Investigation of a Transferred Voltage Surge Distribution Within a Tertiary Winding of a Power Transformer

M. Trbušić, A. Hamler, K. Lenasi

Abstract-- In the paper, the influence of a transferred surge wave from a high voltage winding to a tertiary winding of a power transformer is investigated numerically. When testing high-voltage winding of the power transformer on the lightning impulse, some voltage is transferred to the non-tested windings While the transformer windings are coupled mutually capacitively and magnetically, the oscillations in the transferred voltage to non-tested windings are to be expected. In the case where non-tested windings are short-circuited and grounded, the maximal amplitude of the oscillations appears in the middle of the winding and drops to zero at the winding ends. To determine a transferred voltage, a transient model of transformers' windings should be used. In this case, an equivalent circuit based on self and mutual capacitive and inductive elements of the windings is employed, where a resistance of the windings is omitted to emphasise the oscillations of the transferred voltage. Omitting windings` resistance leads to higher amplitudes in oscillations, thus, an additional safety margin is achieved when a design of winding insulation is based on computational methods. For the equivalent circuit model of a transformer winding, the system of differential equations of nodal voltages and inductive currents is set and solved numerically by using Octave software. The calculations were performed on a transformer unit similar to the one used in the Slovenian Distribution Network (31,5 MVA -110/21(10,5) kV –Ynyn6+(d5)). Here, the results show approximately a sinusoidal distribution of the amplitudes in self-oscillations along the tertiary winding, which is in good agreement with the analytical predictions based on the oscillation theory.

***Keywords*: transformers, lightning impulse, transients, overvoltages, transferred voltage.**

I. Introduction

When testing the high voltage winding of a power transformer on the lightning impulse, some voltage is transferred to the non-tested windings. The reason should be referred to the capacitive and inductive links that exist among windings [1]-[4]. The most critical is the transfer from the HV to regulation windings, where the amplitude of voltage oscillations reaches as much as 50% of applied lightning impulse peak value. This level of transferred voltage could, in certain cases, cause damage to the winding insulation, which, consequently, leads to the failure of a transformer unit [1][2]. Less critical, but not unimportant when over-voltages within winding are the subject of consideration, is the voltage transfer from the HV to Low Voltage (LV) or Tertiary Winding (TW), which is usually mounted close by the magnetic limb. Especially when the LV winding is of a special design, the influence of transferred voltage to the winding could be fatal for the winding insulation.

The purpose of the paper is to investigate the voltage conditions inside a TW winding when testing HV winding on the Lightning Impulse (LI). Since a TW, as a rule, is not tested on the LI, such calculations could be valuable data in designing the winding insulation.

II. Mathematical Model

A. A mathematical model of the Lightning Impulse wave shape (surge wave)

As was mentioned, the purpose of testing high voltage transformers' windings on the LI is to test the strength of the transformer insulation to withstand overvoltages of external origin [2]. The characteristic of the lightning impulse wave shape is a steep front where the impulse reaches its peak in the range of a few microseconds, and flat tail, where the voltage falls to half of the peak value. In the absence of superimposed oscillations, this fall occurs within a few tens of microseconds (Fig. 1) [1]-[5]. The shape shown in Fig. 1 is an aperiodic surge wave, distinctive for the atmospheric discharges arising commonly in electric power systems. The IEC impulse wave shape is defined by the nominal impulse test voltage U_0, amplitude factor η, front time T_s and time to half value T_r, where T_s and T_r determine the slope of the front and descent of the tail respectively (1)(Fig. 1)[5][6].

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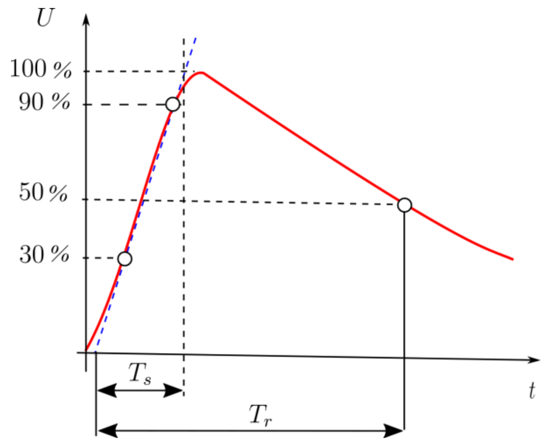

Fig. 1: Standard Lightning Impulse (LI) voltage shape in accordance with IEC 60076-4.

$$u_0(t) = \eta U_0 \left(e^{-s_1 t} - e^{-s_2 t} \right) \qquad (1)$$

Values of the IEC Standard wave 1,2/50 μs parameters with applied tolerances and meaning of labels from (Fig. 1) and (1) are as follow: η is the amplitude factor (1,036), U_0 is the nominal value of the test voltage level, s_1 is the time constant of the tail ($15000\ \mathrm{s}^{-1}$), s_2 is the time constant of the front ($2470000\ \mathrm{s}^{-1}$), T_s is the front time ($T_s = 1{,}2\ \mu\mathrm{s} \pm 30\%$) and T_r is the time to half value ($T_r = 50\ \mu\mathrm{s} \pm 20\%$).

B. A transient model of a transformer

In the case study, a transient model of a three-phase power transformer unit 31,5 MVA - 110/21/(10,5) kV YNyn6+(d5), similar to the one used commonly/regularly in the Slovenian Distribution Network, has been adopted in the calculations. The windings\` arrangement in the transformer window is shown in Fig. 2, where the voltage regulation on the HV side is in the range of +/- 16 % (8×+/-2%), and consists of the coarse-fine type, where GR and FR stand for the coarse-step and fine-step windings respectively. The label u_{01} in Fig. 2 indicates free voltage oscillations of a tertiary winding with respect to ground, which, in general, is a spatial-time function $u_{01} = u_{01}(x,t)$ [1].

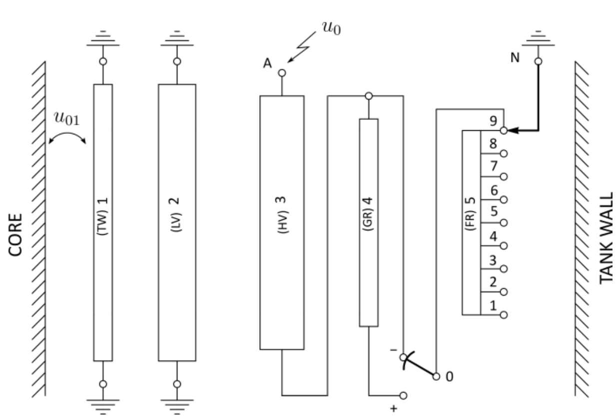

Fig. 2: Winding arrangement of the 31,5 MVA-110/21(10,5) kV - YNyn6+(d5) transformer unit.

For our purpose, the transformer windings could be represented as a complicated capacitance-inductance system with a very thigh magnetic linkage between the individual turns. Practical and accurate implementation of the model requires a division of windings into sections which should be interconnected capacitively and inductively in the proper way (Fig. 3) [2][7]-[10]. For convenience, the markings referring to mutual inductances are given only for the tertiary winding, and the same applies to other windings. In the model, determination of series capacitances of winding sections (capacitances between turns, discs, and layers), as well as shunt capacitances between sections of neighboring windings and earthed parts (core, tank), is based on the analytical expressions.

Much more effort should be enforced in calculations of inductances for which a special computer program has been developed which is able to compute self and mutual inductances of cylindrical coils in any desired mutual configuration [11][12].

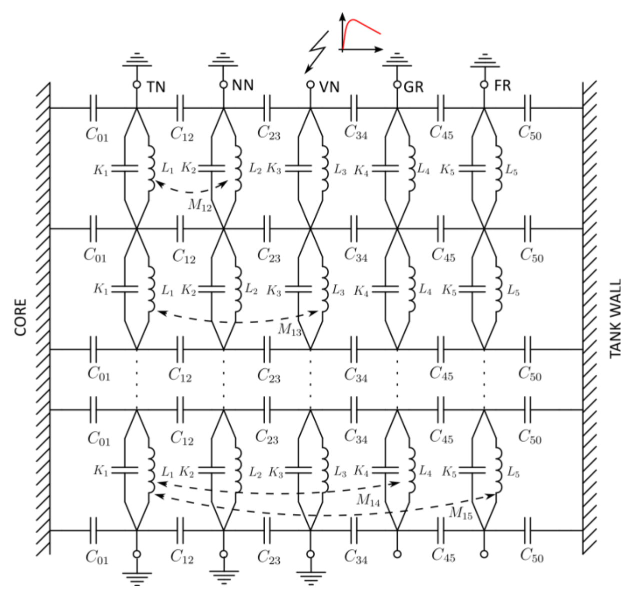

Fig. 3: The transient model of transformer windings represented by the equivalent electric circuit.

For the equivalent circuit of transformer winding, the system of differential equations of nodal voltages $u(t)$ and inductive currents $i(t)$ is set (2) and solved numerically by using Octave software [8][9][10]. In the system (2) C and L stand for the capacitive and inductive matrices, respectively, D is an incidence matrix, E is the vector of capacitive connections between the stroked node and other nodes, F represents a vector defining the node to which the impulse voltage u_0 is applied.

The resistance of the windings is omitted to emphasize the oscillations of the transferred voltage. From the practical point of view, omitting windings\` resistance leads to higher amplitudes in oscillations, thus, an additional safety margin is achieved when the design of a winding insulation is based on computational methods . This is especially favorable, because computed values of inductances and capacitance could deviate from its real ones up to 30% [8].

$$\begin{bmatrix} \frac{du}{dt} \\ \frac{di}{dt} \end{bmatrix} = \begin{bmatrix} 0 & C^{-1}D \\ -L^{-1}D^{T} & 0 \end{bmatrix} \begin{bmatrix} u \\ i \end{bmatrix} + \begin{bmatrix} C^{-1}E\,\frac{du_0}{dt} \\ L^{-1}F\,u_0 \end{bmatrix} \quad (2)$$

The solution to system (2) along with the initial and boundary conditions, gives a time response of inductive currents $i(t)$ and nodal voltages $u(t)$ respectively; here, the latter are of particular interest in the investigation of a surge voltage transfer between transformer's windings.

From the theoretical point of view, transfer of the lightning impulse from the tested to non-tested windings is a boundary value problem, where the connection of the windings end terminals, which could be earthed or non-earthed (free), plays the key role in the spatial distribution of the transferred voltage along the windings [1][2]. During the LI test performed on the HV winding, the windings not connected directly to the tested winding are short-circuited and earthed, here the neutral point of the HV winding is earthed as well (Fig. 2). Considering the aforementioned stipulations, the Dirichlet type of boundary conditions could be imposed on the TW winding, where the potential value at the earthed windings` ends would be known. In practice, earthed parts of a transformer are presumed to be bound to the reference potential value of zero volts. On the basis of the oscillation theory, the spatial distribution of free voltage oscillations` peaks along the TW is expected to obey the sine law approximately (3) (Fig. 4). Here, U_{01} and b_g stand for the maximal voltage to earth and the height of the TW respectively [1][2][13]. It is worthwhile to mention that a TW is often designed as a single-layer winding; this is possible because, as a rule, only one-third of the transformer rated power is required for the TW.

$$u_{m01}(x) = U_{01}\sin\left(\frac{\pi x}{b_g}\right) \quad (3)$$

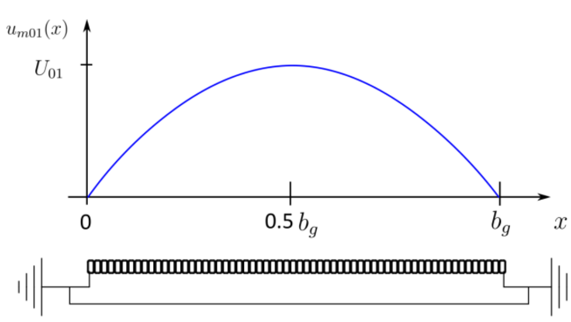

Fig. 4: Spatial distribution of free oscillations' amplitude values along the short-circuited and earthed single layer winding.

III. Results

The simulations of the transferred surge voltage from the HV to the TW winding have been performed on a transient single phase model pertaining to the 31,5 MVA 110/21/(10,5) kV-YNyn6+(d5) transformer unit using the Octave software [15]. The winding end terminals, as well as the tap selector position, were connected so as to meet a case of the most unfavorable test condition, where the "upper" end of the regulation windings is connected to the "lower", earthed end of the HV winding, as is shown in Fig. 2. Here, the highest amplitude of a transferred surge is expected due to the highest turn ratio between the TW and HV winding [1][2]. The standard 1,2/50 µs (1) lightning impulse wave-shape with a peak of $U_0 = 550$ kV, regularly enforced in testing a 110 kV insulation level of transformer windings, has been applied in the simulations [5][6].

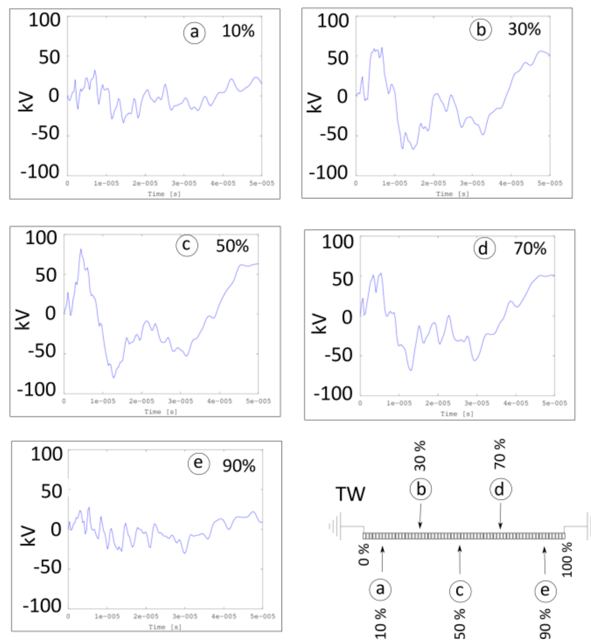

Fig. 5: Time responses of free voltage oscillations along the TW winding $u_{01}(t)$, based on calculated values. Here, the time frame in an individual oscillogram corresponds to 50 µs.

Simulations of free voltage oscillations along the TW winding that appear when the standard LI is applied to the phase terminal of HV winding are shown in Fig. 5. From the time response of the transferred surge, it could be noted that the amplitudes of the fundamental free oscillation increase by approaching the midpoint of the winding [9][14]. This is somehow in accordance with the oscillation theory, where an earthed winding is expected to oscillate in spatial half-waves around the reference potential level and, thus, represents a standing wave, as is shown in Fig. 6. In the case study, the maximal transferred voltage from the HV to the TW winding is about $U_{01} \approx$ 80 kV, relative to the applied LI peak value this is $\frac{U_{01}}{U_0} \approx$ 0,15 which is close to the turn ratio between the TW and HV winding. At this point, it is somehow important to point out the influence of the sense in which the windings are wound to the phase of the transferred surge free oscillations. Namely, if both windings are wound in the same direction, then the transferred surge will start to oscillate in the opposite directions of the one imposed by the impact impulse; the contrary situation appears when windings are wound in the same direction. Considering a sense in which a non-tested winding is wound is especially important in the case where the LV winding consists of two oppositely wound layers, here a rather hazardous overvoltage could occur between the midpoints of the layers.

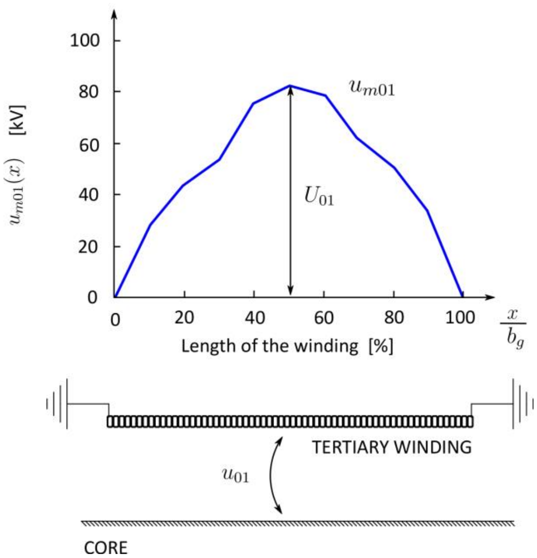

Fig. 6: Calculated values of free voltages` oscillations peaks $u_{m01}(x)$ distribution along the TW winding.

IV. Conclusions

The numerical investigation of transferred voltage surge has shown that amplitudes of free oscillations in the TW winding transferred by the LI from the HV side are distributed spatially approximately in a half sine wave along the winding. In the study case, the ratio between the maximal transferred voltage value and the peak value of applied impulse is in the range of the highest turn ratio between the two windings $\frac{U_{01}}{U_0} \approx \frac{N_{TW}}{N_{HV}}$, here N_{TW} and N_{HV} are the number of turns in the TW and HV winding, respectively. It should be beared in mind that the transferred voltage, in general, depends on the winding type, turn ratio and its arrangement with respect to the tested winding, thus, the transferred voltage should not be estimated solely on the turn ratio basis.

Despite the fact that a tertiary winding is rarely tested on the LI, it is still exposed to the effect of overvoltages transferred from another winding. Maximal voltage gradients of the transferred surge which affect the inter-turn insulation are expected to appear at the winding's ends, and do not pose a threat to the TW winding insulation, due mainly to technological reasons, where a number of paper layers consisting of an inter-turn insulation of a single-layer TW winding is, in general, much higher than the minimum required to withstand the dielectric stresses.

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