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Study on locating transformer internal faults using sweep frequency response analysis

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ABSTRACT

As an extensive network of resistances, capacitances, and inductances, a transformer has inherent characteristic parameters that are functions of frequency. The form of these functions is predicated on the geometric design of the transformer and materials that comprise it. Any change in the structure of a transformer will be reflected in its frequency response characteristics. Of the possible changes that can take place in a transformer structure, an internal short circuit is one of the far-reaching incidents that has been recently reported for many wind-farm transformers. Detecting the location of an internal short circuit that has occurred in a transformer winding is therefore beneficial in the repair process and also in improving future designs. In an effort to identify trends with inter-turn fault locations and frequency responses, this research investigates the effect of the location of deliberately initiated internal faults on parameters such as transfer voltages and input impedances by means of sweep frequency response analysis (SFRA). The analysis of three different model transformers with different core and winding designs shows several trends in frequency response patterns, depending on the location of the internal short circuits. The paper discusses such trends as a potential use of SFRA in locating inter-turn winding failures that may result in noticeable short circuits.

1. Introduction

In wind-farms, connecting and disconnecting a transformer from the grid using fast switching breakers is essential due to variations in wind speed. Transformers operating in wind-farms are exposed to fast transients at a multitude of times due to frequent switching operations, thereby stressing the winding insulation to high frequency stresses. The severity of such stresses are significantly high in wind-farm transformers due to the interaction between capacitance and inductance of both connecting cables and transformers involving fast operating vacuum circuit breakers and power electronic converters [1–3]. On the other hand, detection of transformer insulation faults by using frequency response analysis (FRA) has been introduced and developed by previous researchers as a method that adopts changes in frequency responses to diagnose physical and/or chemical changes in the transformer. For this purpose, both online and offline procedures [4] have been developed using frequency response analysis (FRA) as the most prominent measurement methods.

Secue and Mombello [5] reviewed literature related to the application of sweeping frequency response analysis (SFRA) for diagnosis of transformer failures. This review explains a number of aspects that must be considered with respect to implementation of SFRA, such as, frequency range and connection of non-tested terminals. The authors have also discussed the sensitivity of SFRA as well as the associated sources of uncertainty and inaccuracies that influence measured data. It has been concluded that SFRA can be a useful technique for detecting winding movement and loss of clamping pressure. In Ref. [6], a combination of SFRA and an impedance measurement method is proposed as a means of enhancing diagnosis of mechanical failure in windings.

In addition to the work related to mechanical failures mentioned above, other studies have focused on detection of inter-turn short circuits in general. In Ref. [7], changes in maximum input admittance values are described with respect to short circuits in electrical machines. Wilk and Adamczyk [8] found that variations in amplitude at resonance frequencies represent a U-shaped trend as an inter-turn fault develops; this occurs because the amplitude of the transfer function is closely related to the amount of power loss due to short circuit resistance. Since this trend is related to energy, as

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Table 1
Transformers specification.

Geometrical dimensions	Transformer I	Transformer II	Transformer III
Rated output	500 kVA, three phase	9 kVA, single phase	1 kVA, single phase
Voltage	240 V/11 kV	345 V/19.8 kV	115 V/6.6 kV
Frequency	50 Hz	60 Hz	60 Hz
Oil immersed/not immersed	Not immersed	Oil filled	Oil filled
Number of layers for HV winding	12	37	41
Number of turns for HV winding	1334	7480	10,496

the fault develops, consumed energy increases in the early stages, while the opposite effect occurs during later stages of fault development. Resonance occurred at higher frequencies as the inter-turn fault developed.

Utilising FRA measurements, authors of this paper (Soloot et al.) have previously investigated the effects of winding design on resonance overvoltages in transformer windings [9]. The FRA method was adopted to measure voltage-drops between adjacent layers and discs of transformer windings through a wide range of frequency. The results showed that depending on the design of the windings, transformers show different patterns of internal stresses. It was concluded that disc winding has a higher internal stress at resonance frequencies compared to that of pancake and layer windings; layer structure showed the highest resonance voltage at winding terminals. In another work by other authors of this paper (Khanali and Jayaram) [10], a comparison is made between frequency responses of electrostatically shielded and non-shielded layer type transformers with the focus being on identification of differences in their resonant overvoltage behaviours. Further, it has been shown that resonances that occur with many frequency components can lead to high stresses and eventually cause layer-to-layer short circuits. Such resonance initiated high stresses particularly in transformers connected to wind-farms are also reported by Banda and Van Coller [11].

Through the literature, it is evident there is less focus on detection of the position of internal short circuits using FRA method. Knowing the location of an internal fault can benefit operators and manufacturers by: reducing cost and time required for repair, and also providing statistical information about the areas of the windings in which internal faults occur more often. The latter would be useful for more effective insulation reinforcement in future designs. Greater reliability and efficiently reinforced insulation is especially valuable for transformers located in offshore wind-farms because of higher maintenance and repair costs. In addition, due to the exposure of wind turbine transformers to high dV/dt voltages from frequent switching, inter-turn and inter-layer insulation of such transformers is under higher stress compared to their power-grid counterparts, as an internal short circuit is more likely to happen.

With an experimental approach on model transformers, the aim of the research presented is to identify the relationship between locations of an internal fault and patterns of transformer frequency responses. To estimate the location of short circuits, the FRAs of faulty windings, with short circuits positioned at different locations, are compared with one another and also with healthy winding as a reference. Comparison is based on use of statistical parameters along with visual observations of trends in frequency spectra. This research also compares sensitivities of different transfer functions with respect to location of the fault.

2. Experimental

Three custom designed model transformers (Table 1) have been used in this study with special features to facilitate the creation of artificial short circuits at different locations of the windings. This feature is made possible by inserting several connection leads along the HV winding at different layers. Detailed designs of all three transformers are described in Refs. [9,10,12]. The proposed scheme of using SFRA in identifying trends with fault locations in different layers are carried out using the model transformer I in detail while the other two model transformers II and III, are used to verify the applicability of the SFRA approach to different designs.

Table 2
Fault numbering based on the position of short circuits according to Fig. 1.

Fault number	Location of short circuit (between connection leads)
1	2 and 6
2	4 and 8
3	6 and 10
4	8 and 12
5	10 and 14
6	12 and 16
7	14 and 18
8	16 and 20
9	18 and 23

Unlike conventional FRA tests on transformers wherein the responses are used to detect faults such as winding deformations or core dislocations, in this investigation, frequency responses of different parameters are measured against a known defect. For this purpose, nine short circuits were created at different locations by short-circuiting a certain number of HV winding turns. Details of the windings of model transformer I that is used in the analysis is given in Fig. 1. It is also presumed that access to the terminals of each individual winding is available for measurement. It should be noted here that although model transformer I is a three-phase design, only one phase is considered in this study, while the unused phase windings are short circuited. As the effect of the core for magnetic coupling between windings of different legs (phases) is negligible for frequencies above 10 kHz (due to the huge drop in core permeability) [13]. Windings of different legs have insignificant mutual effects on each other.

Transformer I is designed in a way that the number of turns between each two consecutive connections is 56 except for the taps (21–26) which have 32 turns between one another. This means that, in terms of number of short circuited turns, all implemented faults have the same number of turns (112) except the fault in the outermost layer, which has eight more turns. Fault numbering along with short circuit locations are given in Table 2.

Both transfer functions; HV/LV and LV/HV are measured, respectively, from HV and LV terminals while the other side is excited. In addition, input HV impedances with LV terminals shorted are also utilised to correlate measured impedances with defect locations. An Agilent® network analyser E5061B and high-frequency oscilloscope probes P2220 are used for voltage transfer measurements, as well as special Ionphysics® current sensors CM-100-6L-IR50 for wide-band impedance measurements (Fig. 2).

3. Fault analysis

Variations that occur in transformer frequency responses due to changes in the location of fault are investigated. The network analyser generates sinusoidal waveform with variable frequencies at