Electric Power Systems Research 138 (2016) 11–17

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

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

Andreas Theocharis[a], Marjan Popov[b,*], Vladimir Terzija[c]

[a] Higher Colleges of Technology, Faculty-ETS, Nahyan the 1st Street, Shab Al Ashkar, PO Box 17155, Al Ain, United Arab Emirates
[b] Delft University of Technology, Faculty of EEMCS, Mekelweg 4, 2628CD Delft, The Netherlands
[c] The University of Manchester, School of Electrical and Electronic Engineering, M13 9PL Manchester, UK

ARTICLE INFO

Article history:
Available online 20 January 2016

Keywords:
Lumped-parameters model
Overvoltages
Internal voltage distribution
Transformer
Transients
Modeling

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.

1. 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

☆ Paper submitted to the International Conference on Power Systems Transients (IPST2015) in Cavtat, Croatia June 15–18, 2015.

* Corresponding author. Tel.: +31 15 278 6219; fax: +31 15 278 1182.
E-mail addresses: atheocharis@hct.ac.ae, theoxar@ece.upatras.gr (A. Theocharis), M.Popov@ieee.org (M. Popov), vladimir.terzija@manchester.ac.uk (V. Terzija).

http://dx.doi.org/10.1016/j.epsr.2016.01.001

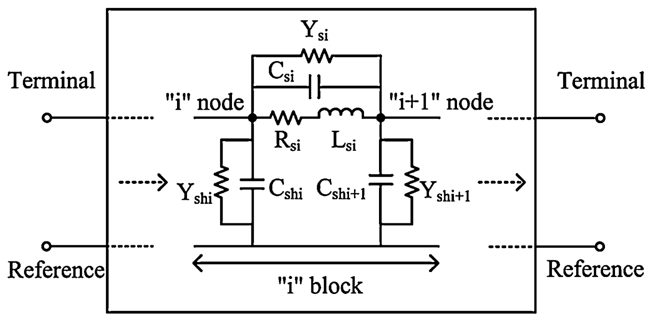

Fig. 1. The typical equivalent circuit block for internal voltage computations.

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.

2. 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

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 ith 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

$$N_{tm,k} = \frac{e_{t,k} - e_{m,k}}{e_{k,k}} \tag{1}$$

where e represents the node-to-reference voltage in frequency domain. In view of Fig. 1, $t = 1$ or $t = n$, $m = 1, \ldots, n$ 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 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

$$e_{m,k} = e_{t,k} - N_{tm,k} e_{k,k}. \tag{2}$$

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” $t = 1$, $m = 1, \ldots, n$ and $k = 1$, and for the input voltage at terminal “n” $t = n$, $m = 1, \ldots, n$ and $k = n$.

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

$$\left[e_{m,1}\right] = \left[Z_{ij}\right] \left[i_{m,1}\right] \tag{3}$$

where $\left[e_{m,1}\right] = \left[e_{1,1} \quad e_{2,1} \quad , \ldots, \quad e_{n,1}\right]^T$ the nx1 vector of the node voltages when the input is at terminal 1, $\left[Z_{ij}\right]$ with $i = 1,.,n$ and $j = 1, \ldots, n$ is the $n \times n$ impedance matrix of the equivalent circuit in Fig. 1 and $\left[i_{m,1}\right] = \left[i_1 \quad 0 \quad , \ldots, \quad 0\right]^T$ $n \times 1$ 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

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

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

$$[e_{m,n}] = \left[Z_{ij}\right] [i_{m,n}] \tag{5}$$

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

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

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

$$[e_m] = \left[e_{m,1}\right] + [e_{m,n}] \tag{7}$$

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

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

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