Detection of winding inter-turn faults

Detection based on frequency response analysis - Part I

ABSTRACT

This article deals with inter-turn fault detection in the transformer winding, inter-turn fault which occurs due to insulation degradation between one or more sequential turns of the winding. If the fault is not detected at the earliest stage, it propagates to the nearby turns of the winding during certain period of time and it causes irreversible damage to the winding. Therefore, it is necessary to detect inter-turn fault to save the transformer from catastrophic failure.

KEYWORDS

detection, fault factor, inter-turn, SFRA, transformer

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Inter-turn fault - a short circuit of a few turns of the winding - is one of the leading cause of power transformer failures

1. Introduction

Power transformers are critical components of the energy transmission and distribution process in electric power system. In view of increasing demand for reliable and high-quality energy supply, electrical utilities are more interested in avoiding transformer failures. Transformers are in service under different environmental, electrical, and mechanical conditions and may be subjected to enormous hazards during the course of operation. Any fault in transformers will cause the interruption of the power supply.

Inter-turn fault in the windings is one of the internal faults within the transformer. A short circuit of a few turns of the transformer winding will give rise to a heavy fault current in the short-circuited turns, but changes in the transformer terminal current will be very small, due to the high ratio of transformation between the whole winding and the short-circuited turns [1].

Once the inter-turn faults occur, a large circulating fault current is induced in the shorted turns, leading to localized thermal overloading in the defective region of the winding. Over certain period of time, the generated heat in the defective region will cause the fault to increase in size, and will involve another phase or ground conductor [2].

In the present study, transformer winding is modelled using ANSYS software (using finite element method and analysis through electrostatics and magnetostatics solvers) based on physical dimension data of the winding; parameters such as capacitance and inductance are extracted by performing electric and magnetic field analysis and capacitance and inductance parameters are used for circuit modelling of transformer winding for inter-turn fault detection study. Proposed methodology will be useful for design engineers to detect inter-turn faults by predicting the fault factor characteristics with the help of electrical equivalent circuit model of transformer winding using only the physical dimension data of the transformer.

The changes in the transformer winding impedance due to inter-turn short circuit fault serve as diagnostic parameter and impedance characteristics are obtained by measuring impedance over wide frequency range (10 Hz to 25 MHz) using sweep frequency response analysis (SFRA). A frequency response trace of winding changes due to different percentage of fault

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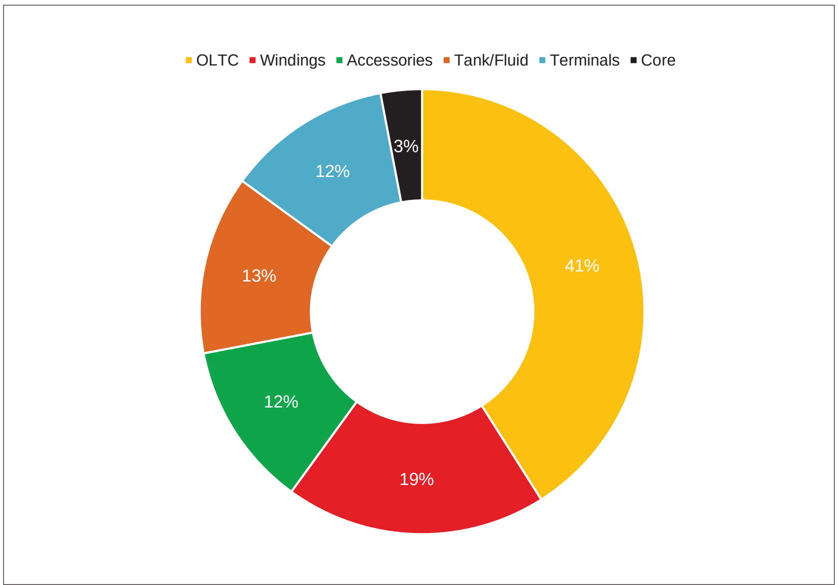

Figure 1. Survey of faults in transformer [3]

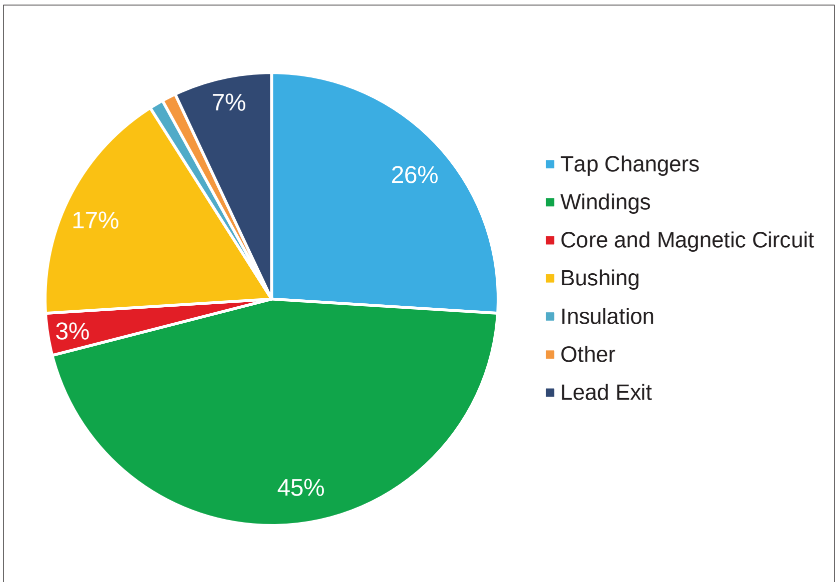

Figure 2. CIGRE failure statistics [4]

and the location of inter-turn fault due to the influence of winding distributed parameters such as series capacitance, shunt capacitance, inductance and resistance. In order to study the impacts of shunt and series capacitances on FRA trace, a continuous disc winding model, consisting of 12 discs including 15 conductors per disc is used as the test object with aluminium made static end ring (circular cross section) placed over the top of the winding, grounded inner core and aluminium tank housing on detection of inter-turn fault is considered as case study to validate the efficacy of the proposed methodology in practical cases.

2. Transformer winding - fault diagnosis methodology

Transformer winding faults are classified as inter-disc fault, turn to ground fault, double turn to ground fault, winding deformations, core connection problems, partial winding collapse etc. Among the detection of various faults, detection of inter-turn fault is critical since its effect is not easily comprehendible at lower magnitude in the signatures of terminal voltage and current. Among these faults, winding inter-turn fault is challenging to monitor and detect, especially at lower magnitude of the fault current [3]. Around 19 % of faults that occur in transformers are winding faults as shown in Figure 1. CIGRE working group A2.37 transformer reliability survey [4] is shown in Figure 2 and 30 % of faults in transformers due to winding [5] are shown in Figure 3.

A breakdown of insulation results in inter-turn fault. Following factors may cause breakdown or degradation of the insulation in the windings:

- Ageing of insulation due to high temperature [6]
- Moisture ingress in the insulation [6, 7, 8-10]
- Partial discharges in the insulation [11, 12]
- Transient over voltages [13, 14]

Most of the researches on modelling inter turn faults and investigations are focused on techniques of modelling a transformer under the inter-turn fault conditions, especially in the recent years. Accordingly, it would be advantageous to detect inter-turn fault to prevent further damage to the transformer, thereby reducing repair costs and transformer outage time. The proposed method for detection of inter-turn fault is based on:

- Transformer winding model approach
- Sweep frequency response analysis

Transformer windings have very complicated distributions of resistance, inductance and capacitance. Each winding turn is inductively linked to others to a greater or lesser extent, whether in the same disc, layer or winding. Each turn is also capacitively linked to its immediate neighbours, with a hierarchy of capacitances, e.g., turn-turn, disc-disc, winding and winding-earth. Winding inductances and capacitances are a function of material properties, geometry and any short circuit in the winding and the winding movement will result in substantial changes to these values at a local level [15].

Figure 4 represents a transformer assembly schematic diagram, where R represents the winding resistance, L_S represents self-inductance of winding and L_M represents mutual inductance between the windings. $C_{L\text{-}V}$ represents capacitance between LV and HV winding. The ground capacitance C_g constitutes the capacitance between the winding and the core or the grounded structures such as tank housing. The inter-disc and inter-turn capacitance constitute the total series capacitance of the winding C_s.

3. Detection of inter-turn fault in transformer winding using SFRA – circuit modelling

Using SFRA, it is possible to analyse the integrity of transformer without the prior dismantling. Changes in geometric configuration change the impedance of network which in turn changes the transfer function. Changes in transfer function will reveal a wide range of failure modes. SFRA allows the detection of changes in transfer function of individual windings within transformers and reactors and indicates movement or distortion in core and windings of the transformer [15].

The sweep frequency response of a transformer winding (often called the SFRA response curve) is quite complex and consists of decreasing and increasing magnitude (in dB) with respect to frequency. The various resonances (maxima) and anti-resonances (minima) are determined by the electrical characteristics of the transformer winding. These characteristics can be represented by the transformer equivalent circuit and would include the elements of resistance, inductance, and capacitance. The inductance and capacitance values in this equivalent circuit are determined by winding structure, geometry, insulation

Transformer windings have very complicated distributions of resistance, inductance, and capacitance, which are a function of material properties and geometry

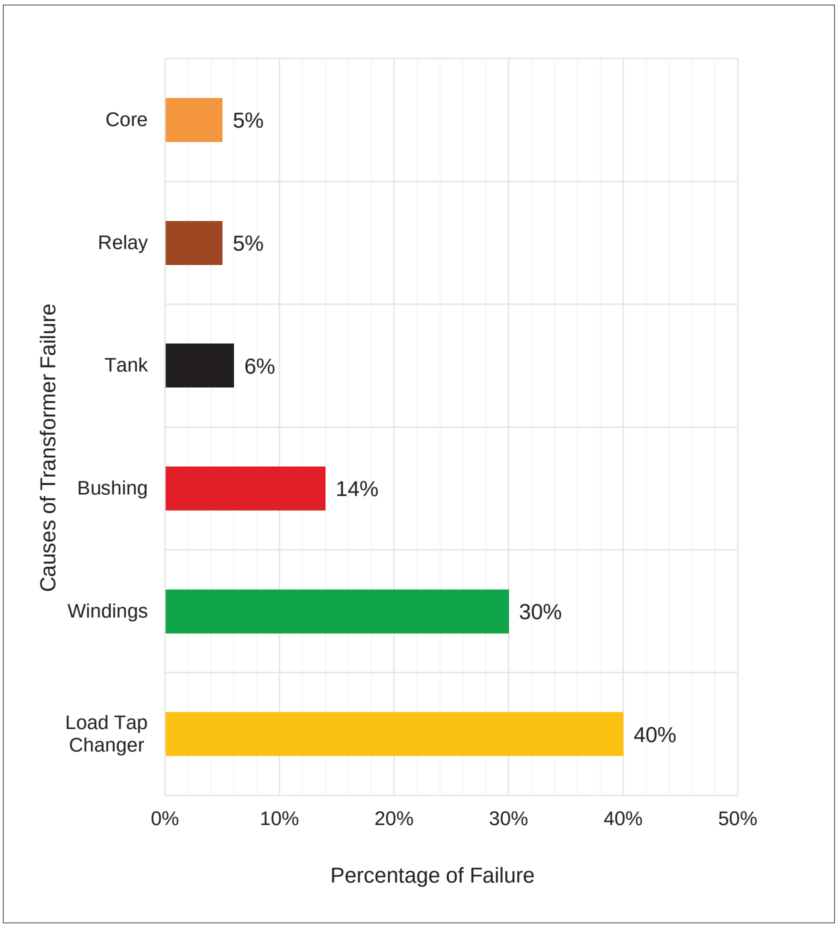

Figure 3. Causes of transformer failure [5]

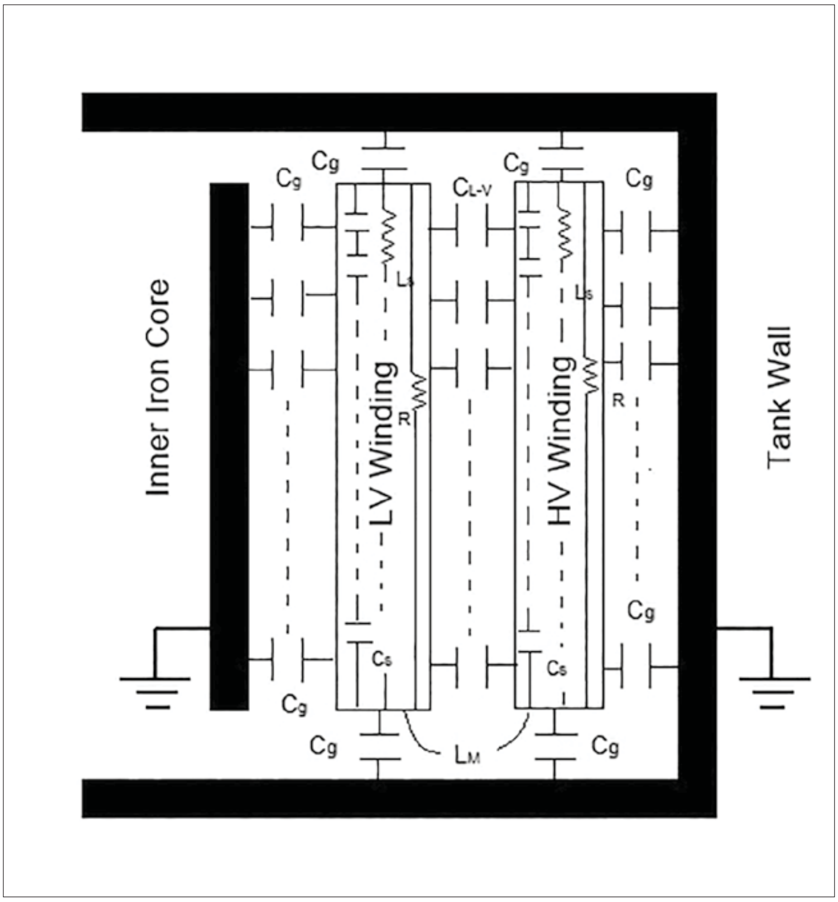

Figure 4. Transformer assembly schematic diagram

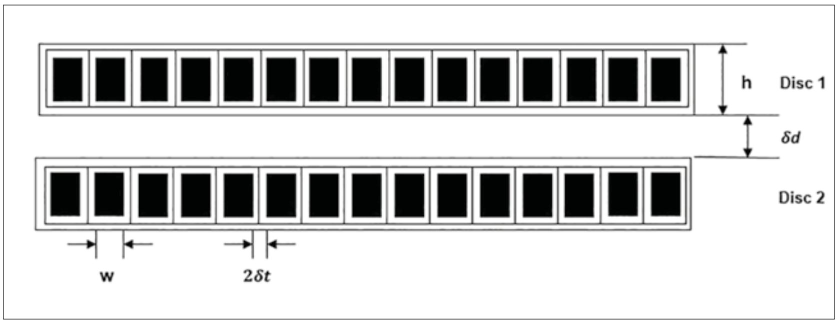

Figure 5a. Representation of transformer winding (two disc)

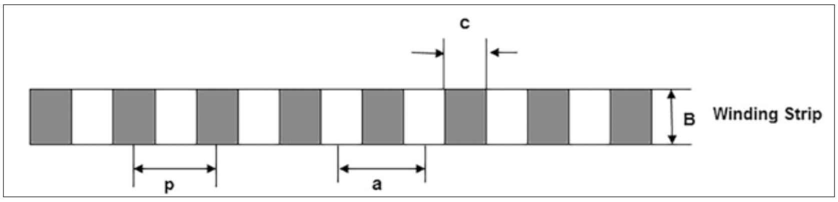

Figure 5b. Representation of winding strip used for inductance calculation

Any short circuit in the winding and the winding movement will result in substantial changes to resistance, inductance, and capacitance at a local level

structure and clearance. The resistance is contributed by conductive loss and dielectric loss [16].

The winding impedance shows a complex behaviour with change in frequency, as it is a combination of the resistance, inductance, and capacitances. At low frequencies, the capacitive network behaves as a purely open network. Hence, the current tends to flow only through the series path containing resistance and inductance. At high frequencies, inductive network behaves as a purely open network and the current flows through the capacitive elements in the circuit. Hence the equivalent circuit of transformer winding consists of only capacitive elements such as C_s and C_g. For transient studies transformer winding are modelled using resistance *R*, inductance *L*, series capacitance *Cs* and ground capacitance C_g. The C_g constitutes the capacitance between the winding and the core or the grounded structures such as transformer tank wall. The inter disc and inter turn capacitance constitutes the series capacitance C_s of the winding [17].

The mutual inductance has significant contribution to the winding impedance but due to the following reasons mutual inductance is omitted in the lumped parameter model:

- Complexity of model will be increased if we introduce mutual inductance that is each turn to other turns in a single disc, turn to nearby discs up to 'N' number of discs in the winding by using coefficient of coupling *K*.
- At low frequencies, the capacitive network behaves as a purely open network. Hence, the current tends to flow only through the series path containing resistance and inductance. At high frequencies, inductive network behaves as a purely open network and the current flows through the capacitive elements in the circuit. As frequency increases, inductive reactance will have values high enough to be neglected. Hence the equivalent circuit of transformer winding consists of only capacitive elements such as C_s and C_g. Present study on fault detection is based on resonant frequencies of higher order.
- Mutual inductance will have significant impact on electromechanical fault studies of transformer winding (axial and radial winding deformation due to short circuit current).

3.1. Transformer winding circuit modelling - parameter calculations

3.1.1. Calculation of capacitance

The series capacitance of the winding depends on the type of the winding connection i.e. continuous disc and layer winding. There is a number of analytical methods described for the calculation of C_s. It is not possible to calculate C_s for any complex geometry without approximation with a single analytical formula.

For transformer windings [18] analytical formulae for calculation of the inter-turn and inter-disc capacitance have been used. The formulae used are accurate only when the diameters of the windings are high compared to thickness of the inter turn insulation in the winding.

The representation of transformer winding (two disc) are shown in Figure 5a. The series capacitance of the continuous disc winding is composed of two parts, inter-turn and inter-disc capacitance. The voltage is assumed to be evenly distributed within the winding. The calculation of the resultant capacitances of the disc coil is based on the principle that the sum of energies accumulated in all the capacitance's parts within a section is equal to the entire energy of the section. Within the capacitance, it is equal to entire energy of the disc coil. Inter-turn capacitances between the turns C_t and between adjacent coils C_{dr} and turn to core C_g capacitance.

- Inter – turn capacitance C_t

$$C_t = \frac{\varepsilon_0\, \varepsilon_t\, \pi D(h+2\delta_t)}{2\delta_t} \tag{3.1}$$

Where:
δt - Thickness of inter-turn insulation (mm)
h - Height of the disc (including insulation and conductor)
D - Mean diameter of the winding

- Resultant inter – turn capacitance C_{tn}

$$C_{tn} = \frac{(n\text{-}1)C_t}{Nn^2} \tag{3.2}$$

Where:
n - Number of turns per disc (turns per section)
N - Total number of discs or sections in the winding
C_t - Inter – turn capacitance

- Inter – disc capacitance C_{dr}

$$C_{dr} = \pi\varepsilon_0 \cdot \frac{D}{3} \cdot \frac{r+\delta_d}{2\frac{\delta_t}{\varepsilon_t}+\frac{\delta_d}{\varepsilon_d}} \cdot e^{-12} \qquad (3.3)$$

Where:
D - Mean diameter of the winding
δ_t - Thickness of inter-turn insulation (mm)
δ_d - Thickness of spacer between discs (mm)
r - Mean radius of the winding (mm)
ε_t - Relative permittivity of inter-turn insulation (kraft paper)
ε_d - Resultant permittivity of (oil + solid) insulation of thickness δ_d

- Resultant inter – disc capacitance C_{dn}

$$C_{dn} = \frac{4(N\text{-}1)C_{dr}}{N^2} \qquad (3.4)$$

Where:
C_{dr} - Inter – disc capacitance
N - Total number of discs or sections in the winding

- Total series capacitance K

$$K = C_{tn}+C_{dn} = \frac{(n\text{-}1)C_t}{Nn^2} + \frac{4(N\text{-}1)C_{dr}}{N^2} \qquad (3.5)$$

3.1.2. Calculation of self-inductance

The self-inductance of circuit elements is associated with magnetic materials and are independent of the values of the current but dependent on the geometry of the system. Self-inductance of the continuous disc winding has been calculated using Grover's formula [19]. The calculation of inductance by Grover's method is tedious due to the mutual inductance of continuous disc winding, involves high error and no straight forward method is given for the mutual inductance between the discs. Representation of winding strip is shown in Figure 5b and is used as a reference to self-inductance calculation.

The inductance is a function of the shape of the coil so that shape ratios, such as $c/2a$ and b/c are involved. The equivalent self-inductance is given by the equation:

$$L's = 0.001 \cdot N^2 \cdot a \cdot p\ \mu H \qquad (3.6)$$

$P = P \cdot F$, where P is a function of $c/2a$ and F takes into account the reduction of inductance due to separation of the turns in the axial direction. The self-inductance of the winding is given by:

$$L = L'_s - 0.004 \cdot \Pi \cdot N \cdot a \cdot (G_1 + H_1) \qquad (3.7)$$

$$G_1 = \log_e\left(\frac{B+C}{P}\right) + \log_e e \qquad (3.8)$$

By using SFRA, it is possible to analyse the integrity of transformer without the prior dismantling

$$H_1 = H + 2\left\{\begin{array}{l}\left[\frac{N-1}{N}\right]\cdot \log_e K + \frac{1}{12}\left(\beta^2-\gamma^2\right)\cdot\left[0.6449 - \frac{\log_e \frac{N}{2} + 1.270}{N}\right] - \\ \frac{1}{60}\left[\beta^4+\gamma^4-\frac{5}{2}\cdot\beta^2\cdot\gamma^2\right]\cdot\left[0.0823-\frac{0.2021}{N}\right]\end{array}\right\} \qquad (3.9)$$

Where:
N - Number of turns per disc
G_1, H_1 - Correction factors
a - Mean radius
H - This value is collected from specific table of reference [19]
B - Height of conductor (mm)
P – $(C/2a)$ is collected from specific table of reference [19]
$\beta = (B)/p)$; $\gamma = (C/p)$;

Transformer winding parameters are extracted using finite element method (FEM) before actual modelling; physical dimension data of winding has been collected and shown in Table 1. The winding analytical calculations such as inter turn capacitance, resultant inter-turn capacitance, inter-disc capacitance, resultant inter-disc capacitance, and self-inductance is calculated.

The schematic of transformer winding (top view) and coil diameter (inner and outer) is visually shown in Figure 6.

Using electro statics and magneto statics solvers in ANSYS software, capacitance and inductance are extracted. Also, analytical and FEM values are compared for accuracy in calculation and shown in Table 2, and then the values used for winding circuit modelling are shown.

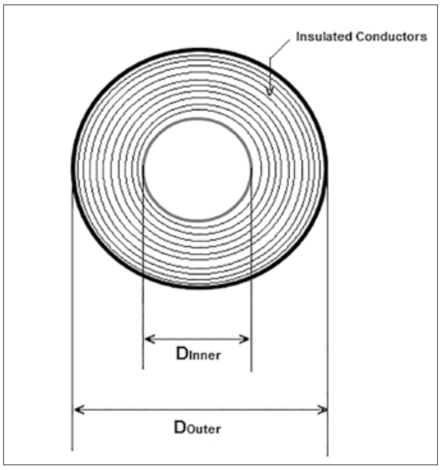

Figure 6. Schematic of transformer winding (top view)

Table 1. Dimension data for modelling of transformer winding

Specifications of continuous disc winding	
Number of turns per disc or turns per section (n)	15
Average turn length (L)	136 mm
Number of discs / sections (N)	12
Thickness of insulation between conductors (δ_t)	0.3 mm
Height of bare conductor (h)	11 mm
Coil outer diameter (D_{outer})	308 mm
Coil inner diameter (D_{Inner})	170 mm
Mean diameter of the winding (D)	239 mm

Table 2. Transformer winding parameters comparison

Parameters of the winding for each turn	Analytical calculation	Extraction using FEM
Inter-turn capacitance (C_t)	267.33 pF	273 pF
Self-inductance (L_s)	4.581 mH	4.647 mH
Shunt capacitance (C_g)	Extraction using FEM	
	0.187 pF	

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