Transformer Winding Diagnostics Using Deformation Coefficient

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Abstract—This work presents the use of terminal capacitance measurements to detect deformations in transformer windings. The lumped parameter representation of windings is considered. The Deformation Coefficient (DC) derived from the measurements is used to detect winding deformations. The extent and location of deformation can also be determined by this method. This paper presents the mathematical basis underlying the method of using DC for windings. The formulation of DC is also explained. Simulation results are given to demonstrate the applicability of the method for deformation diagnostics.

Index Terms—Deformation coefficient, frequency response analysis, power transformer, series capacitance, ground capacitance, winding deformation.

I. INTRODUCTION

Determining deformations using Frequency Response Analysis (FRA) is one of the active research areas in transformer diagnostic studies [1-5]. However, it is not easy to correlate the changes in transfer function, obtained after swept frequency measurements, to deformation location and characteristics. For getting a single transfer function a several hundred measurements at various frequencies, from few hundreds of Hz to about 1 MHz, are required. A fast data acquisition system is also essential to reduce the time required for the diagnostic test. Furthermore, diagnostic conclusions derived for one transformer may not be applicable for another transformer. Therefore, there are continuous efforts by researchers to improve the diagnostic capabilities of the FRA technique [6]. Also, any alternative method, which can make deformation diagnostics a deskilled work, would be beneficial.

Recently, an elegant method has been proposed [7] that can be applied to any current carrying coil or winding, with a simple procedure for deducing the status of the winding. In this novel method, instead of a sweep frequency analysis, only a few measurements are required at selected high frequency and one at selected low frequency are required. In [8], application of this method is explained for a single transformer winding through simulation studies. There are two principal innovative aspects of this method: measurements from both the winding ends and Deformation Coefficient (DC), which help in determining the location and extent of a deformation. The procedure used to calculate the DC makes it lie in a very narrow range for all winding sections irrespective of the extent of deformation.

This paper describes the method briefly and discusses the mathematical basis and characteristics of DC. Simulation studies are reported in which the DC characteristics as a function of changes in series and ground capacitances (due to deformations) are revealed. The underlying assumptions/approximations, present applicability of the method and future work are also enumerated.

II. THE PROPOSED DIAGNOSTIC METHOD

Transformer windings are generally represented by a lumped parameter equivalent circuit [9]. The winding model shown in Fig. 1 is considered as the most appropriate for description of a transformer winding for a wide range of frequencies. The equivalent circuit of a transformer winding consists of a finite number of sections having elements like \( C_i, C_s, L_{ij}, \) and \( L_{ii}, \) which are the sectional shunt capacitance, series capacitance, self inductance and mutual inductance, respectively. Each section of the winding is represented by a pi (Π) model with \( C_s/2 \) as its two legs.

Fig. 1. Lumped parameter model of a transformer.

It is well-known that the driving point impedance characteristics for any transformer winding show that the terminal impedance is capacitive at high frequencies. In the proposed method, at such a selected high frequency, terminal impedance (capacitance) measurements are done at both ends of the winding. The first measurement is carried out between terminals 1 and 1’ (termed as \( C_{11H} \)) and the second between terminals 2 and 2’ (termed as \( C_{2H} \)) with reference to Fig. 1.
While performing the measurement at one end, the other terminal of the same winding is left open and terminals of all the remaining windings, if any, are grounded. Any deformation leads to a change in the measured capacitive reactances. After the terminal capacitances are measured at both winding ends, their deviations from fingerprint values are obtained, and then the ratio of the deviations at the two ends is computed. Any non-limiting function of this ratio is defined as the deformation coefficient. For example, the DC can be obtained as:

\[
DC = \log_{10} \left( \frac{C_{1H} - C_{1H}'}{C_{2H} - C_{2H}'} \right)
\]  

(1)

where, \(C_{1H}\) and \(C_{2H}\) are the fingerprint (intact) values of measured terminal capacitances at the selected high frequency and \(C_{1H}'\) and \(C_{2H}'\) are the terminal capacitance values at terminals 1 and 2, respectively, after deformation.

Using this coefficient, the deformed section can be located effectively as demonstrated in the next section. With additional two measurements, one at high frequency between the two ends of the winding (terminals 1 and 2 in Fig. 1) termed as \(C_{1H} \times \frac{1}{2}\) and the other at a low frequency (say, about 50 to 100 Hz) between any one end and ground (i.e., between terminals 1 and 1' or between terminals 2 and 2') termed as \(C_s\), the extent of deformation can also be determined [7, 8].

One can calculate the values of \(C_s\) and \(C_f\) using standard formulae given in books/published literature. For windings with uniform values of sectional capacitances, these can be determined from the terminal measurements as explained in [7, 8].

### III. SIMULATION STUDIES

The results presented in this section are based on the method described in [7]. It is shown that the value of DC for any winding section remains nearly constant with changes in extent of deformation. Sectional series or ground capacitance is changed to observe the DC behaviour. It is assumed that the changes in ground capacitances do not affect the series capacitances and vice versa. This assumption is valid for minor deformations. For simulation, deformation up to 20% is considered to highlight very small variation of DC even at substantial deformation values.

#### A. DC as a Function of Ground Capacitance Changes

By changing both \(C_s / 2\) capacitance values for a given section in the pi (Π) model representation, sectional ground capacitance changes during deformations can be simulated. One can calculate the terminal capacitance seen from either end when the sectional ground capacitance is changed for any section. Table I gives the expressions of DC as a function of \(x\) which is per unit (p.u.) decrease in ground capacitance. The base values are: \(C_s = 1 \text{nF}\) and \(C_f = 2.2 \text{nF}\). The winding under consideration is divided into eight sections. From the fifth to eighth sections, the DC expressions are negative of that of the fourth to first sections, respectively, due to assumed symmetrical nature of the winding.

A chart can now be prepared for the DC, which may be represented in a tabular form or graphical form. The values of DC for a particular section lie in a narrow range as evident from Fig. 2. Thus, each section has an almost constant and distinct DC value irrespective of the extent of deformation. This is due to the fact that DC expression (a constant times \(f(x)\)) for each section has a distinct and widely different constant multiplicand to \(f(x)\). The variation of \(f(x)\) for the sections 1, 2, 3 and 4, as \(x\) is varied from 0.01 to 0.2 p.u., is: -1.87 to -1.73, 0.632 to 0.619, 0.894 to 0.889, and 0.974 to 0.973, respectively. Hence, due to distinct value of multiplicand and narrow variation in \(f(x)\), the DC values for any section lie in a narrow range as \(x\) is varied. This distinctive feature of DC for each section can be used to determine the deformation location.

The deviation \((C_s - C_f)\) in measured magnitude of terminal capacitance at the selected low frequency, during a diagnostic test, from that of its reference value is the net change in the sectional ground capacitance due to deformation (during this measurement, the measured terminal capacitance is the parallel combination of sectional ground capacitances with the other terminal open). For minor deformations, the changes in ground capacitances can be directly correlated to the extent of radial deformations [4]. Thus the extent of radial deformation is provided by a change in \(C_s\), whereas its location is indicated by DC.

<table>
<thead>
<tr>
<th>Sectional Ground Capacitance Change</th>
<th>DC for first section</th>
<th>DC for second section</th>
<th>DC for third section</th>
<th>DC for fourth section</th>
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<tr>
<td>DC log 954.410 29.898 19.32 72.745</td>
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<td>DC log 1337.110 8.985 8.53</td>
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<td>DC log 56.010 210.502 17.529 57.402</td>
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<td>DC log 3.810 210.755 17.15 54.164</td>
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<td>DC log 0.01 0.5 1.5 2.5 3.5 4.5</td>
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<td>Sectional Ground Capacitance</td>
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Fig. 2. DC v/s p.u. change in \(C_s\).
B. DC as a Function of Change in Series Capacitance

The terminal capacitances seen from either end are calculated when the sectional series capacitance is changed for any section. Table II gives the expressions of DC as a function of \(y\) which is p.u. decrease in series capacitance. Again, the values of DC for a particular section lie in a narrow range as shown in Fig. 3. Each section has almost constant and distinct DC value irrespective of the extent of deformation. This is obvious by looking at the expressions of DC in Table II; the variation of \(y\) from 0.01 to 0.2 p.u. does not affect much the DC value for any section. Also, the DC values are quite distinguishable between the sections due to a large difference in the corresponding multiplicands. This distinctive feature of DC for each section, thus, helps to determine the deformation location.

Now using the same winding representation, one can find an expression for a change in the capacitance between terminals 1 and 2 \(\Delta C_{12H} = C_{12H}' - C_{12H}\) for various sectional series capacitance changes as shown in Table III. One can easily observe a pattern in the variation of \(\Delta C_{12H}\) with different p.u. changes in \(C_s\) at different sections. It is almost proportional to \(y\), as can be concluded from its expression in Table III, since the value of \(y\) is small as compared to the constant in the denominator (i.e., 1.4764). This characteristic can help in determining the extent of axial deformation during diagnostic tests, since for minor deformations the changes in series capacitances can be directly correlated to the extent of axial deformations [4]. Thus, the extent of axial deformation is provided by a change in \(C_{12H}\) whereas its location is indicated by DC.

| TABLE II |
| DC AS A FUNCTION OF P.U. CHANGE IN SECTIONAL SERIES CAPACITANCE |
| Sectional Series Capacitance Change | DC for first section | DC for second section | DC for third section | DC for fourth section |
| First section deformed | DC = \(\log_{10} \left( \frac{74083.0 \times (y - 1.1830)}{y - 1.9386} \right) \) | \(|\Delta C_{12} = -196.1 \left( \frac{y}{y - 1.4764} \right) \) | \(|\Delta C_{12} = -55.0 \left( \frac{y}{y - 1.4764} \right) \) | \(|\Delta C_{12} = -17.6 \left( \frac{y}{y - 1.4764} \right) \) |
| Second section deformed | DC = \(\log_{10} \left( \frac{1146.1 \times (y - 1.3805)}{y - 1.5703} \right) \) | \(|\Delta C_{12} = -55.0 \left( \frac{y}{y - 1.4764} \right) \) | \(|\Delta C_{12} = -17.6 \left( \frac{y}{y - 1.4764} \right) \) | \(|\Delta C_{12} = -8.3 \left( \frac{y}{y - 1.4764} \right) \) |
| Third section deformed | DC = \(\log_{10} \left( \frac{59.08 \times (y - 1.445)}{y - 1.4945} \right) \) | \(|\Delta C_{12} = -17.6 \left( \frac{y}{y - 1.4764} \right) \) | \(|\Delta C_{12} = -8.3 \left( \frac{y}{y - 1.4764} \right) \) | \(|\Delta C_{12} = -8.3 \left( \frac{y}{y - 1.4764} \right) \) |
| Fourth section deformed | DC = \(\log_{10} \left( \frac{3.8387 \times (y - 1.4644)}{y - 1.4743} \right) \) | \(|\Delta C_{12} = -8.3 \left( \frac{y}{y - 1.4764} \right) \) | \(|\Delta C_{12} = -8.3 \left( \frac{y}{y - 1.4764} \right) \) | \(|\Delta C_{12} = -8.3 \left( \frac{y}{y - 1.4764} \right) \) |

C. Procedure for Subsequent Diagnostic Tests

Reference tables/charts can be prepared as explained in the previous sub-sections for a transformer winding along with reference values for terminal capacitances, and selected high and low frequencies. During an actual diagnostic test (after transport, some field use or a short-circuit event), measurements need to be taken as outlined in [7]. Three
measurements at the selected high frequency ($C_{12H}$, $C_{12L}$) and one at the selected low frequency ($C_{1L}$) need to be taken for the winding under test.

Any deviation in the values of $C_{1H}$ and $C_{1H}$ as well as $C_{2H}$ and $C_{2H}$ from the reference values indicates a deformation, and a difference between the values of $C_L$ and $C'_L$ indicates a change in the sectional ground capacitance. This can be correlated to the extent of radial deformation as explained earlier in Section III-A. Comparison of the calculated DC with the values in the reference chart corresponding to ground capacitance changes (Fig. 2) gives the deformed section number. No appreciable difference between the values of $C_L$ and $C'_L$ indicates a series capacitance change. Comparison of calculated DC with the reference chart corresponding to series capacitance changes (Fig. 3) gives the deformed section number. Finding the difference between $C_{12H}$ and $C_{12L}$ and comparing it with the values corresponding to the deformed section number in the reference chart of Fig. 4 gives the extent of axial deformation. Interpolation may be required to find the exact extent of deformation from the figure.

IV. CONCLUSIONS

Winding deformations (displacements) may occur during transport or after some use at a site or due to short-circuit forces. Considering the special requirements of FRA (instrumentation and interpretation skills), a simple, easy to apply and generalized method is desirable for deformation diagnostics. This paper has presented a novel and elegant method which requires a few high frequency (three in number) and one low frequency terminal capacitance measurements to determine the location and extent of deformation.

Deformation Coefficient (DC), derived from the terminal measurements, is found to be an effective indicator for locating a winding deformation. It is a function of ratio of change in terminal capacitance at one end of the winding to the corresponding change at the other end. It has been shown, using derived closed form expressions, that DC for each section is distinct and lies within a narrow range of values for any practical extent of deformation. In the case of a deformation leading to a ground capacitance change, the extent of deformation can be determined from the low frequency terminal capacitance measurement. The capacitance, as measured across the two terminals at the selected high frequency, is found to give the extent of series capacitance change. The proposed method, with its simplicity in procedure and a reduction in the number of parameters to be measured, and the most importantly, inherent ease of analysis, makes it a serious contender for deformation diagnostics.

The applicability of the method is demonstrated for a single winding whose two terminals are accessible for measurements (e.g., bank of single-phase transformers wherein the neutral end can be isolated and made available). Experimental verification on laboratory scale model coils is currently underway and results obtained so far are encouraging. The values of series and ground capacitances in the simulation studies have been chosen so as to facilitate the experimental verification. The method can be applied to star and delta connected windings of three-phase transformers. Multiple deformations may also be detected. Finally, the method needs to be validated on actual transformers. All such future work would be reported separately.

REFERENCES