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A new vibration analysis approach for transformer fault prognosis over cloud environment

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ABSTRACT

Internet of Things (IoT) and its applications are becoming more prevalent among researchers and companies across the world. IoT technologies offer solutions to many industrial challenges and, as such, they replace classical diagnostic methods with prognostic techniques that can potentially lead to smart monitoring systems. One of the vital applications of IoT is in smart monitoring of major electric power equipment such as transformers whilst in service. Mechanical integrity and operation condition of energized transformers might be evaluated by employing vibration method, which is a non-destructive and economic approach. However, researchers have not yet reached a consensus on how to interpret the results of this method. A new approach has been introduced in this study in order to evaluate transformer real-time vibration signal. A detailed discussion has been provided on transformer vibration modelling and interpretation challenges of the results. Furthermore, a novel method is introduced to evaluate transformer vibration signal during short circuit contingency. As we show, it is straightforward to implement the introduced methods over the cloud environment. Practical studies are conducted on two distribution transformers to examine the introduced methods. The results demonstrate that the methods are remarkably effective, fast and feasible to be programmed over cloud for transformer short circuit fault prognosis.

1. Introduction

Today, more than ever, asset management is a critical component of many industries. Intelligent predictive assessment is obviously more desired than asset restoration after catastrophic failure, especially when online asset prognostic techniques are dealt with. On the other hand, smart systems are gradually merged with Internet of Things (IoT) and cloud computing. In particular, the advent of emerging fourth industrial revolution (Industry 4.0) is further driving demand for utilizing IoT in different aspects of power systems. Systems and equipment are designed and manufactured to conform with IoT protocols, transfer, restore and analyze data through cloud environment. However, there are significant challenges that we confront—for example, how to develop automated algorithms; how to manage and connect an equipment to the cloud system; or how is real-time evaluation of equipment performance conducted.

It is well-known that power transformer is one of the most expensive assets amongst electric power system equipment. This valuable equipment is potentially and constantly in service in various climates and under different electrical and mechanical conditions [1]. Therefore, transformers is continually exposed to a variety of hazards over the course of operation. System operators are always keen to have as precise information as possible about internal mechanical integrity through collecting continuous data from transformer condition. Different on-line and off-line methods have been introduced and implemented for transformer mechanical integrity assessment [2–7]. However, many of practically applicable methods such as Frequency Response Analysis (FRA) are still performing off-line [8]. Implementation of on-line FRA is seriously under study and development. Electric power industry would benefit hugely as FRA becomes available in real-time. There are also other methods that provide reliable information on transformer mechanical integrity. Online short circuit impedance measurement [9], transformer sound analysis (specifically ultrasound interpretation) [10], deformation coefficient [11], communication based method as well as a technique based on locus diagram have been introduced before for transformer winding deformation detection [12–15].

Evaluation of transformer mechanical integrity might be conducted through its vibration assessment. Transformer vibration can be considered to be the repetitive movement of transformer inner parts

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covered by an oil tank or the movement of active parts in dry-type transformer. The vibration takes place around a reference position, which is the position where the transformer attains once it is out of service. Although this method is quite economical and could be easily implemented in real-time as it does not need any complicated test setup to be deployed for transformer monitoring, it has not been as widely discussed in the literatures as other methods. One possible reason might be due to a lack of unique interpretive method for vibration observations, or the nature of noisy vibration signal and its dependency on various factors. Transformer vibration might be interpreted using winding displacement, velocity, and acceleration. In fact, collected vibration signal is usually interfered by a wide range of undesirable environmental or auxiliary equipment oscillations, which make transformer vibration time-series too complicated to analyze. Furthermore, vibration signal noise is unpredictable in different transformer types and generally does not allow the development of a reliable interpretive method in real-time. For instance, in large power transformers, the vibration of active parts of a transformer (main vibration signal) is mixed with oil pump, tap-changer, fans and cooling systems' vibrations, which, in turn, make the interpretation process unreliable. This scenario would become even more complicated when a fault is initiated in transformer. For instance, by using magnitude of vibration signal alone, it is not clear whether a fault is initiated in transformer winding or core, or it is originated from auxiliary equipment.

Many studies on transformer vibration characteristics have been conducted over the past few decades. A study by Garcia et al. [16] discussed vibration analysis and its benefits to recognize transformer winding deformation. Optimum placement of vibration sensor for oil-filled transformer is investigated in the same research, [16], and also it is studied by [17]. Another study by Ji et al. [18] has introduced an online technique called "On-load Current Method (OLCM)" to distinguish transformer core from winding vibration when transformer is in service. In our previous study [19], the vibration method was presented and discussed as an on-line method in transformer winding deformation recognition. In [20], three different indices are discussed to analyze transformer mechanical assessment. Vibration correlation to find transformer winding conditions is introduced in [21]. The authors in [22] mainly focus on electromagnetic vibration noise analysis using Finite Element (FE) and state that "FE model is applicable for transformer noise prediction. This model can be used to predict the transformer noise and provide basis for noise reduction". In order to analyze transformer condition, networking of vibration measuring nodes with integrated signal processing is introduced in [23]. Vibration signature analysis is also used for estimating motor efficiency and its performance in [24].

Undoubtedly, vibration method and information extraction from its collected observations has been widely discussed before. However, studying disturbances in vibration time-series and providing a reliable solution to transformer vibration data analysis over cloud environment has been missed in the literature.

In this study, a mathematical model for transformer vibration phenomenon is provided and a novel approach is introduced to analyze vibration spectrum. Moreover, a new transformer vibration analysis to understand transformer condition in normal and abnormal conditions (turn-to-turn and disc-to-disc short circuit) is introduced and discussed. This method is implemented over a cloud system and is able to evaluate transformer condition simply via IoT protocols. Practical studies are conducted on two open wounded distribution transformers and real-time short-circuit fault is emulated to assess the performance of the introduced algorithm.

2. Transformer core vibration modelling

The state of strain of a ferromagnetic material depends on the direction and extent of magnetization. The length change of a ferromagnetic material once under magnetization is known as magnetostriction [25]. When a material is in relaxation and it is not exposed to magnetic field, its small magnetic domains are randomly spaced and oriented. Since the magnetic field is activated and increased, magnetic domains start to orient themselves to the field as illustrated in Fig. 1. The anisotropy principle axes would be then collinear to the magnetic field. More increase of magnetic field will lead to large mechanical deformation in ferromagnetic material. This deformation is maximized when the material magnetic domains orientation is reached to saturation point. This phenomenon was discovered by J. Jole in 1842 [26]. Magnetostriction is quite significant in ferromagnetic and ferrimagnet materials such as iron. In contrast, it is insignificant in antiferromagnetics, paramagnets and diamagnetic.

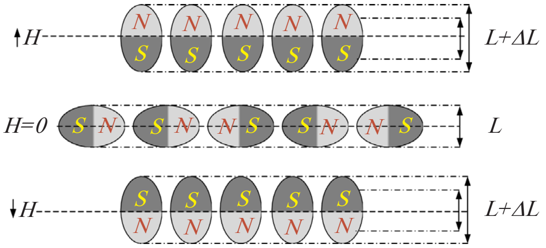

Fig. 1. Ferromagnetic material magnetostriction.

Transformer core vibration is mainly due to magnetostriction. Suppose a slab of ferromagnetic core material of length L, width w, and thickness b, is exposed to the magnetic field.

Due to magnetostriction, the expansion or contraction of substance is characterized through magnetostriction coefficient λ. Also, induced EMF due to Faraday's induction law is given by [18],

$$U_0\sin\omega t = -N_w\frac{d\phi}{dt} = -N_w A\frac{dB}{dt}, \tag{1}$$

where U_0 is the voltage source applied to the winding, ω is the angular frequency, N_w is the number of winding turns, B is the magnetic induction, and A is the cross section area of single core laminate. Hence, magnetic induction calculation is obtained as [18]

$$B = \frac{-U_0}{N_w A}\int \sin\omega t dt = \frac{U_0}{N_w A\omega}\cos\omega t = B_0\cos\omega t, \tag{2}$$

where B_0 is less or equal to the level of induction saturation (B_s) as given by [18].

$$B_0 = \frac{U_0}{N_w A\omega} \leqslant B_s. \tag{3}$$

On the other hand, the relation between magnetic flux density and field intensity of material is obtained as

$$B = \mu H, \tag{4}$$

where μ is the magnetic permeability, and H is the magnetic intensity. For the saturation level where H experiences its maximum value, the magnetic intensity of saturation (H_c) is given by

$$B_s = \mu H_c. \tag{5}$$

Therefore, the relationship between saturated induction and magnetic intensity and applied magnetic field intensity is obtained as

$$B = \frac{B_s}{H_c}H. \tag{6}$$

Replacing (2) in (6), yields the applied magnetic field intensity:

$$H = \frac{H_c B_0}{B_s}\cos\omega t. \tag{7}$$

Any change in ferromagnetic core laminate is initiated by change in filed magnetic intensity. Hence, maximum movement of core laminate due to the field intensity variation is given by [18]