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Power transformer winding model for lightning impulse testing

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Abstract

This paper presents a method for calculating the internal voltage transients useful for power transformer winding modelling. The method is based on lumped parameter model of a transformer winding and the transient response is obtained using time-domain analysis. Lumped circuit parameters are calculated using self-developed solvers which are benchmarked using professional finite element method (FEM) software. The results show that the presented approach gives satisfactory results and is computationally very fast.

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Keywords: power transformers; numerical simulation; electromagnetic transients; time-domain analysis; coils; internal overvoltages

1. Introduction

Power transformers are an essential part of every electrical power system and are typically designed to be in operation almost continuously for several decades. During their lifetime, they are exposed to high frequency transient overvoltages due to switching operations and lightning strikes [1-3]. Therefore, when determining the geometry and type of the winding, one of the typical design criteria is the winding's ability to withstand transient voltage surges.

Under steady-state operating conditions, voltage is distributed uniformly along the winding of a transformer [3]. However, winding's behavior during high-frequency transients is much more complicated. Capacitances between the winding conductors, which are negligible at nominal frequency, become significant at higher frequencies. They are generally responsible for the initial nonuniform voltage distribution along the winding during transient conditions [1]. Moreover, capacitive connections together with the inductive connections inside the winding give rise to voltage

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oscillations along the winding. These oscillations become more pronounced if the frequency spectrum of the transient input signal contains frequencies which are close to fundamental resonant frequencies of the winding under consideration [3].

Nomenclature

BEM	boundary element method
DC	direct current
FEM	finite element method
FRA	frequency response analysis
LI	lightning impulse
ε_r	relative permittivity of the surrounding medium
σ	electrical conductivity of a conductor

Because of the abovementioned winding behavior under transients, it is of interest to transformer manufacturers to be able to predict the winding's transient response and optimize its geometry and insulation during the design stage.

1.1. Scope of the paper

The analysis of fast transient overvoltages and the behavior of the transformer winding under such conditions are of great interest and has been a topic of various papers [1-6]. There are two main approaches, one based on the winding modelling and the other one on measurements. The former is of interest to transformer manufacturers since they have the insight into winding's geometry needed for detailed numerical models [2,6]. The latter approach is of use to power system operators which usually use FRA methods in obtaining the transformer behavior under transient conditions [7,8].

When modelling the transformer winding, it is usually represented with an electrical circuit consisting of a number of resistances (R), inductances (L) and capacitances (C). The winding models can be broadly divided in two groups: models based on lumped parameters [2,4,6] and models based on distributed parameters [5]. The most daunting task in both approaches is in determining the mentioned RLC parameters.

Since the power transformer usually consists of several hundreds to couple of thousands of turns, it is very complicated and time-consuming to obtain all the RLC parameters for every turn. Therefore, they are either calculated using simple analytical expressions which cannot take detailed winding geometry into account, or the turns are grouped and then a reduced winding model is constructed [9].

This paper presents a numerical method for determining the RLC parameters of the winding's lumped parameter model which is both computationally fast and yields more precise results compared to analytical formulations. The developed model is useful in analysis of the winding when subjected to high-frequency overvoltages (up to a couple of MHz). The emphasis is given on capacitance and inductance calculation, for which numerical procedures have been developed. Each turn of the winding is treated individually and no reduction of turns is made. The conductors are assumed to be of a rectangular cross section since they are typically used in power transformers.

The obtained results from the presented approach are benchmarked against the results calculated using the professional FEM-based software *Infolytica® MagNet®* and *Infolytica ElecNet®*.

The winding's design and its ability to withstand atmospheric discharges is usually tested using the 1.2/50 μs voltage signal, as defined in IEC 60076-3. For that reason, the response of the model of the winding presented in this paper will be simulated using the same input signal. The analysis will be done using a transient solver developed for this purpose based on formulations made by Dommel [10].