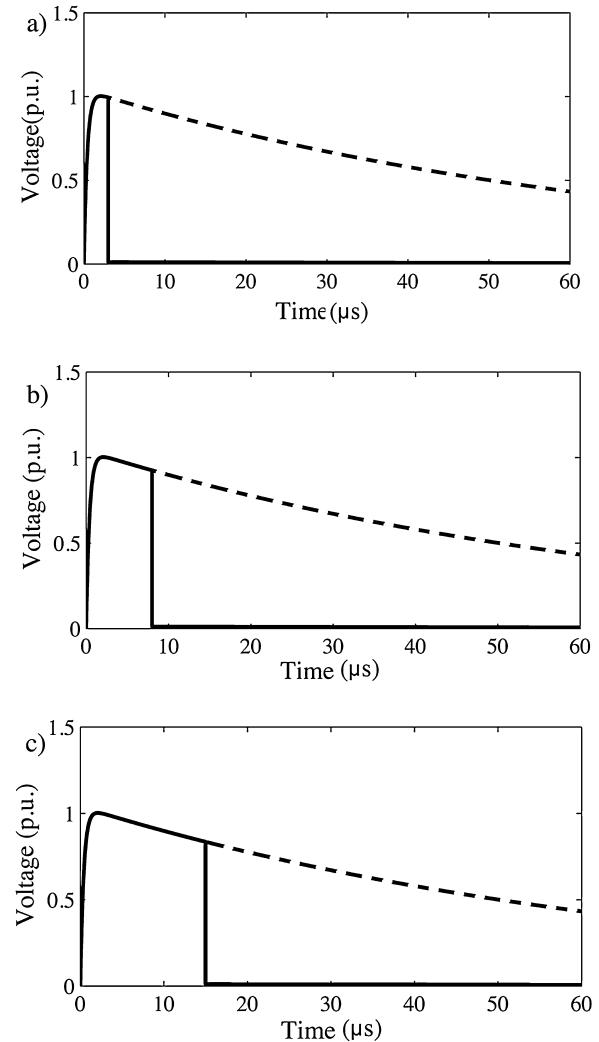


Fig. 4. Chopped lightning impulse voltage waveform at (a) 3 μ s, (b) 8 μ s, and (c) 15 μ s.

voltages are shown in Tables 4 and 5 respectively. In general, it has been found from the figures placed in Table 4 that the maximum voltage to ground, maximum voltage across the coils and the occurrence of the maximum potential are inversely proportional to each other, i.e. when the maximum voltage to ground/maximun voltage across the coil is high the time of occurrence is low. The voltage distribution along the winding of the transformer is different under different impulse waveforms. The voltage amplifies at certain locations of the winding depending upon its physical configuration and waveform parameters. The non-standard waveform

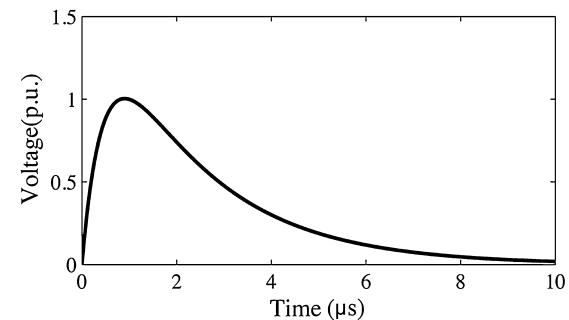
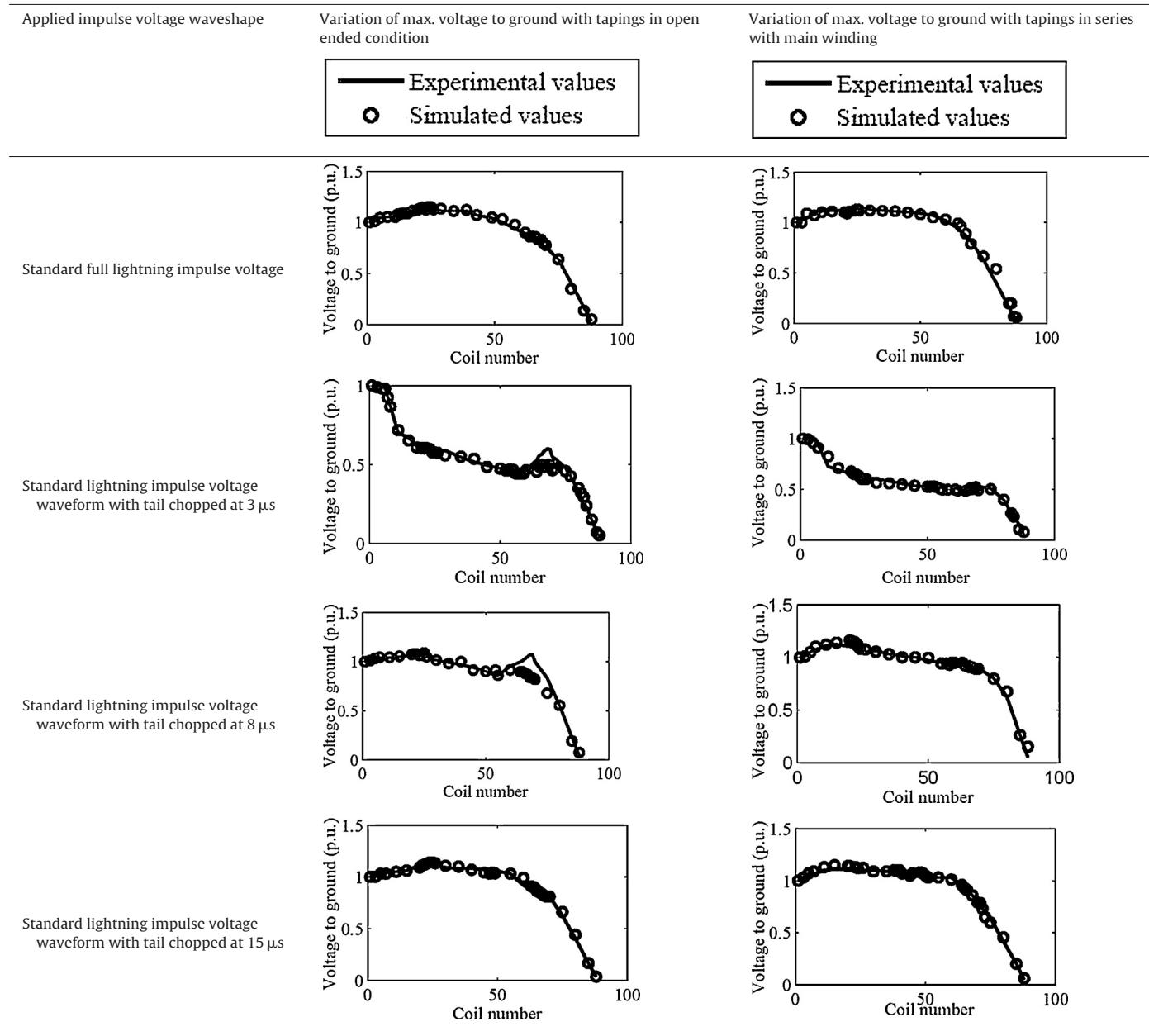


Fig. 5. Single pulse impulse voltage waveform.

Table 2

Characteristic curves showing the variation of maximum voltage to ground along the winding in simulated and the experimental models.

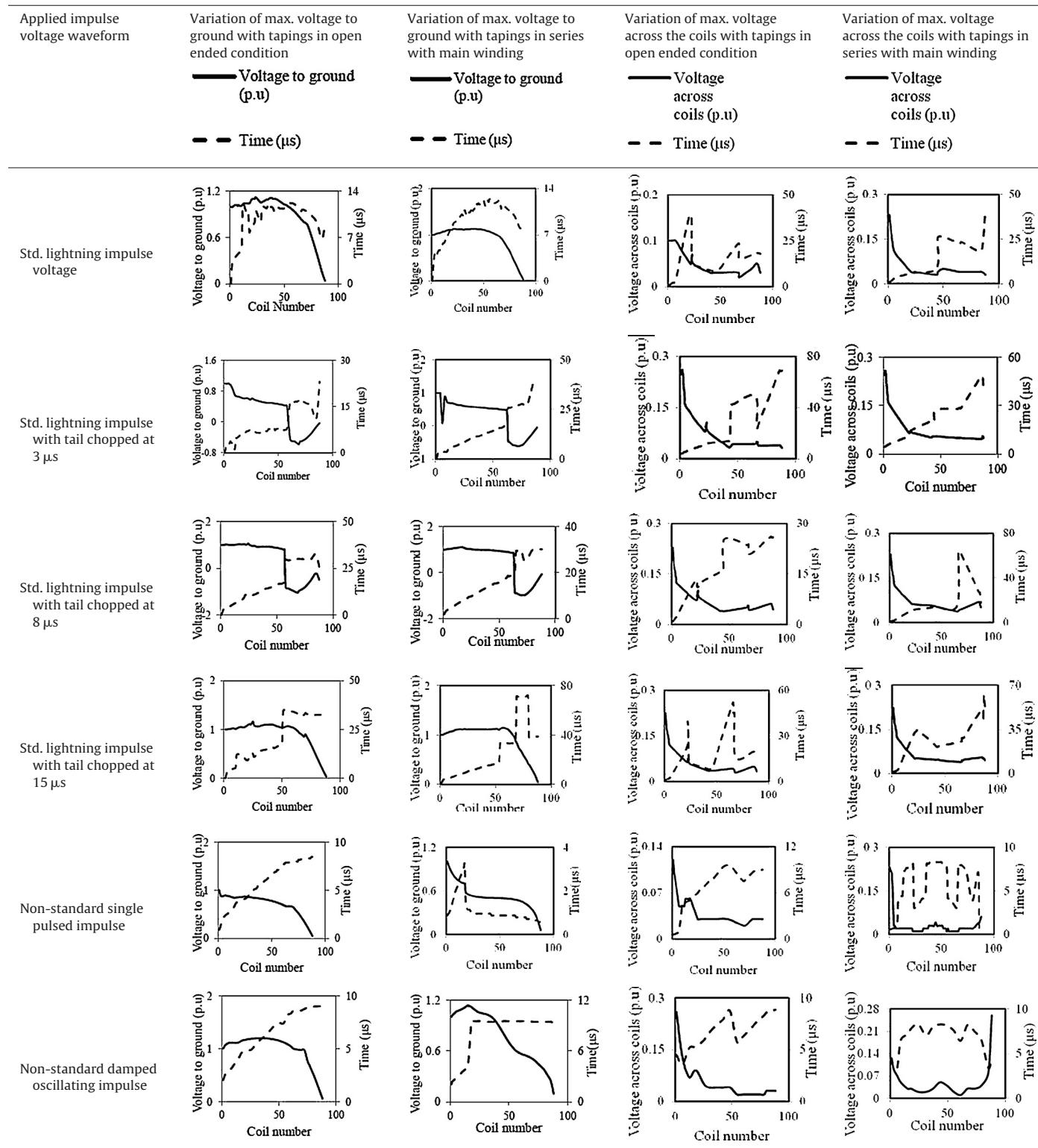
**Table 3**

Comparison of experimental and simulated results.

| Tapping condition | Applied impulse voltage waveshape | Max. voltage to ground (p.u.) Experimental | Max. voltage to ground (p.u.) Simulated | Error (%) |
|--------------------------|--|---|--|-----------|
| Open ended | Standard full lightning impulse voltage | 1.11 | 1.12 | -0.90 |
| Series with main winding | Standard full lightning impulse voltage | 1.14 | 1.12 | 1.75 |
| Open ended | Standard lightning impulse voltage waveform with tail chopped at 3 μs | 1.00 | 1.00 | 0 |
| Series with main winding | Standard lightning impulse voltage waveform with tail chopped at 3 μs | 1.03 | 1.01 | 1.94 |
| Open ended | Standard lightning impulse voltage waveform with tail chopped at 8 μs | 1.09 | 1.06 | 2.75 |
| Series with main winding | Standard lightning impulse voltage waveform with tail chopped at 8 μs | 1.12 | 1.10 | 1.78 |
| Open ended | Standard lightning impulse voltage waveform with tail chopped at 15 μs | 1.16 | 1.15 | 0.86 |
| Series with main winding | Standard lightning impulse voltage waveform with tail chopped at 15 μs | 1.12 | 1.14 | -1.78 |

Table 4

Characteristic curves with tapings in open ended condition and in series with main winding for voltage to ground and voltage across the coils against application of standard and non-standard impulse voltage waveforms.



with steep front and damped oscillating tail develops high voltage between the coils and ground and across the coils. In most of the cases, higher voltage profile is obtained with open ended taping condition than in the case of taping coils in series with main winding. The electric stresses across the line end coils are comparatively much greater as compared to those in other parts of the winding.

For the series stress, the average voltage across the coil is 0.0125 for tapings in open ended condition and 0.011 for tapings in series with main winding. Hence, the maximum voltage across the coil is expressed in terms of linear voltage distribution in Table 6. It is observed that for open ended tapping coils the maximum voltage across the coil varies from 8 to 20.80 times with the change of input

Table 5

Maximum voltage to ground and maximum voltage across the coils with tapings in open ended condition and in series with main winding for voltage to ground and voltage across the coils against the application of standard and non-standard impulse voltage waveforms.

| Applied impulse voltage waveforms | Open ended taping coils | | Taping coils in series with main winding | |
|--|------------------------------|---------------------------------|--|---------------------------------|
| | Max. voltage to ground (p.u) | Max. voltage across coils (p.u) | Max. voltage to ground (p.u) | Max. voltage across coils (p.u) |
| Standard lightning impulse voltage waveform | 1.12 | 0.10 | 1.12 | 0.23 |
| Standard lightning impulse voltage waveform with tail chopped at 3 μs | 1.00 | 0.25 | 1.01 | 0.25 |
| Standard lightning impulse voltage waveform with tail chopped at 8 μs | 1.06 | 0.23 | 1.10 | 0.23 |
| Standard lightning impulse voltage waveform with tail chopped at 15 μs | 1.15 | 0.22 | 1.14 | 0.22 |
| Non-standard single pulsed impulse voltage waveform | 1.00 | 0.12 | 1.00 | 0.23 |
| Non-standard impulse voltage waveform with steep front and damped oscillating tail | 1.19 | 0.26 | 1.13 | 0.26 |

Table 6

Voltage across coils in terms of linear voltage distribution.

| Applied impulse voltage waveforms | Open ended taping coils | Taping coils in series with main winding |
|--|-------------------------|--|
| Standard lightning impulse voltage waveform | 8 | 20.90 |
| Standard lightning impulse voltage waveform with tail chopped at 3 μs | 20 | 22.72 |
| Standard lightning impulse voltage waveform with tail chopped at 8 μs | 18.40 | 20.90 |
| Standard lightning impulse voltage waveform with tail chopped at 15 μs | 17.60 | 20 |
| Non-standard single pulsed impulse voltage waveform | 9.60 | 20.90 |
| Non-standard impulse voltage waveform with steep front and damped oscillating tail | 20.80 | 23.63 |

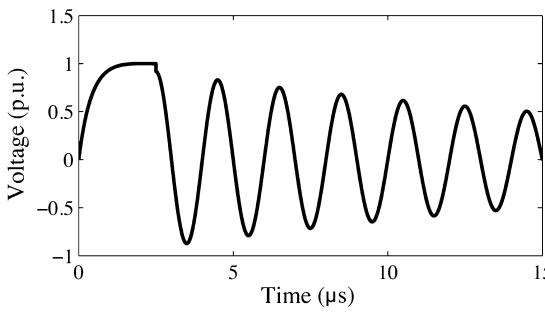


Fig. 6. Damped oscillating impulse voltage waveform.

impulse voltage waveforms whereas the variation is small (from 20 to 23.63 times) for taping coils in series with main winding.

3. Conclusions

The effects of standard and non-standard impulse voltage waveforms on a 3 MVA, 33/11 kV, 3-phase, 50 Hz, Dyn 11 power transformer were investigated in this work. The variation of maximum voltage to ground and voltage across the coils along the transformer winding under standard full lightning impulse voltage waveform, impulse voltages with different chopping times, non-standard, non-oscillating single pulsed wave and non-standard damped oscillating impulse voltage waveforms were studied using an analog and a simulated transformer model. Modeling and simulations are performed using MATLAB Simulink. Test results showed that non-standard impulse voltage waveforms develop high voltage stresses posing highest risk to the equipment's insulation. For open ended tapping coils, the maximum voltage across the coil

is 20.80 times the average voltage across the coil and for taping coils in series with main winding the maximum voltage is 23.63 times the average voltage across the coil. The peak value, steepness, front and tail of wave play a dominant role in determining the insulation performance. However, the obtained results provide the basis for introducing non-standard impulse voltages or make necessary correction in the existing impulse testing standards like the IEC 60076-3(2013), IEEE Std. C57.98 (2011), IEEE Std. 4 (2013), IEC 60060-1(2010), IEC 62475 (2010), etc. after detailed experimental test. In future work, attempts will be made to use ATPDraw to simulate the surge-transferred overvoltages more accurately over a wide frequency range including the effects of high frequency overvoltages produced by the re-strokes and pre-strokes during the opening or closing of a switching device. Also, improvements will be made in the surge model by taking into account terminal impedance characteristic, mutual inductive coupling, bushing, frequency-dependent losses, etc. Additional work will be done to use vector fitting method along with experiments to validate the results.

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