Electric Power Systems Research 152 (2017) 306–315

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Experimental data-based transient-stationary current model for inter-turn fault diagnostics in a transformer

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ARTICLE INFO

Article history:
Received 5 April 2017
Received in revised form 12 July 2017
Accepted 20 July 2017

Keywords:
Inrush current
Inter-turn fault
Transformer
Short-circuited turns
Transformer diagnostics
Transformer winding

ABSTRACT

Inrush current has been well-studied in transformers using different methods to diagnose internal faults. In this paper, a new methodology is proposed using experimental data for obtaining a time-model based on inrush currents. The main contribution of this paper consists of providing a model that accurately reproduces the inrush and steady state currents of single-phase transformers, offering the unique ability to analyze several severity levels of turn to turn faults. The obtained model considers eleven cases of inter-turn fault (2, 3, 4, 5, 10, 15, 20, 25, 30, 35, and 40 short-circuited turns) and allows the study of indices to detect inter-turn faults. The proposed model is based on two functions: a steady-state function based on Fourier series and a residual transient function based on a sum of Gaussian functions. The model allows the study of harmonic content because of its direct time-frequency representation. The model is developed using experimental signals measured from a single-phase transformer, which is validated by means of error criteria that assesses experimental and modeled signals. Its capability to reproduce non-modeled signals with different inter-turn fault cases is also evaluated. The modeling of these signals can be a useful tool for simulation-based applications where a reliable waveform reproduction is needed. On the other hand, indices such as total harmonic distortion, energy spectral density and second harmonic ratio are obtained from the proposed model to study its behavior, depending on the severity of the inter-turn faults. Results demonstrate its usefulness to characterize the level of fault severity.

1. Introduction

Transformers play a key role in the electric system, as they connect generation stations with the points of use and provide proper voltage levels for different applications [1,2]. The growing demand of energy, proliferation of complex loads, inadequate maintenance and environmental issues such as lightning or moisture make transformers prone to failures since they are subjected to mechanical, electrical or thermal stresses which may damage their components, causing severe outage problems [2]. Inter-turn winding faults appear because of the insulation breakdown between contiguous turns of the winding. This breakdown is commonly associated to high levels of current and voltage as result of atmospheric overvoltages, ground faults, and ageing or deterioration of the cellulosic insulation due to chemical influence of the transformer oil [3]. High current levels inside of short-circuited turns are often strong enough to damage the winding. The current amplitude is associated with both fault severity and location, which can be several times higher than the winding rated current [4]. Although, a small inter-turn winding fault presents imperceptible effects on transformers in the initial stages, they can quickly lead to more serious faults such as low impedance, phase-to-ground, low voltage winding to high voltage winding, or phase-to-phase faults [5]. One of the main protection schemes is the differential protection which has been applied successfully on transmission

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http://dx.doi.org/10.1016/j.epsr.2017.07.020
0378-7796/

lines and generators. However, a key problem for fault detection is to distinguish between a fault current and an inrush current due to the energization of transformers [6], which can occur in high- and low-power transformers. In this regard, methodologies that provide fault indices related to fault severity using inrush current are sought to operate the transformer under safer conditions.

Several methods for the analysis of transformer faults have been reported in the literature [6–14] in order to prevent catastrophic conditions, avoid further damages, reduce repair costs and outage times. For instance, the analysis of electromagnetic transients has been carried out to understand and estimate internal faults, where methodologies such as symmetric components analysis [5], harmonic analysis [6], curve fitting methods [7], equivalent instantaneous inductance [8], differential current method [9], Hidden Markov model [10], Park transform [11], frequency response analysis [12,13] and higher-order statistics [14] have been explored. These methods usually use a threshold value in accordance with some reference parameters to detect a fault condition. For example, different numerical values obtained using kurtosis-based indices are used to distinguish an inrush current from an internal fault current [14]. However, the severity of the fault is not quantified. On the other hand, model-based approaches have also been studied to represent the power transformer behavior. For instance, equivalent electric circuit representations in combination with magnetic equivalent circuit and finite element models have been proposed to represent the nonlinearities caused by the magnetizing characteristics of the transformer silicon steel core [15–18]. Also, studies of internal faults have been carried out [19–24] and accompanied by the development of topology-based models. A three-phase transformer model for winding fault studies using the processing of inductances matrix is introduced in Ref. [19]. It allows the simulation of any kind of internal fault such as turn-to-earth or turn-to-turn fault. A permeance-based transformer model is proposed to investigate the behavior of power transformers under permanent or intermittent winding insulation faults [20], where a methodology based on the Park's vector is used for fault detection. Variations of the transfer function of inter-turn faults are studied through an improved lumped circuit model, where the resonance frequency is proposed as a parameter to detect an early inter-turn fault [21]. In addition, lumped circuit parameters, obtained by frequency response interpretation, are analyzed for mechanical failure diagnosis [12]. Also, the frequency response analysis is used for locating inter-turn faults [13]. The inter-turn fault is studied with an autotransformer circuit represented with state-space equations for different types of magnetically coupled circuits, such as transformers and rotating machines [22]. Topology-based methods can provide an accuracy and reliable approximation to investigate inter-turn faults. Although the vast majority of the proposed methods are validated through experimentation, the accuracy of these methodologies depends upon transformer parameter estimation, as different types of transformers with different power ratings, insulation types, cooling systems, etc. are considered. In general, topology-based techniques are excellent design tools which can provide a very accurate response for simulation purposes. However, they have a high complexity during their implementation. Curve-fitting techniques have been carried out to reduce complexity of topology-based models, where nonlinearities are constructed using diverse mathematical functions [8]. These functions adjust their parameters in order to model different types of transformers and different fault conditions. Although, there are several model-based works that study inter-turn faults in transformers using the inrush current phenomenon, issues such as model complexity and the assumptions taken for simulation purposes may compromise their usage as tools for transformer fault diagnostics in real practice. Therefore, the development of methods and models that provide more efficient and reliable results in terms of simplicity and performance for the analysis and diagnostics of inter-turn faults is still an important topic of research, if different severity levels and experimental signals are considered.

In this paper, a new methodology for the obtaining of transient-stationary current time-models using experimental data is proposed. The proposal is applied to inrush current signals with different severe cases of inter-turn fault, where the in-test transformer is a low-power single-phase transformer of 120VA with epoxy resin insulation, operating at 127 V as input and 24 V as output. As a result, a new transient-stationary inrush current model is obtained, which allows the study and development of indices to diagnose inter-turn faults. These indices are an important tool for correct diagnostics of transformers. The proposed model for the transformer inrush current is obtained by means of mathematical functions. Firstly, the inrush current is divided into two parts: steady-state and residual transient. The steady-state signal is modeled using harmonic sinusoidal functions, which is considered as part of the inrush phenomenon of the entire signal. Secondly, the residual transient signal is modeled using a sum of Gaussian functions. Then, the aforementioned models are combined to obtain a transient-stationary time model. The model also considers the inter-turn fault severity which depends on the number of short-circuited turns, where 2, 3, 4, 5, 10, 15, 20, 25, 30, 35, and 40 short-circuited turns are considered in the proposal. In this regard, the proposed model allows constructing inrush current waveforms with different inter-turn fault severity levels. The study of transformer energization is important for design purposes and fault analysis. Hence, the proposed model can be used to provide inrush current waveforms with different inter-turn fault severity levels. Finally, the indices of energy spectral density of harmonic components, total harmonic distortion (THD) and rate between the second harmonic and the fundamental component are presented as tools for diagnosing the severity of faults using the information provided by the proposed model. It is worth noting that these indices allow the determination of the fault severity, which is a deciding factor to perform maintenance operations. In addition, they can diagnose inter-turn faults from the first cycle of the inrush current and during the steady-state. The severity level from two short-circuited turns can also be assessed. Results demonstrate the usefulness and effectiveness of both the proposed models and the diagnostic indices.

2. Theoretical background

2.1. Transformer inrush current

Inrush current refers to a transient phenomenon occurred when a transformer is switched-on, where high levels of current, even greater than the nominal current, can be produced for a few cycles. In addition, a partial decay on the current magnitude is experienced depending on the transformer design [11,23]. Simulation of this phenomenon represents an important and complex issue due to the nonlinear behavior of the transformer core. As a matter of fact, the transformer should be modeled with a great detail in order to correctly reproduce the behavior associated to the core saturation [15–18]. Analytical formulas of inrush peak and rate of decay can be derived from single phase transformer theory [24], but they are not valid for the entire waveform. In general, it is fair to say that theoretical models offer satisfactory results when compared to the behavior of actual transformers. However, their accuracy depends on truthfulness of the chosen design parameters which are usually subjected to assumptions and simplifications.

2.2. Steady-state model based on harmonic components

Harmonic models have been proposed for power transformers to understand the influence of harmonic content on other compo-