Experimental and Theoretical Analysis of Vacuum Circuit Breaker Prestrike Effect on a Transformer

Marjan Popov, *Senior Member, IEEE*, René Peter Paul Smeets, *Fellow, IEEE*,
Lou van der Sluis, *Senior Member, IEEE*, Hans de Herdt, and Jan Declercq, *Member, IEEE*

***Abstract*—The work presented in this paper deals with the investigation of circuit breaker prestrike effect that occurs during energizing a distribution transformer. An experimental test setup that consists of a supply transformer, a vacuum circuit breaker (VCB), a cable and a test transformer is built, and the prestrikes in the VCB are recorded. The test transformer is a prototype distribution transformer, with installed measuring points along transformer windings in each phase. Voltage oscillations are measured along the windings and transformer terminals. The transformer is modeled by lumped parameters extracted from telegrapher's equations in discrete form.**

Voltage oscillations during switching-in operations are recorded and calculated with and without a cable installed between the VCB and the transformer. Computed voltages show good agreement with the measured voltages. Described method can be used by transformer manufacturers to estimate voltage wave forms during switching or lightning, to provide useful information for insulation coordination studies, and to investigate resonance effects in transformer windings.

***Index Terms*—Modeling, switching tests, transformer, vacuum circuit breaker.**

I. INTRODUCTION

IT IS well known that during switching highly inductive loads like transformers and motors, under specific conditions, multiple restrikes in the circuit breaker can occur. Multiple restrikes are fast voltage surges which proceed along the cable and reach transformer or motor terminals. Because of different surge impedances at terminals, a wave reflection and absorption takes place. Voltage oscillations which proceed toward windings are continuously superposed by new voltage waves from new upcoming surges. Hence, voltage waveforms along the transformer winding within a particular time interval can have very different amplitude and rate of rise. Their oscillations contain a broad frequency range which can be from a few kilohertz up to a few megahertz. These are unwanted phenomena which cause deterioration and failure of the equipment insulation. Almost one third of all motor failures occur because of fast switching surges [1]. Switching surges which enter the windings are non-linearly distributed [2]. Besides, sometimes high inter-turn overvoltages can take place which stress the thin insulation and accelerate its failure. So far, a lot of work has been done on transformer and motor switching [3]–[9]. However, voltage transients are measured on transformer terminals and prediction of the voltage distribution along the windings is difficult to be done. In [10] a computer model for motor windings is described which is applied during sequential pole closing [11]. It is also applied for determination of inter-turn voltages during energizing a motor with a VCB [12].

Most of the time, the geometry of the windings and dimensions are not known. Furthermore, a proper model based on transformer geometry and type of windings is difficult to develop. Consideration of the frequency-dependent losses is another problem.

So far, there was successful work done on transformer modeling. In [13] and [14], a hybrid model based on transmission line theory was successfully applied to describe the wave propagation in large shell-type transformers. An accurate approach for modeling transformers and motors is done by applying the so called vector fitting [15]. This model is based on the measured frequency admittance matrix of the transformer, the elements of which are admittances measured from any provided measuring point in the transformer windings [16]. The advantage of the latter model is that it gives the possibility to use existing simulation software like EMTP.

In this work, the prestrike effect during energizing the transformer was investigated. Voltage waveforms on transformer terminals are measured and they are used as an input parameter to the transformer model. A lumped-parameter model based on discretized telegraphist's equations is applied [17]. It was found that this approach can be successfully applied for computation of voltages along the windings, even for matrices with large dimensions (100×100). Computations are done in frequency domain, and time domain solutions are provided by applying inverse continuous Fourier transform [18]. Measurements and computations are also done with and without a cable applied between the VCB and transformer. The computations are verified by laboratory measurements.

II. TEST TRANSFORMER AND ITS REPRESENTATION

A. Transformer Description

The test transformer is a three-phase layer-type transformer. However, the computation and measurements of the voltages

---

Manuscript received March 06, 2008; revised July 02, 2008. First published May 08, 2009; current version published June 24, 2009. This work was supported by the Dutch Scientific Foundation NWO/STW under Grant VENI, DET. 6526. Paper no. TPWRD-00147-2008.

M. Popov and L. van der Sluis are with the Faculty of Electrical Engineering, Mathematics and Computer Science, Delft University of Technology, Delft 2628CD, The Netherlands (e-mail: M.Popov@ieee.org).

R. P. P. Smeets is with KEMA, 6800 ET Arnhem, The Netherlands, and the Department of Electrical Engineering, Eindhoven University of Technology, Eindhoven, 5600 MB, The Netherlands (e-mail: Rene.Smeets@kema.com).

H. de Herdt and J. Declercq are with Pauwels Trafo Belgium N.V., B-2800 Mechelen, Belgium (e-mail: Hans.de.Herdt@pauwels.com; J.Declercq@HansenTransmissions.com).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPWRD.2009.2013383

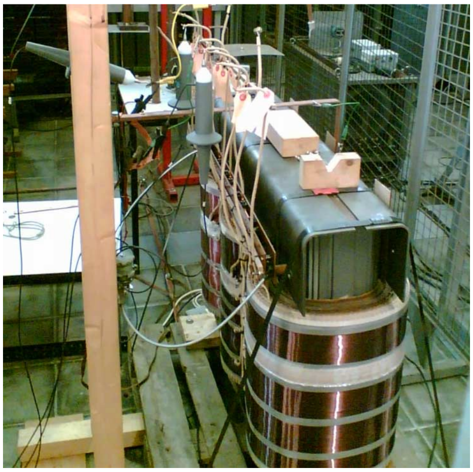

Fig. 1. Test transformer.

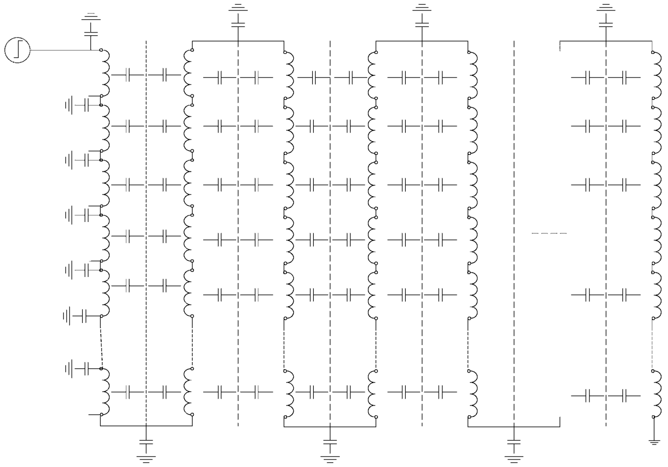

Fig. 2. Transformer capacitances and inductances.

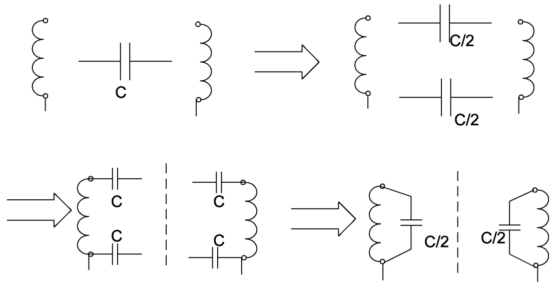

Fig. 3. Simplification of a section of the transformer.

TABLE I
TRANSFORMER DATA

Transformer Power	630 kVA
Transformer ratio	15375 V / 400 V
No-load losses	770 W
No-load current	0.3 %
Number of layers (HV side)	10
Number of turns in a layer	~ 140
Inner radius of HV winding	135.3 mm
External radius of HV winding	163.3 mm
Inner radius of the LV winding	97 mm
Wire diameter	3.0 mm
Double wire insulation	0.1 mm
Distance between layers	0.4 mm
Coil's height	425 mm

along the windings is done per phase whilst other two phases are not connected to the studied phase.

The primary transformer winding consists of layers with approximately 140 turns. The transformer is equipped with special measuring points in each phase. In phase A, measuring points are installed at the 3rd and the 5th turn. In phase B, the measuring points are at the 290th and the 580th turn, and in phase C, the measuring points are at the 444th and the 888th turn. All measuring points can be directly reached as it can be seen from Fig. 1. The most important parameters of the transformer are summarized in Table I.

B. Transformer Representation

Studied transformer is a layer-type prototype transformer particularly produced for this research. The transformer has measuring points installed in each phase. The tank and the oil are removed so that an easy access to the windings can be provided. The transformer with capacitances and inductances is represented in Fig. 2. The inductance matrix is formed by the self inductances of a group of turns and mutual inductances between the turns. The capacitance matrix is formed by capacitances between layers and capacitances from the top and the bottom of the layers to the transformer tank.

The transformer represented in Fig. 2 can be simplified by rearranging the capacitances. To do this, we will consider an equipotential surface between the layers [2]. In this way, one can divide a group of winding in the following way. Half of the capacitance between coils is added to the edges of the coils [19]–[21]. Then, it is assumed that there is an equipotential line in the middle of the coil, so that the capacitance between coils can be added as a cross-over capacitance at each coil with a value equal to the half of the value of the total capacitance. The description is given in Fig. 3.

Fig. 4 represents the simplification of the transformer model from Fig. 2, and Fig. 5 is the final model of the transformer. It has to be pointed out that the cross-over capacitances which belong to the first and last layer are a half of the cross-over capacitance of the other layers. Capacitances to ground in this case are small because the surface of the top and bottom of the coil is small. They are estimated as less than 1 pF.

C. Inductance and Capacitance Matrix

Inductances are calculated by the well known Maxwell formulas on a turn-to-turn basis [22]. The **L** matrix is formed in a way that diagonal elements of the matrix correspond to a group of turns. The off-diagonal elements are mutual inductances between different groups of turns. For simplicity in this case, the number of turns in a group is kept constant. The studied transformer has ten layers with approximately 142 turns per layer. Each layer is divided in ten groups with 14 turns per group. So, we assume that a layer consists of ten groups. So the transformer **L** matrix is of order 100×100. The capacitance matrix is built on a node-to-node basis and because the number of nodes