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Review

Frequency response analysis (FRA) of transformers as a tool for fault detection and location: A review

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ABSTRACT

Power transformers are one of the most important components of the electrical power networks. A wide range of mechanical and electrical stresses in addition to the aging could cause failures in these apparatuses. As a result, evaluating the condition of the transformers during their lifetime is crucial to the power network reliability and service continuity. A large number of different fault diagnosis techniques are introduced for this purpose. Frequency Response Analysis (FRA) is sensitive to the great number of electrical or mechanical changes in the transformers that could occur during the manufacturing, transportation, installation, maintenance or operation of the device. Therefore, FRA is considered among the powerful methods of transformers' condition assessment. This paper explains the frequency response analysis of transformers method, its application and test procedure as well as providing a comprehensive review of the researches and attempts that are done on different aspects of this field for enhancing quality and repeatability of the test and the interpretation of the results.

Contents

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1. Introduction

Power transformers are indisputable components of power generation plants, transmission systems and large industrial plants. There is a direct relation between the integrity and operation quality of transformers and the reliability of the system that is erected of these apparatuses. Furthermore, the high economic value of transformers adds to their importance. A great quantity of failures such as axial deformation (AD), radial deformation (RD), disk space variation (DSV), bulk movement of coils, inter-turn short circuits, open circuits, core defects and etc. which are mainly caused by electrical, electromagnetic, dielectric, mechanical, thermal or chemical stresses could contribute to malfunction of the power transforms [1]. Consequently, regular non-destructively monitoring of the transformers for diagnosing any change or fault in the early stage is crucial to the service continuity of the systems.

As long as the time that transformers are used in power networks, varied techniques are introduced for condition assessment of them, and a lot of research works tried to develop or improve these techniques. Dissolved gas analysis (DGA), dielectric dissipation factor (DDF), insulation resistance (IR), polarization index (PI), leakage reactance, partial discharge (PD) detection techniques, frequency domain spectroscopy (FDS), recovery voltage measurement (RVM), polarization and depolarization current (PDC) beside frequency response analysis (FRA) are some of the advanced and practical methods that are widely accepted by experts [2].

FRA was first introduced by Dick and Erven in 1978 [3]. It is a non-intrusive and non-destructive test that can be used either as a stand-alone method for detecting failures or as a complementary procedure for ensuring the results of other tests or locating the damages detected in them. The FRA test is based on measuring the transformer response in a wide frequency bandwidth. These responses provide the diagnostic information in the form of a transfer function which is related to the RLC network structure of the under test transformer. On the other hand, the RLC network represents physical geometry and construction of the test specimen [4]. For example, faults or problems which are related to the wires of the windings such as short circuit or breaks in the conductors will mainly affect the resistance and inductivity of the transformer RLC network. Moreover, failures that cause changes in the shape and position of the windings like axial and radial deformations lead to variation in the capacity or inductivity of the network. Thus, comparing the actual frequency response with a reference response which is measured when the transformer did not have any problems could reveal changes in the power transformers' characteristics and results in fault diagnosis. The reference response is called "signature" or "fingerprint".

Frequency response analysis has received a great deal of attention during past few decades mainly due to the developments in the measuring equipment that reveals FRA accuracy and capability for transformer fault detection. In addition, complete investigation on the FRA performing and interpretation routine is a prerequisite for regulating a standard on this topic. Researches in the field of FRA have considered different practical and theoretical subjects that are listed in the following: technical considerations for enhancing test repeatability, applicable frequency range for the test, finding the exact affected frequency range in different failures, developing an accurate and automotive method for fault diagnosis with FRA, pinpointing the most accurate detection method or comparison coefficient, improving FRA reliability by introducing collaborating methods and diminishing the effects of noise and non-failure changes on the results. These issues are reviewed and discussed in the following sections of this article.

Although there is not any widely accepted international standard for the frequency response analysis of the transformers test procedure and interpretation routine, some countries, associations and societies have provided standards, guidelines and technical reports on this issue. In 2005, National Development and Reform Commission (NDRC) of the People's Republic of China published a standard which specifies the basic requirements in the frequency response analysis on deformation of transformer winding [5]. In 2008, CIGRE issued a technical report that mainly deals with performing procedure of the FRA test and interpretation of the results [6]. In 2012, IEC presented a standard for FRA testing which discusses the measurement technique and measuring equipment to be used when a frequency response measurement is required [7]. IEEE released a guideline for the application and interpretation of FRA for oil-immersed transformers in 2013 [4]. In 2016, OMICRON published a report which covers the measurements principle of FRA on transformers and result interpretation [8]. These guidelines and technical reports are the main references for the FRA practice.

The purpose of this paper is to present a general view of the transformer frequency response analysis. In order to accomplish this goal, Section 2 presents a summary of the FRA test's routine and also deals with technical and practical issues in this field. Subsequently, some of the recent and most important researches that are mainly in close relation with FRA interpretation and a better understanding of test results are sorted and discussed in detail in Section 3. Finally, Section 4 summarizes topics that are discussed and also suggests points that require more research in future work.

2. Frequency response analysis practice

Frequency response analysis is a comparative based diagnostic test that due to its high sensitivity has the potential for detection of failures which other condition assessment techniques may not be able to find them. Therefore, in addition to the routine diagnostic measurement protocol of the transformer, it is recommended to use this test in other conditions and some of them are listed here: after short circuit test in the factory to ensure that no damage occurred during the test, after shipment or repositioning of the transformer for detecting any possible defects in the transportation, after installation and commissioning process, after a significant short circuit fault or lightning collision close to the transformer in order to check the effect of the electromagnetic forces on the windings, after any severe natural disaster occurrence in the transformer area like earthquake, after a transformer's relays alarm or major change in online diagnostic condition for example Buchholz relay alarm [4].

In order to perform a FRA measurement, a signal is injected to the one of the transformer's terminal. This signal that can be a sweep frequency, an impulse signal or a step voltage is measured with respect to the ground (transformer's tank) and used as the reference signal for FRA calculation. The response signal is taken across the measurement impedance which is connected to one of the other terminals of the transformer according to the measure-