Chapter 6
Transformer Modelling for Impulse Voltage Distribution and Terminal Transient Analysis

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ABSTRACT

Voltage surges arising from transient events, such as switching operations or lightning discharges, are one of the main causes of transformer winding failure. The voltage distribution along a transformer winding depends greatly on the waveshape of the voltage applied to the winding. This distribution is not uniform in the case of steep-fronted transients since a large portion of the applied voltage is usually concentrated on the first few turns of the winding. High frequency electromagnetic transients in transformers can be studied using internal models (i.e., models for analyzing the propagation and distribution of the incident impulse along the transformer windings), and black-box models (i.e., models for analyzing the response of the transformer from its terminals and for calculating voltage transfer). This chapter presents a summary of the most common models developed for analyzing the behaviour of transformers subjected to steep-fronted waves and a description of procedures for determining the parameters to be specified in those models. The main section details some test studies based on actual transformers in which models are validated by comparing simulation results to laboratory measurements.

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INTRODUCTION

Transformer windings may be subjected to high-frequency waves arising from switching operations, lightning discharges, and from any change in the operating conditions of the system (Greenwood, 1991). A high number of transformer failures have occurred due to the failure of inter-turn insulation (Morched, Marti, Brierly, & Lackey, 1996; IEEE PES, 1998). The failures on the line-end coils were due mainly to the concentration of voltage arising in those coils as a result of the relative values and distribution of the inductance and capacitance between the turns of the coils (Greenwood, 1991; Chowdhuri, 1996; Degeneff, 2007).

Experience shows that transient overvoltages are not only dangerous because of their amplitude, but also because of their rate of rise; that is, frequent overvoltages with lower amplitude and higher rate of rise can be as dangerous as overvoltages with higher amplitude.

As introduced in the chapter on Basic Methods for Analysis of High Frequency Transients in Power Apparatus Windings, electromagnetic transients in transformers due to high frequency waves (i.e., steep-fronted waves) are commonly studied using internal models, which consider the propagation and distribution of the incident impulse along the transformer windings, and terminal (black box) models, which consider the response of the transformer from its terminals and may also permit the calculation of transferred voltages (de León, Gómez, Martinez-Velasco, & Rioual, 2009; Hosseini, Vakilian, & Gharehpetian, 2008).

Wave propagation phenomena along the winding can be accurately reproduced with a distributed-parameter model and taking into account the frequency-dependent losses. Although models based on the multiconductor transmission line theory have been successfully used (Rabins, 1960; Guardado & Cornick, 1989), a lumped-parameter model can also give adequate results for fast transients (up to 1 MHz). Therefore, transformer models for high-frequency transient analysis can be described either by a distributed-parameter representation, or as a ladder connection of lumped-parameter segments (de León, Gómez, Martinez-Velasco, & Rioual, 2009). Proper choice of the segment length for lumped-parameter modelling is fundamental. Analysis of steep-fronted transients (in the order of dozens or hundreds of kHz) using one segment per coil of the winding can be sufficient, whereas very fast front transients (in the order of MHz) may require considering one segment per turn.

In general, it is assumed that for high frequencies, the flux does not penetrate in the core and the iron core losses can be neglected accordingly, that is, the core inductance is considered to behave as a completely linear element since high frequencies yield reduced magnetic flux density. The flux penetration into the core can be neglected for very fast front transients, such as those related to switching operations in gas insulated substations (GIS), considering that the core acts as a flux barrier at these high frequencies. However, it has been reported that even up to 1 MHz, the iron core losses influence the frequency transients (Abeywickrama, Podoltsev, Serdyuk, & Gubanski, 2007), so the flux penetration dynamics in the core should be taken into account for fast front transients, mainly those due to switching with frequencies below 100 kHz (CIGRE WG 33.02, 1990).

Voltage distribution along the transformer windings depends greatly on the waveshape of the voltage applied to the windings. It can be noticed that, at power frequency, the distribution is linear along the windings, but in the case of fast front transients, a larger portion of the voltage applied is distributed on the first few turns of the winding (Greenwood, 1991; Chowdhuri, 1996). Transformers are designed to withstand such stresses and the performance is checked by lightning and switching impulse laboratory tests.

Overvoltages appearing at the transformer terminals may have oscillations in a wide range

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