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Locating faults in a transformer winding: An experimental study

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ABSTRACT

Based on terminal measurements on a single, continuous-disc winding of a transformer, it is demonstrated how faults introduced at different positions along the winding could be localized with reasonable accuracy. Fault in the present context represents a discrete change, e.g. short-circuiting a few turns within a disc (i.e. predominantly an inductive change) and/or addition of some tens of pico-Farad capacitance between a disc and ground (i.e. predominantly a capacitive change). Open-circuit and short-circuit natural frequencies are determined by sweep frequency measurements, in addition to measuring effective resistance, shunt capacitance and inductance, at the terminals. The proposed method aims at utilizing the measured data to iteratively synthesize a lumped-parameter ladder network, corresponding to each set of measurement. Comparison of such synthesized circuits with a reference (or fault-free) circuit reveals the location, quantum, and nature of fault. Results presented demonstrate the potential of this method.

1. Introduction

Techniques like low voltage impulse (LVI) test, transfer function (TF) and sweep frequency response analysis (SFRA) have proven to be satisfactory for detecting mechanical deformation/damage of transformer windings [1–6]. Once the occurrence of a fault is detected, the next ensuing task is that of its localization. For this purpose, obviously, a non-invasive approach would be most attractive as it would circumvent disassembly of the winding. In this context, it is desirable to look for newer methods, which could afford (apart from detection abilities), the additional feature of fault localization.

In the recent past, a simplified version of the localization problem was successfully demonstrated, albeit, on a model coil [7]. In that work, considering a single lumped-parameter model coil and based on terminal measurements, localization of changes (made to individual capacitances in the model coil) was shown to be a possibility. The basic philosophy was to realize a mapping between the physical model coil and the synthesized ladder network. Prompted by this success, it was considered worthwhile to examine the extension of this approach to an actual transformer winding. The success achieved in the earlier work and the challenges posed when an actual winding is considered, were the two main motivations of this paper.

2. Objective, principle

The primary goal is to construct an equivalent circuit representation of an actual transformer winding based on data measured at the input terminals. However, the subtle difference here is that an actual winding (wherein capacitances and inductances are distributed) needs to be mapped onto a lumped-parameter ladder network (i.e. to discrete nodes), as illustrated in Fig. 1.

This task essentially turns out to be a circuit synthesis exercise, subject to the constraint that the synthesized circuit must exhibit exactly the same terminal characteristics as that measured on the actual transformer winding. Although circuit synthesis is a non-unique operation, this constraint has been carefully avoided by employing an iterative approach and by invoking properties uniquely exhibited by driving-point functions and assuming a fixed circuit topology. Initially, a fault-free or reference circuit is synthesized. Thereafter, additional circuits are synthesized (keeping topology fixed) corresponding to every new set of measured data. A comparison of the respective elements in the synthesized circuit with the reference circuit reveals the nature and location of the fault along the length of the winding.

When considering an actual winding, the following issues are to be addressed additionally as opposed to the model coil.

- In an actual winding, the capacitances (shunt and series) and inductance are all truly distributed, in contrast to discrete series and shunt capacitances used in a model coil. Further, in the model coil, all sections of the synthesized ladder circuit were made

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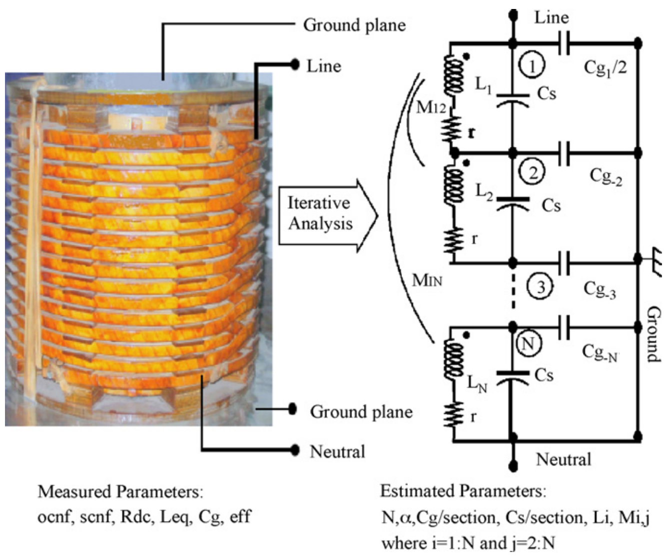

Fig. 1. Ladder network representation of a transformer winding.

identical, whereas, in a real winding shunt capacitance depends crucially on the physical disposition of discs/conductors, clearances to ground, thickness of insulation, and so on. Hence, the condition of uniform distribution cannot be invoked here. In fact, shunt capacitance is higher at the neutral-end compared to the line-end in the setup used, due to proximity of ground.

- In a model coil, it is easy to compute the voltage distribution constant (α), since the total series and shunt capacitances can be readily determined (i.e. measured and calculated). Whereas, in an actual winding such flexibility does not exist, and hence 'α' has also to be iteratively estimated. However, knowledge of the type of winding (continuous-disc or interleaved) facilitates in narrowing the search-space, e.g. if it is an interleaved winding, then lower and upper bounds for 'α' can be chosen as two and four, respectively.
- Capacitive changes (increase and/or decrease) on model coil were manifested as capacitance changes at pertinent nodes [7]. However, when inductance is changed (essentially short-circuiting a few turns), it does not manifest as a discrete change in the synthesized circuit but affects the self and all mutual inductances (i.e. results in a widespread change to the entire inductance matrix). But, on an actual winding, when a few turns of a disc are shorted, such a widespread change is inevitable and therefore suitable modifications have to be built into the circuit synthesis procedure. Furthermore, due to loss of symmetry in the inductance matrix following an inductive change, each individual element of the inductance matrix needs to be iteratively estimated, thereby significantly increasing the computational burden. Lastly, whenever an actual mechanical deformation occurs, in order to enable its correct representation, it is obvious that both inductive and capacitive changes have to be simultaneously considered.
- Compared to the solution for model coil, the solution for an actual winding involves iterative estimation of several quantities, and each of them has to be chosen from a large search-space. To be precise, as opposed to estimating two parameters (viz. self and mutual inductances), a total of five parameters (viz. number of sections, voltage distribution constant, shunt capacitance, self and mutual inductances) have to be iteratively estimated in the present case. Thus, synthesizing a circuit for a real winding is computationally intensive and requires a lot of computer time, even for a reasonably small-sized circuit to be synthesized.

For the above-stated reasons, synthesizing a circuit for an actual transformer winding (from measured data) is a far more onerous task, compared to the model coil problem dealt earlier.

Lastly, introduction of mechanical deformation to the actual winding (similar to other contributions in [3,4,8,9]) was not possible in the present experimental setup. So, as a first approximation, only discrete faults (capacitive and/or inductive) were introduced at selected positions along the winding. Such a procedure achieves the desired goal of introducing a change in inductance and/or capacitance at specified positions on the winding. Furthermore, it assists in checking the correctness of the obtained results.

3. Literature review

Studies on the subject matter of this paper have so far been confined to introducing systematic displacement/deformation in winding, followed by observation of a deviation (if, any) in the measured quantity against a reference signature. Additionally attention has also been focused to determine methods that are best suited for observing even the slightest of deformation/displacement and abilities to discriminate a particular type-of-fault (like radial, axial, etc.). However, interpretation of monitored data has not received the attention it deserves. In perspective, the previous efforts can be classified into the following.

- *Detecting deformation in transformer windings*:
  Ability of monitoring methods to detect the smallest change after introducing a physical deformation (i.e. axial, radial, etc.) on actual transformer windings (either specially manufactured for this purpose or foraged from discarded units) was examined [3,4,8,9]. The task of distinguishing the type-of-fault based on changes observable in the transfer function spectrum has been reported [8]. It is shown that radial and axial winding faults produce changes in transfer function at different frequency intervals, thereby providing a discriminating feature. In [10], a correlation is shown to exist between a particular mechanical deformation in the winding and changes affecting only particular type of circuit elements of the ladder network. Another goal pursued has been to determine the smallest deformation, which could be unambiguously detected. In [8] it was reported that as low as 10 mm of axial displacement could be detected. Notwithstanding these progresses, interpretation of monitored data has largely remained subjective, i.e. based on visual comparison or a matter of expert opinion.
- *Correlation between fault types and measured quantity*:
  Frequency response of the transformer winding is sensitive to its physical parameters. Hence, the resonant pole frequencies, phase and amplitude of the impedance function will show changes with winding condition. In [9], Ryder concludes that different types of faults dominate the frequency response at different ranges, viz. low frequency response is affected by ungrounded core and short-circuited turns, the medium frequency response is sensitive to faults due to both axial and radial deformation and high frequency response is largely contributed by localized winding damage. The type-of-fault is correlated with parameter changes in [10,11], viz. inductance for disc deformation, shunt capacitance for radial deformation, series capacitance for insulation ageing, etc. However, a general consensus has not emerged on what type-of-fault is responsible for which parameter change and their frequency ranges.
- *Developing circuit models*:
  Another topic of interest has been to either build circuits (mostly non-ladder networks), starting from data available from terminal measurements [12–16] and experimental tests