Electric Power Systems Research 92 (2012) 115–122

Contents lists available at SciVerse ScienceDirect

Electric Power Systems Research

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

Detailed three-phase circuit model for power transformers over wide frequency range based on design parameters

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ARTICLE INFO

Article history:
Received 24 October 2011
Received in revised form 25 April 2012
Accepted 25 June 2012
Available online 20 July 2012

Keywords:
High frequency
Power transformers
Design parameters
Surge voltage
Lightning discharge

ABSTRACT

This paper presents a detailed three-phase transformer model, the elements of which are expressed analytically according to the physical layout and the design construction parameters of the power transformer. These expressions have been calculated theoretically and verified through finite elements simulations.

The proposed model allows to obtain the internal voltage distribution through the three-phase transformer in any type of operating condition, particularly when it is simulated in an electromagnetic time domain transient simulation tool, providing an external and internal characterization of the transformer in a frequency band that can appear in a power system (up to 1 MHz).

The obtained results have been compared with both lightning and low frequency tests measurements, showing a good agreement.

1. Introduction

Transformers are probably one of the most common components in a power system and also turn to be one of the most difficult to be properly modelled. Transformers are often exposed to a variety of high voltage transients. Lightning discharges, several types of faults, switching operations, and nonlinear loads, often cause high frequency oscillations and produce transient high voltage stresses at the transformer windings [1].

If a transformer is under a voltage transient, like lightning discharges or switching surges, it could reach undesirable operation points, near to its resonance frequency, which may cause the collapse of the transformer [2,3].

Power transformers are critical components of energy transmission and distribution processes. In view of increasing demand for reliable and high-quality energy supply, electrical utilities are more interested in avoiding transformer failures [4,5].

From the manufacturer point of view, the interest is to have a more accurate cost-effective design of the power transformer, especially in the internal insulation, having an exact knowledge about the internal behaviour of the transformer with its surroundings. Once an inter-turn fault occurs, high fault current flows through shorted turns, leading to a severe damage of the defective region in the winding [6]. Therefore, a good knowledge of transformers in disturbance conditions is needed. The variety of proposed models can be classified as [7]: black box models, physical models and hybrid models.

Black box models are dependent on the measured data from the terminals of the transformer. These models do not allow considering any internal fault. Its admittance matrix is calculated from measurements, and then each element of this matrix is approximated with an equivalent circuit. The method used for this modelling is powerful, but the admittance matrix measurement is difficult to be handled and have no useful information about the real phenomena inside the transformer [7–9]. The use of simple models like black box models may be justified by a lack of available information.

Physical models are based on Finite Element Method (FEM) or several Resistance, Inductance, Capacitance (RLC) elements, then the simulation run time is expensive and their usage by power network analysis is limited due to their numerous elements [10–13].

Hybrid models combine both previous models and are commonly used to increase the frequency limit range of simulations [14–16]. These models are constructed by combining the transformer detailed lumped parameter equivalent model and the Multi-conductor Transmission Line (MTL) model. The hybrid model parameters are calculated employing the detailed lumped equivalent model parameters and then, based on these parameters the MTL formulation is employed for partial discharge location. This

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http://dx.doi.org/10.1016/j.epsr.2012.06.015

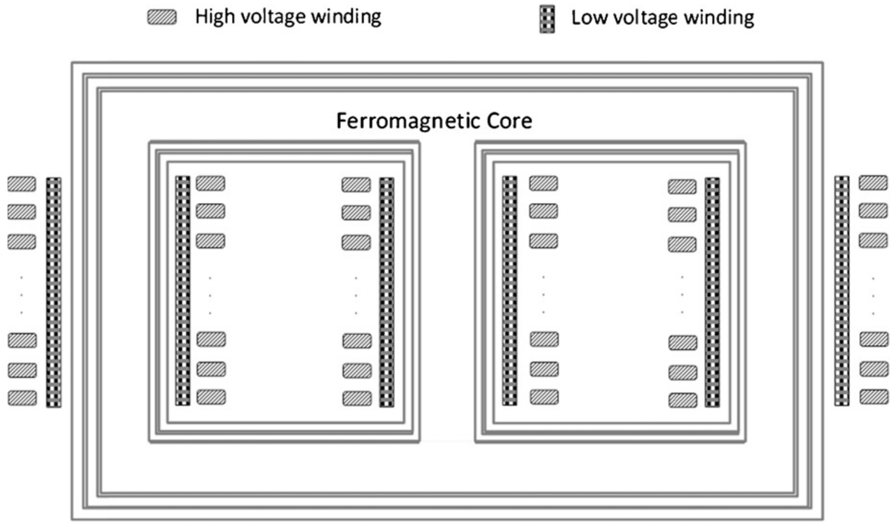

Fig. 1. Internal transformer composition.

combination is suggested to be able to model the transformer winding for a wide range of frequencies [17–22].

The aim of this paper is to create a hybrid model based on transformer design parameters through analytical formulas [23], so the parameter of this model does not require any costly and time-consuming measurements. The external and internal behaviour of the developed model has been compared with experimental tests. This model allows calculating accurately the voltage in any part inside the transformer and also to be simulated as black box in large power network simulations.

2. Distributed parameter circuit for transformer model

A discretized model of three-phase power transformers has been developed through electromagnetic transient program, to reproduce voltage distribution along its internal composition once an overvoltage discharge appears.

A blueprint of the internal composition of the power transformer, including the high and low voltage windings and the ferromagnetic core is shown in Fig. 1. This schematic helps to understand the real construction layout and the equivalent model configuration developed. Fig. 2 outlines the geometrical dimensions of three-phase power transformer used to evaluate the developed model.

The transformer is constructed by a laminated ferromagnetic core and HV and LV coils, wounded to a cylindrical column of core. In Fig. 1 each one of the three HV and LV windings are shown. They are composed of n discs, built each one of them by coil turns of conductive material and isolated by epoxy.

To create a power transformer model able to reproduce the internal behaviour, the transformer has been divided in n sections which correspond to the n discs of HV winding. The electromagnetic effects that each one of these divisions has with their surrounding are considered.

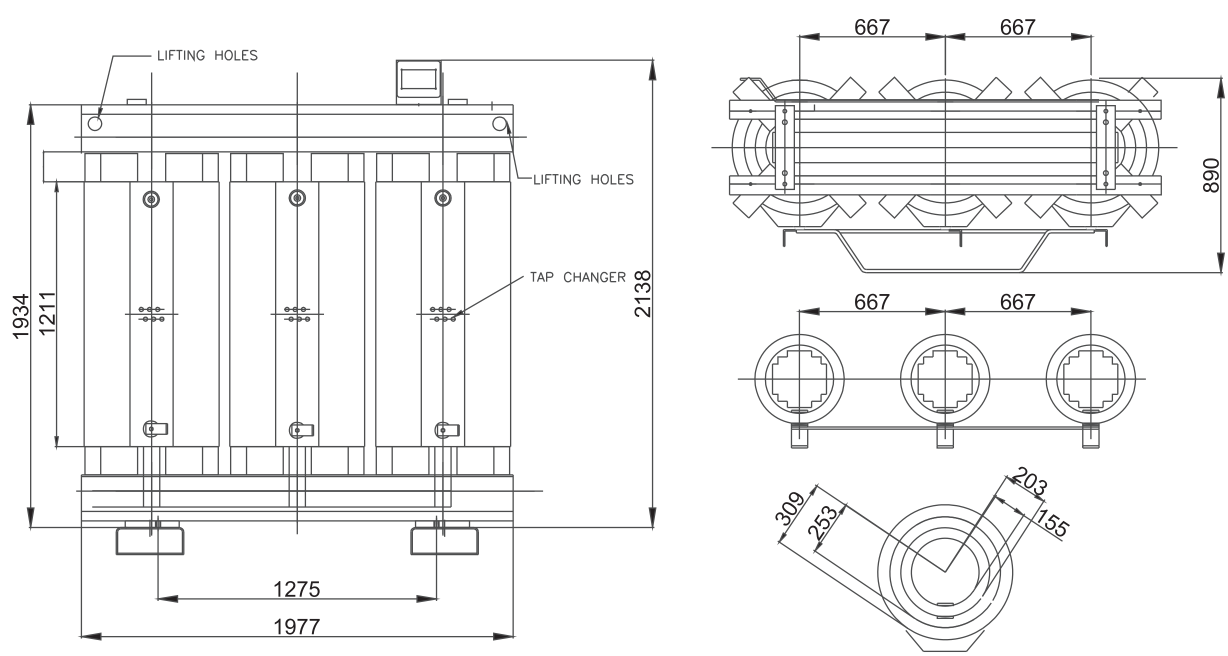

Fig. 2. Drawings of the power transformer modelled.