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¹Computation of internal voltage distribution in transformer windings by utilizing a voltage distribution factor

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***Abstract--*In this paper, a method for the application of the black-box transformer models to the lumped-parameter transformer winding models is presented. The methodology is based on applying terminal transformer voltages as input parameters that could be provided by using the powerful black box vector fitting. Then, internal voltage distribution is determined by applying a lumped-parameter model approximation. In particular, the paper is focused on the direct computation of the internal voltage distribution, by avoiding a complicated procedure of solving the lumped-parameter winding model. The method is based on the transformation matrix utilization of the voltage distribution factors. This transformation matrix reflects the voltage distribution at specific internal points along the winding with respect to the input terminal voltages. At this stage, the inputs for the lumped-parameters model are provided by measured voltages at transformer terminals and the**

transformation matrix is determined through geometrical data of the transformer. The implementation of the proposed method with the black-box modeling approach in existing simulation software tools like EMTP is under development. The method is verified by comparing measured with computed waveforms.

***Keywords:* Lumped-parameters model, overvoltages, internal voltage distribution, transformer, transients, modelling**

I. INTRODUCTION

TRANSIENT overvoltages may occur as a consequence of the high-frequency interaction between the system and the transformer [1]-[6]. From the activities of Cigre Joint Working Group (A2/C4.39) has been concluded that when the natural frequency of a surge impulse matches the natural frequency of the system in which the transformer participates, a resonance in the system occurs [3], [4], [7]-[21]. Furthermore, when input surge impulses at transformer terminals cause internal transformer resonances, extreme overvoltages and finally insulation failures may occur [1], [14], [15].

Generally, three types of transformer models are distinguished for switching transient events. Transmission line models [22]-[28] are considered as an approach for very fast transients and voltage propagation studies [26]. They require very detailed design information of the transformer and they are time consuming. In addition, they cannot directly be implemented into electromagnetic transient software. The lumped-parameter models are used for the simulation of lightning impulses [29]-[35] and switching fast transients [14], [36]-[38]. These models can be used to study the interaction of the transformer with the surround network as well as to evaluate the internal voltage distribution [14], [39]. They can be implemented in electromagnetic transient software package [37]-[39] and are based on transformer geometrical data. The black box models are based on frequency admittance matrix measurement from any provided measuring point on the transformer winding [10]-[12], [16]-[21], [41]. These models are used to analyze the transformer interaction with the system and to study transferred overvoltages between terminals. In addition, they can be combined to existing simulation software tools like EMTP [16, 21] but

however, they cannot determine the voltage propagation along the windings.

From the above, it is obvious that a reliable model for wide band terminal and internal switching transient overvoltage studies, which does not require accurate and detailed geometrical data, has not been established so far. At this point, the idea to combine black box transformer models, already implemented into EMTP-based software, to suitable lumped-parameter winding models for internal voltage distribution studies seems to be attractive [42], [43]. The terminal voltages computed from a black box model are used as inputs for the lumped-parameter model. That combination overcomes the disadvantage for a unified model suitable for terminal and internal transient overvoltage studies. Nevertheless, the drawback for detailed geometrical data remains. Moreover, the computation time could be significant because in the first step, the solution of the black-box model provides terminal currents and voltages and in the next step, the solution of the lumped-parameters model provides internal voltages. In order to overcome these disadvantages, on one hand, a method for direct internal voltage distribution computation needs to be established. On the other hand, that method has to be based on parameters that can be determined not only from geometrical data but also could be measured or calculated from several alternative methodologies.

In this paper, a method for direct computation, by avoiding digital solution of the lumped-parameter winding model, of the internal voltage distribution is developed for given terminal transformer voltages. Furthermore, the method is based on the direct transformation of the terminal input voltages to internal voltage distribution by utilizing a transformation matrix that we will call a matrix of voltage distribution factors. The method is verified by laboratory measurements performed on a three-phase distribution transformer.

II. METHODOLOGY

The final equivalent electrical circuit of a transformer winding is derived with respect to winding geometry [15]. The final circuit is constructed as a connection of lumped-parameter blocks as shown in Fig. 1. The typical equivalent circuit block for internal voltage computations.

Each block represents a segment of the winding. The segment could be one turn or a group of turns of the winding. The values of the lumped parameters of the blocks are computed by suitable methods as those given in [40]. For the equivalent circuit in Fig. 1, L_{si} , C_{si} and R_{si} , Y_{si} are the self-inductance, series capacitance and the associated series resistance and conductance as well as C_{shi} and Y_{shi} are the associated shunt capacitance and conductance to "reference" of the i^{th} block. For simplicity, the mutual inductive components are not shown in the figure. Usually, in order to avoid matrices of extremely large dimensions and long computation times, one segment corresponds to a number of winding's coils.

By making use of the amplification factor [29], one can write that the amplification factor $N_{tm,k}$ from an external node " t " to a particular internal node " m " with respect to the node " k " at which an input is applied is determined by

$$N_{m,k} = \frac{e_{t,k} - e_{m,k}}{e_{k,k}} \quad (1)$$

where e represents the node-to-reference voltage in frequency domain. In view of Fig. 1, $t=1$ or $t=n$, $m=1, \dots, n$ and k is an integer between 1 to n . The amplification factor $N_{tm,k}$ depends on the winding structure and it can be computed in terms of the impedance matrix of the equivalent circuit in the Fig. 1. In this way and by the presumption that the input voltage is known and applied on winding terminals, the internal node voltage $e_{m,k}$ can be computed by

$$e_{m,k} = e_{t,k} - N_{m,k} e_{k,k} \quad (2).$$

The method is developed for a delta-wye transformer and is validated by measurements. At the delta side, terminal and internal voltage measurements have been recorded during three-phase switching operation of the transformer through a vacuum circuit breaker (VCB). Because of the delta connection, a primary winding is excited by two impulses, each impulse at different phase terminal; for the input voltage at terminal "1" $t=1$, $m=1, \dots, n$ and $k=1$, and for the input voltage at terminal "n" $t=n$, $m=1, \dots, n$ and $k=n$.

Applying nodal analysis when the input is placed at terminal $t=1$

$$[e_{m,1}] = [Z_{ij}] [i_{m,1}] \quad (3)$$

where $[e_{m,1}] = [e_{1,1} \ e_{2,1} \ \dots \ e_{n,1}]^T$ the $n \times 1$ vector of the node voltages when the input is at terminal 1, $[Z_{ij}]$ with $i=1, \dots, n$ and $j=1, \dots, n$ is the $n \times n$ impedance matrix of the equivalent circuit in Fig. 1 and $[i_{m,1}] = [i_1 \ 0 \ \dots \ 0]^T$

$n \times 1$ is the vector of the source currents. By combining (1) and (3) one can easily derive the relation for the amplification factor in respect to the input at terminal "1" as

$$N_{1m,1} = 1 - \frac{Z_{m1}}{Z_{11}} \quad (4).$$

In the same way, the input is placed at terminal $t=n$

$$[e_{m,n}] = [Z_{ij}] [i_{m,n}] \quad (5)$$

where $[e_{m,n}] = [e_{1,n} \ e_{2,n} \ \dots \ e_{n,n}]^T$ is the $n \times 1$ vector of the node voltages when the input is at terminal n , $[Z_{ij}]$

with $i=1, \dots, n$ and $j=1, \dots, n$ is the $n \times n$ impedance matrix of the equivalent circuit in Fig. 1 and

$[i_{m,n}] = [i_n \ 0 \ \dots \ 0]^T$ $n \times 1$ the vector of the source currents.

The combination of (1) and (5) results in an amplification factor with respect to the input at terminal "n" as

$$N_{nm,n} = 1 - \frac{Z_{mn}}{Z_{nn}} \quad (6).$$

The node voltages of the delta connected winding can be expressed by superposition

$$[e_m] = [e_{m,1}] + [e_{m,n}] \quad (7)$$

By substituting (2) into (7) for the pair $t=1$ and $k=1$ as well as for the pair $t=n$ and $k=n$,

$$[e_m] = \begin{bmatrix} 1 - N_{11,1} \\ 1 - N_{12,1} \\ \vdots \\ 1 - N_{1n-1,1} \\ 1 - N_{1n,1} \end{bmatrix} e_{1,1} + \begin{bmatrix} 1 - N_{n1,n} \\ 1 - N_{n2,n} \\ \vdots \\ 1 - N_{nn-1,n} \\ 1 - N_{nn,n} \end{bmatrix} e_{n,n} \quad (8)$$

For the application of (8), the amplification terms are computed by (4) and (6). Since $e_{1,1}$ and $e_{n,n}$ are the voltages when only terminal 1 and terminal n are excited respectively, they need to be determined. They can be computed by the 2×2 system of equations consisting of the first and the last row in (8) for which e_1 and e_n are known in the frequency domain. The solution in matrix form is

$$\begin{bmatrix} e_{1,1} \\ e_{n,n} \end{bmatrix} = \begin{bmatrix} c_{11} & c_{1n} \\ c_{n1} & c_{nn} \end{bmatrix} \begin{bmatrix} e_1 \\ e_n \end{bmatrix} \quad (9)$$

where e_1 and e_n are the values of the measured voltages at transformer terminals. The values of c -parameters in (9) result from the matrix inversion consisting of the first and last vector elements in (8).

By using (9) in (8), the internal node voltages are given by

$$[e_m] = [T_{m,1} \ T_{m,14}] \begin{bmatrix} e_1 \\ e_n \end{bmatrix} \quad (10)$$

for $m=2, \dots, n-1$ and

$$[T_{m,1} \ T_{m,14}] = \left[\begin{array}{c} \left[\begin{array}{c} 1-N_{12,1} \\ 1-N_{13,1} \\ \vdots \\ 1-N_{1n-2,1} \\ 1-N_{1n-1,1} \end{array} \right] \\ \left[\begin{array}{c} 1-N_{n2,n} \\ 1-N_{n3,n} \\ \vdots \\ 1-N_{nm-2,n} \\ 1-N_{nm-1,n} \end{array} \right] \end{array} \right] [c_{11} \ c_{1n}] [c_{n1} \ c_{nm}] \quad (11)$$

The $(n-2) \times 2$ transformation matrix $[T_{m,1} \ T_{m,14}]$ expresses the voltage distribution at specific internal $n-2$ points along the winding in respect of the two input voltages e_1 and e_n and may be called as matrix of voltage distribution factors. The elements of the transformation matrix are frequency depended and can be computed through the elements of the $n \times n$ impedance matrix of the equivalent circuit that is used for the winding representation. This is a general representation of a transformer winding by applying voltages at remote terminals. In case when the receiving end is grounded, the equation can be simplified since the matrix $[e_{m,n}]$ in [7] can be omitted. Equation (8) will consists of only the first vector multiplied by the excitation $e_{1,1}$. First row and the last row can be omitted since $e_{1,1}$ is equal to the voltage supply and the last node is at potential zero.

APPLICATION AND RESULTS

The proposed method of internal voltage distribution is applied in case of switching events for a GEAFOL cast-resin foil-winding transformer. The complete measurement setup consists of a feeder bus, a vacuum circuit breaker (VCB), a cable, a test transformer and a load. Switch-on and switch-off operations of the VCB have been performed and measured voltage waveforms have been recorded.

A. Description of the test transformer

The measurements have been conducted for a three-phase, 3.75MVA, 36.59/0.65 kV, delta-wye, core-type transformer. The windings at the primary side consist of 13 coils and each coil has approximately 90 foil-type turns. Apart of the terminal measuring points at both HV and LV sides, each primary winding is equipped by a special measuring point at the 90th turn. The most important geometrical parameters of the

transformer are summarized in Table I. In view of Fig. 1, the 13 coils compose an equivalent circuit of $n=14$ nodes where nodes "1" and "14" are the terminal input nodes and the parameter $m=2,\dots,12$.

TABLE I
TRANSFORMER DATA

B. Computation of the matrix of voltage distribution factors

The computation of the voltage distribution factors' matrix is accomplished through successful computation of the impedance matrix of the equivalent circuit in Fig. 1. According to [14], a valid approximation for the computation of the impedance matrix is

$$[Z_{ij}] = ([B_{ij}] + [\Gamma_{ij}])^{-1} \quad (12)$$

The matrices $[B_{ij}]$ and $[\Gamma_{ij}]$ are given by

$$[B_{ij}] = (\omega \tan \delta + j\omega)[C_{ij}] \quad (13)$$

$$[\Gamma_{ij}] = [k_{ij}] \left\{ \left(\sqrt{2\omega/\sigma\mu_0 d^2} + j\omega \right) [L_{ij}] \right\}^{-1} [k_{ij}]^T \quad (14)$$

where ω is the angular frequency, $\tan\delta$ is the loss tangent of the insulation dielectric losses factor, $[C_{ij}]$ is the nodal capacitances matrix, $[k_{ij}]$ is Kron's invariant transformation matrix [29]. $[L_{ij}]$ is the inductances matrix in which core effects are included, d is the distance between the turns of the same coil, σ is the conductor conductivity and μ_0 is the magnetic permeability in vacuum. The computation of the nodal capacitance matrix and the inductance matrix is based on [15].

A dedicated code has been written in Matlab for the computations. The vector of angular frequencies is constructed that contains angular frequencies values up to 1 MHz with angular frequency step 100 Hz. For each one value of that vector, the impedance matrix $[Z_{ij}]$ is computed using (12) for a high voltage (HV) winding of the transformer.

In the following step, the amplification factors $N_{1m,1}$ and $N_{14m,14}$ are computed using (4) and (6) and the

results are shown in Fig. 2.

Fig. 2. The amplification factors in respect to: (a) terminal "1" and (b) terminal "14".

The symmetrical construction of the winding leads to symmetrical impedance matrix and consequently symmetrical amplification factors with respect to the input terminals of the winding. Next, the elements of the 12x2 voltage distribution factors matrix are computed using (11) and the results are shown in Fig. 3.

Fig. 3. The voltage distribution factors in respect to: (a) input voltage at terminal "1" and (b) input voltage at terminal "14".

The same symmetry is observed for the voltage distribution factors as it was expected from the symmetry of the amplification factors.

C. Internal voltage distribution computation

Voltage measurements were recorded during three-phase closing and opening operations of a VCB connected to the loaded test transformer through a cable. A description of the test circuit is illustrated in Figure 4.

Figure 4. An illustration of the measuring setup.

Voltages are measured with a sampling rate of 10MS/s at the transformer HV terminals and some measuring point installed at windings. The test are performed with a voltage about 70% the nominal voltage in order to avoid possible flashover that may occur during prestrike/restrike effect.

Since the windings are connected in delta, the voltage of the last turn of a winding corresponds to the voltage of the first turn of the following winding. The winding inputs are the measured time domain waveforms at the winding terminals. Since the method computes the voltages in frequency domain, firstly the measured time domain input terminal waveforms must be transformed to frequency domain in order to

define the vector of the angular frequencies for the computations. For verification, in order to be sure that the inverse Fourier transform is correctly performed, the measured and computed time domain waveforms at the winding terminals must have perfect matching. When the correct vector of the angular frequencies has been determined, the matrix of voltage distribution factors is computed and finally the internal voltages are also computed by using (10).

In the case of closing operation of the VCB, the co-instantaneously measured waveforms and computed responses are presented in Fig. 5. In Fig. 5(a), the excellent matching between the measured and the computed waveforms at the winding terminals validates the correct performance of the Fourier transform. In Fig. 5(b), the internal voltage waveforms at the 90th turns for each one of the three windings are presented and the agreement with the measured values is very good. In particular, the computed rate of rise is in good agreement with the measured rate of rise. However, slight differences at the peak values for the winding between phases C and A are due to the electromagnetic compatibility issues because of the adjacency of many measuring wires. Moreover, differences between computed and measured values are due to that all measuring points cannot be reached directly onto the turn. A connection between the turn and the outside taps exists which is not reflected into the equivalent circuit in Fig. 1.

For opening operation of the VCB, the co-instantaneously measured waveforms and computed responses are presented in Fig. 6. In Fig. 6(a), the computed waveforms at the winding terminals validate the correct performance of the Fourier's transformations. In Fig. 6(b), the very good matching between the measured and the computed waveforms at the 90th turns for each one of the three windings validates the correct performance of the proposed method. Moreover, the computed rate of rise has good agreement with the measured rate of rise.

Fig. 5. Measured and computed voltages for closing operation of the VCB at the three windings at the phases A, B and C at: (a) terminals of the windings and (b) 90th turns in the windings.

Fig. 6. Measured and computed voltages for opening operation of the VCB at the three windings at the phases A, B and C at: (a) terminals of the windings and (b) 90th turns in the windings.

III. CONCLUSIONS

The combination of black box transformer models to suitable lumped-parameters winding models provide grounds for the development of a unified model for terminal and internal voltage distribution studies. The terminal voltages computed from the black box model are inserted as inputs for the lumped-parameter model. However, the successful combination demands fast and direct voltage computations, especially after the computation of the input terminal voltages, as well as the avoidance of parameters determination from geometrical transformer data.

In this paper, a method for direct computation of the internal voltage distribution is presented by establishing the matrix of voltage distribution factors. This transformation matrix is invariant, its elements are frequency depended and reflects the internal properties and geometrical structure of the transformer winding. The application of the matrix of voltage distribution factors on the vector of the input terminal voltages derives the vector of internal voltages. The comparison of measured with the computed waveforms verifies that the high accuracy of the applied method for analyzing internal transient voltages during VCB transformer switching. The difference between the measured and the computed voltages results mainly because of the frequency dependent and proximity losses that at high frequencies is difficult to be estimated.

In the presented analysis, the method is developed for delta-wye connections of the transformer windings and the determination of the matrix of voltage distribution factors is based on geometrical data. This work opens new horizons in terms of:

- the methodology can be applied for any kind of winding connections for which the impedance matrix is known since the methodology depends on the impedance matrix (it can be also applied for autotransformers or phase shift transformers),
- several options should be established for the determination of the transformation matrix using geometrical data,
- measurements or both options and

- more work should be done in order to make this approach possible for implementation in an electromagnetic transient program environment.

The complete unification of the black-box and lumped-parameter modeling is still under investigation and improvements are going to be presented in future work.

IV. ACKNOWLEDGEMENT

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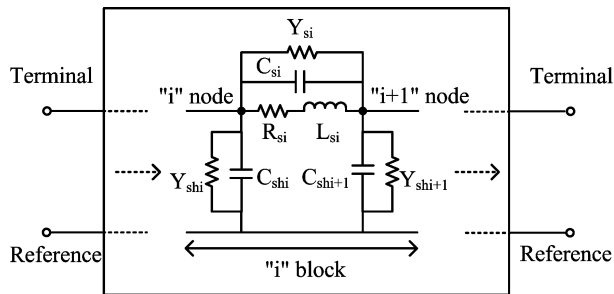
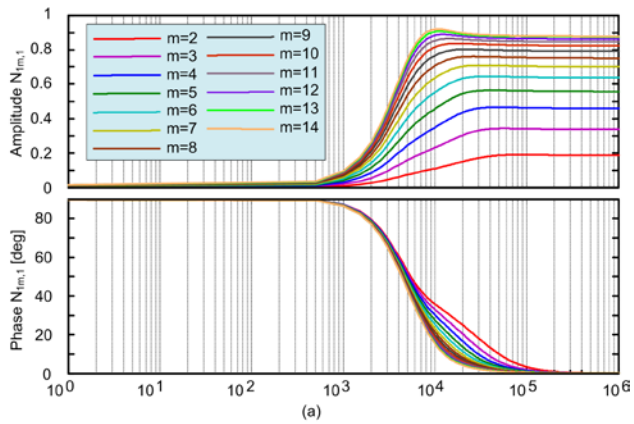
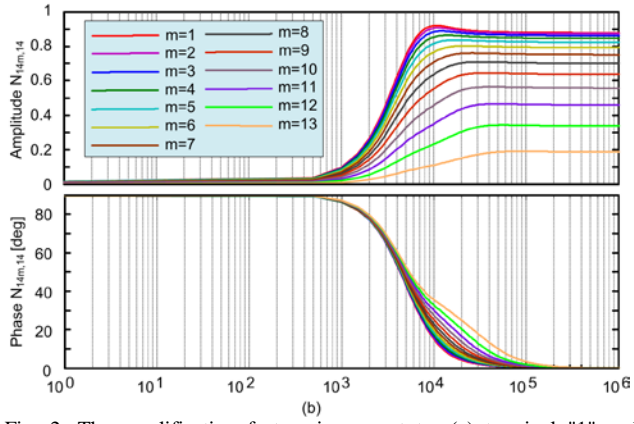


Fig. 1. The typical equivalent circuit block for internal voltage computations.



(a)



(b)

Fig. 2. The amplification factors in respect to: (a) terminal "1" and (b) terminal "14".

TABLE I
TRANSFORMER DATA

	LV	HV
Turns sum	12	1170
Coils	1	13
Turns per coil	12	90
Inner diameter [mm]	376	655
Outer diameter [mm]	450	751
Strip [mm]	1.600x1200	0.400x71

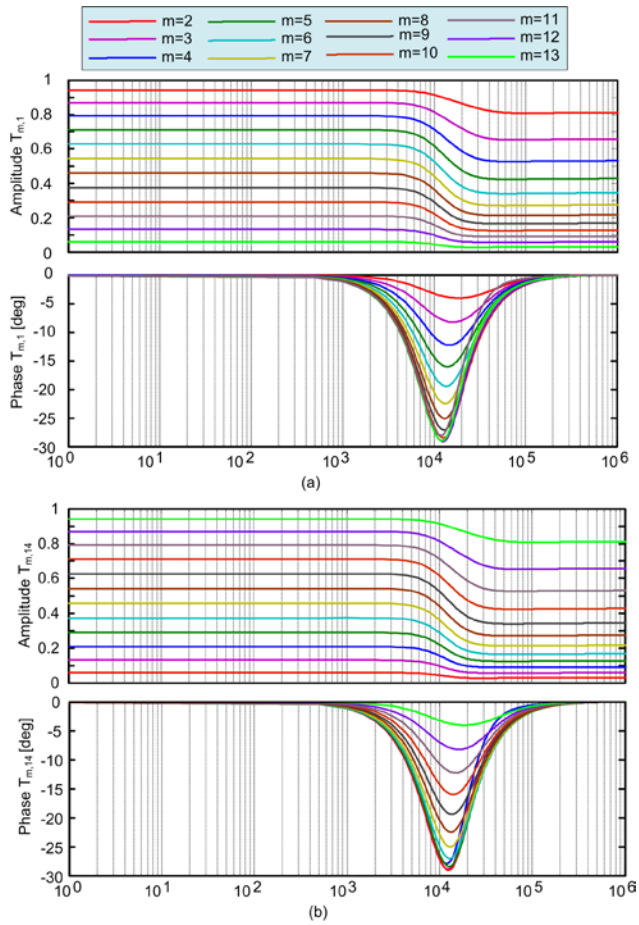


Fig. 3. The voltage distribution factors in respect to: (a) input voltage at terminal "1" and (b) input voltage at terminal "14".

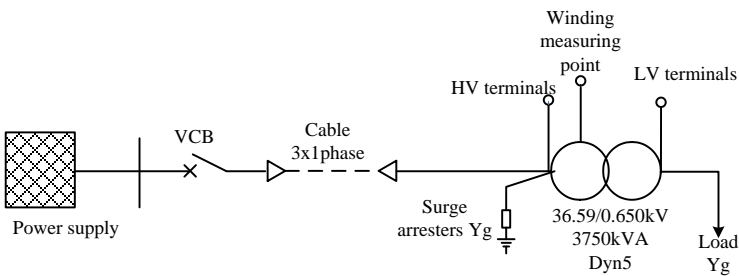


Figure 4. An illustration of the measuring setup.

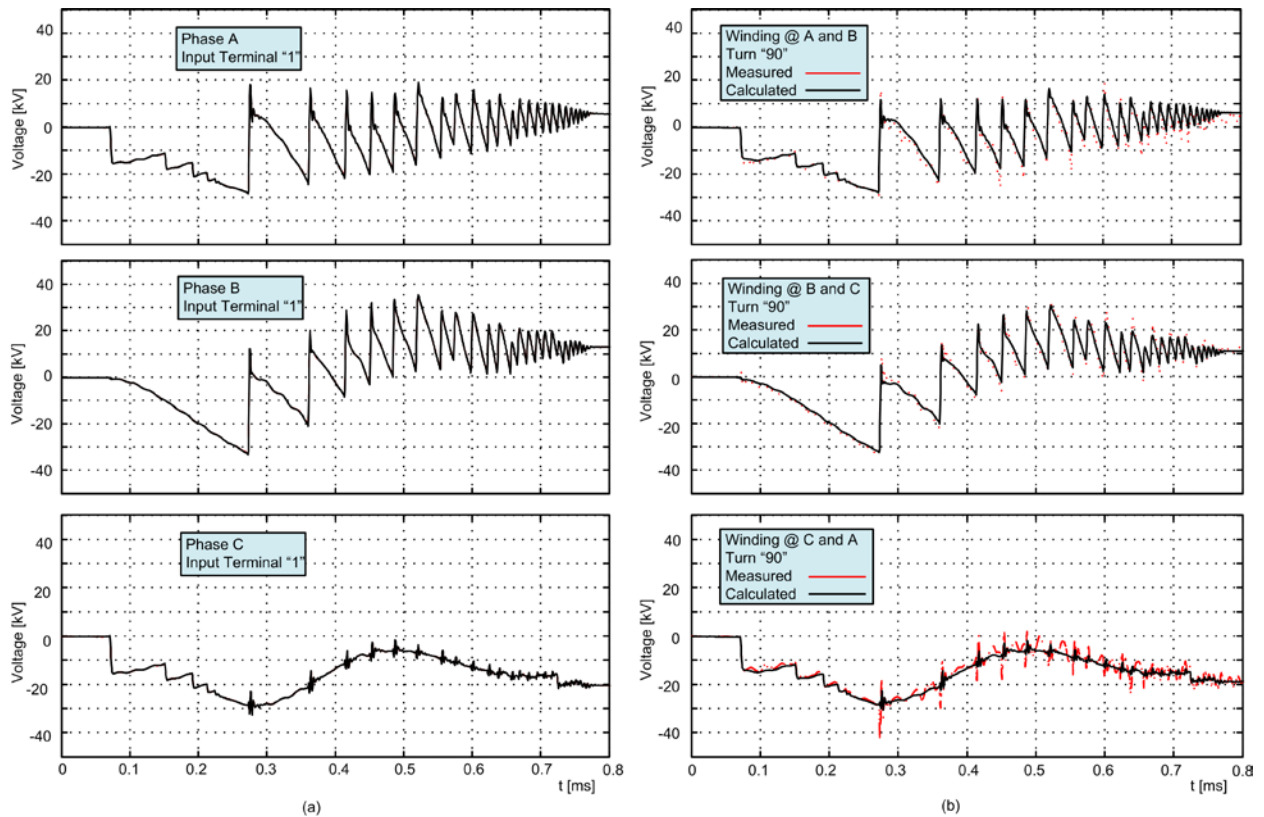


Fig. 5. Measured and computed voltages for closing operation of the VCB at the three windings at the phases A, B and C at: (a) terminals of the windings and (b) 90ths turns in the windings.

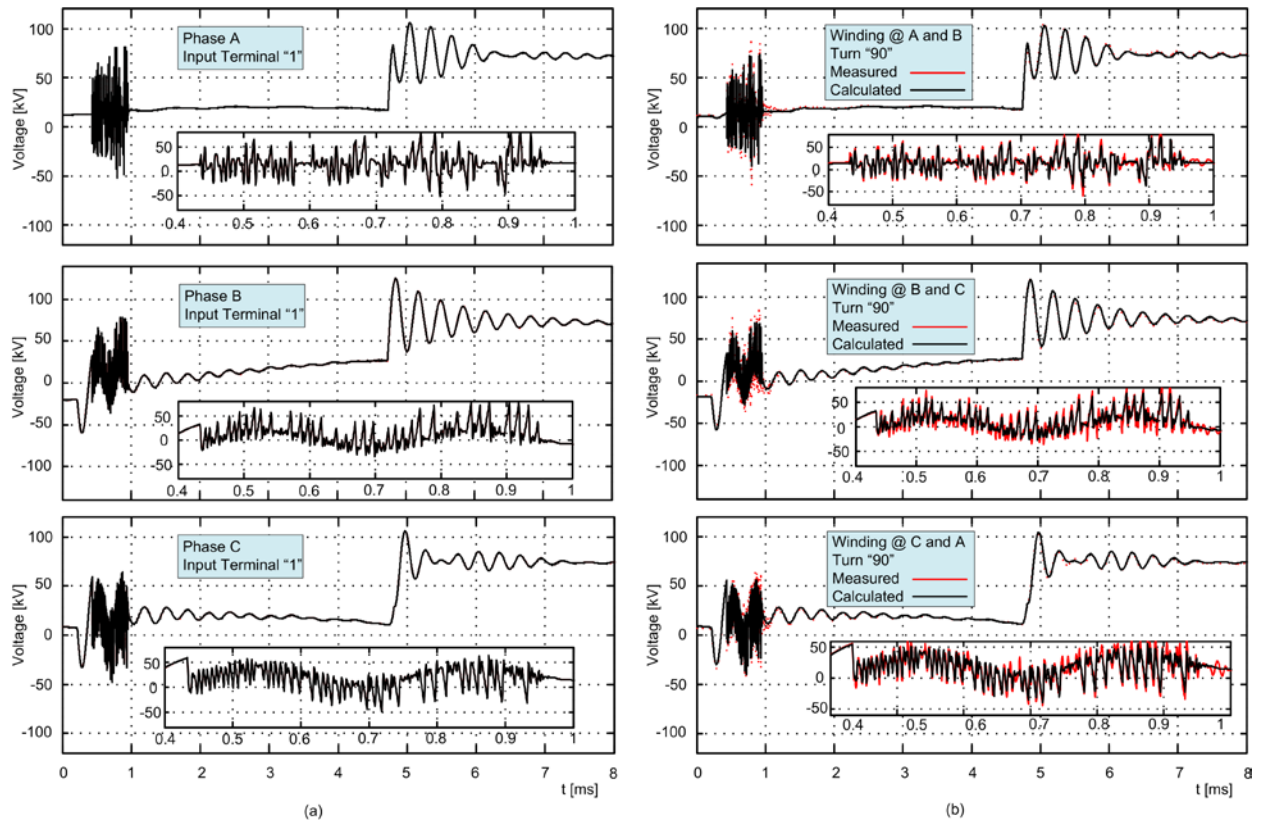


Fig. 6. Measured and computed voltages for opening operation of the VCB at the three windings at the phases A, B and C at: (a) terminals of the windings and (b) 90ths turns in the windings.

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