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ELECTROMAGNETIC METHODS

A Robust Approach for Locating and Assessing Mechanical Faults in an Actual Transformer Winding Using the State Space of Its Lumped Equivalent Model

Rachid Sahnoune Chaouche[a,*], Hamza Houassine[a,b], Samir Moulahoum[a], Moustafa Sahnoune Chaouche[d], and Samir Bensaid[b,c]

[a] *Research Laboratory of Electrical Engineering and Automatic LREA University of Medea, Medea, Algeria*

[b] *Sciences and Applied Sciences Faculty, University of Bouira, Bouira, Algeria*

[c] *Laboratory of Materials and Sustainable Development (LM2D) University of Bouira, Bouira, Algeria*

[d] *Faculty of Technology, Department of Electrical Engineering, University of Medea, Medea, Algeria*

**e-mail: rachid-chaouche@hotmail.fr*

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Abstract—Transfer function and state-space model are two powerful complementary tools have been used to monitoring the physical system. These two ways can be very successful in giving a comprehensive analysis of electrical power transformer malfunctions. This paper proposes a novel robust approach nondestructive to diagnose short circuit (SC) faults by considering axial displacements (AD) in the transformer winding. Initially, elaboration a native autonomously tool to control the LCR meters through computing systems. This platform will control the impedance measurement by the instrument of the LCR meter through MATLAB software. Additionally, achieving estimation autonomously to all the parameters of the lumped equivalent model of the winding accurately using frequency response analysis signal morphology interpretation (FRASMI). On the other hand, obtaining a new representation of the state-space model of the lumped equivalent model of an isolated winding with SC fault between its turns to locate and assess its severity. Finally, the relationship between the model parameters and the resonance frequencies of the frequency response curve can provide an effective nondestructive diagnostic tool for all mechanical damages of winding (e.g., SC with AD) which have been implemented experimentally, in which a new physical index has been proposed making it possible to locate and assess the extent of these defects simultaneously.

Keywords: axial displacement, frequency response, mutually coupled model, short circuit faults, state space model, transformer winding

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1. INTRODUCTION

The electrical transformer is the vital part of electrical system used to link between electrical networks with same frequency. Except that during his life may a set of salient malfunctions that arise silently and without warning. Which affects various components such as the core, the windings and the insulation [1, 2]. For several years a great effort has been devoted to the study of mechanical deformations for instance in [3, 4]. The various mechanical impacts that are the reasons for the failure of the transformer windings are divided into two important parts: The first one, the electromagnetic forces produced by short circuits and the surge voltage [5]. The second part, the transformer damages are due to the routine tests at the factory and during the transportation of the electrical transformer from the factory to the operating set [6]. This requires finding effective ways to deal with these mechanical failures, and to answer a specific question: How can these faults be detected early in order to avoid damaging the electrical transformer? Frequency response analysis (FRA) is one of the most popular recently and most widely used means to achieve required goals [7, 8]. The success of this method of detecting minor mechanical defects has clear foundations, which is accreditation clarity of interpretation [9].



Fig. 1. The experiment test bench.

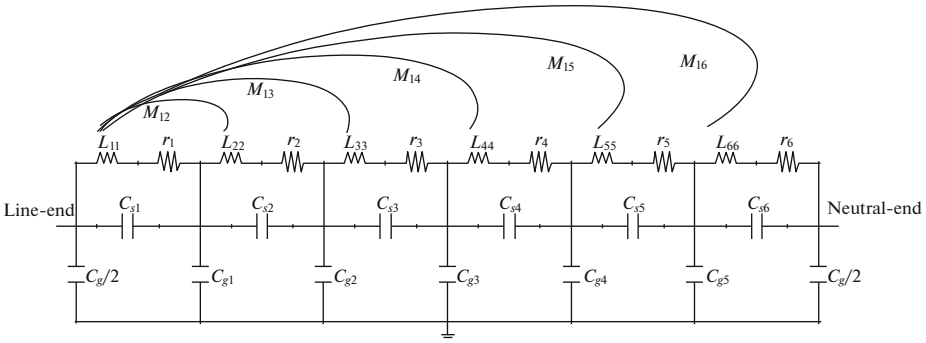


Fig. 2. The lumped model scheme of transformer winding.

2. THE PROPOSED APPROACH FOR SIMULATING, LOCATING AND ASSESSING THE EXTENT OF TRANSFORMER WINDING DAMAGES

As part of the design of an autonomous test platform dedicated to modelling and nondestructive diagnosing transformer winding failures using the FRA technique, the impedance response data acquisition program on MATLAB software was carried out. This platform allows the following tasks to be carried out: first, perform communication and autonomous data acquisition between the LCR meter and the PC. Second, simple control of the LCR meter with MATLAB software. Third, quickly realization of various FRA tests in order to build a large database allowing the analysis and interpretation of these data in order to diagnose the transformer winding failures. An experimental study has been done on isolated transformer winding for 06 disks as shown in Fig. 1.

2.1. State-Space Equation for the Coupled Ladder Network

The lumped mutually coupled model shown in Fig. 2 is currently used for diagnosing and analysis of the power transformer winding failures [6, 10]. This model can represent all physical proprieties of the windings such as; the magnetic couplings between the windings and the disks, and the electrical coupling between the windings and between the turns, and between the winding and the ground by self and mutual inductances, series capacitances between turns, and shunt capacitances between the winding and the ground respectively. Furthermore, the necessary steps to define state-space equations of the coupled ladder network are described as follows:

The most format representation of the state equations are assigned below.

$$\dot{x} = [A]x + [B]u, \tag{1}$$

$$y = [C]x + [D]u, \tag{2}$$

where x is defined as a vector for state variable, u is defined as excitation vector and A, B, C, and D are constant matrices.

2.2. Determination of the Percentage of the Short-Circuited Turn's Number in Each Winding Disk

The short-circuited turns in each disk is designated by n_{cc1} for the disk 1, n_{cc2} for the disk 2, and n_{cci} for the disk i. Let n_T is the total number of turns per disk in the case of a healthy isolated transformer winding. The coefficients n_1, n_2, and n_i are the percentage of the short-circuited turns at disks 1, 2, and i, respectively, of the winding, which are defined as follows:

$$\begin{bmatrix} n_1 = \dfrac{n_{cc1}}{n_T} \\ n_2 = \dfrac{n_{cc2}}{n_T} \\ \vdots \\ n_i = \dfrac{n_{cci}}{n_T} \end{bmatrix}. \tag{3}$$

The coefficients f_i represent the percentage of turns not short-circuited by each disk of the winding. These coefficients defined by:

$$\begin{bmatrix} f_1 = 1 - n_1 \\ f_2 = 1 - n_2 \\ \vdots \\ f_i = 1 - n_i \end{bmatrix}. \tag{4}$$

The resistances, the self, mutual inductances and the series capacitances of the winding depend on their nominal values and of the coefficients f_i, which are given by the following matrices.

$$R = r * \begin{bmatrix} f_1 & 0 & \dots & 0 \\ 0 & f_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & f_i \end{bmatrix}, \tag{5}$$

$$L = \begin{bmatrix} f_1^2 l_{11} & f_1 f_2 M_{12} & \dots & f_1 f_j M_{1j} \\ f_2 f_1 M_{21} & f_2^2 l_{22} & \dots & f_2 f_j M_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ f_1 f_i M_{i1} & f_i f_2 M_{i2} & \dots & f_{ij}^2 l_{ij} \end{bmatrix}, \tag{6}$$

$$K = \begin{bmatrix} \dfrac{C_s}{f_1} + \dfrac{C_{g1}}{2} & \dfrac{-C_s}{f_1} & \dots & 0 \\ \dfrac{-C_s}{f_2} & \dfrac{2C_s}{f_2} + C_{g2} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \dfrac{2C_s}{f_i} + C_{gn} \end{bmatrix}. \tag{7}$$

Note: The shunt capacitance C_g can be defined by the capacitance between winding and ground. However, this capacitance is the equivalent capacitance of the shunt capacitances between the turns and the ground. As the capacitances between turns are not equal, their equivalent shunt capacitance cannot be expressed in terms of the turn's number and therefore cannot be expressed in terms of the faulty coefficient f_i. Besides, the shunt capacitance can be estimated autonomously using the optimization method in healthy and defective winding cases of the winding from the equivalent capacitance, which is extracted directly from the FRA curve in high frequency using the FRASMI method [11]. The complete model of the state-space model represents the coupled ladder network, taking a considerably short circuit of turns in the faulty disk; can take the form of an equation of state and output:

$$\dot{x} = A(0, E_i, I_e, I_i, f)x + B(I_u, 0, 0, 0), \tag{8}$$

$$y = C(C_s, A_y, f)x + D(C_s, B_y, f). \tag{9}$$

For the following matrices E_i, I_e, I_i, I_u, A_y, and B_y, it is clearly and effectively presented in [6].

The transfer function defined by applying the Laplace transformation is as follows:

$$TF = \frac{Y(s)}{E_i(s)} = ([C][SI - A]^{-1}[B] + [D])\left[\frac{1}{S}\right]. \tag{10}$$

The vector of the defects f is given by:

$$f = \begin{vmatrix} f_1 \\ f_2 \\ \vdots \\ f_i \end{vmatrix}. \tag{11}$$

2.3. The Proposed Approach to Locate and Assess the Extent of the SC with AD Faults

The phenomena of short circuit in the transformer windings, due to the destruction of the protective enamel (varnish). It's occurring locally and forms a hot spot. The short-circuit in winding twisted slowly, slowly, to destroy the active part of the electrical transformer. With every short-circuit turn a black point is placed in the transformer winding, and little by little it becomes perishable. The process of increasing the percentage of short-circuit winding clearly shows a decrease in the amplitudes of impedance and increases in the displacement of frequencies resonance. A remarkable change in the self-inductance (L_{ii}), series capacitance (C_{si}) and the mutual inductance (M_{ij}) between disks. However, the mathematical relationship proposed by Mukherjee [12, 13] shown in Eq. (12) links between the resonant frequencies and the parameters of the lumped equivalent model of the winding is a promising tool in the diagnosis field of transformer failures.

$$\Psi_{\text{ocnf}} = \sum_{i=1}^{N} \frac{1}{\omega_{\text{sci}}^2} = \sum_{i=1}^{N} L_{ii}C_{si} + \sum_{i=1}^{N} M_{0i}C_{gi}. \tag{12}$$

In the case of a healthy winding, let's write this equation as follows:

$$\Psi_{\text{ocnf}} - (L_{11}C_{s1} + \ldots + L_{NN}C_{sN}) = \sum_{i=1}^{N} M_{0i}C_{gi}. \tag{13}$$

It should be noted that in the event of an SC fault on a winding disk (e.g., the first disk) causes changes to the model parameters (L_{11}, M_{1j}, C_{s1}, and C_{g1}), which leads to the changing of the relationship in (13), which can be written as by (13).

$$\widehat{\Psi_{\text{ocnf}}} - (\widehat{L_{11}}\widehat{C_{s1}} + L_{22}C_{s2} + \ldots + L_{NN}C_{sN}) = \widehat{L_{11}}\widehat{C_{g1}} + \sum_{i=2}^{N} \widehat{M_{0i}}C_{gi}, \tag{14}$$

where Ψ_{ocnf}, M_{0i}, C_{gi}, L_{11}, and C_{s1} correspond to the ladder network parameters before change, and $\widehat{\Psi_{\text{ocnf}}}$, $\widehat{M_{0i}}$, $\widehat{C_{gi}}$, $\widehat{L_{11}}$, and $\widehat{C_{s1}}$ after change, respectively.

$$\widehat{L_{11}}\widehat{C_{s1}} = L_{11}f_1^2C_{S1}\ 1/f_1. \tag{15}$$

Let's also put;

$$\Upsilon_{\text{ocnf}} = \Psi_{\text{ocnf}} - L_{11}C_{s1}. \tag{16}$$

and

$$\ddot{\Upsilon}_{\text{ocnf}} = \widehat{\Psi_{\text{ocnf}}} - L_{11}f_1^2C_{S1}\ 1/f_1, \tag{17}$$

where Υ_{ocnf} and $\ddot{\Upsilon}_{\text{ocnf}}$ correspond to the ladder networks before and after the change respectively. Hence,

$$\Delta\Upsilon_{\text{ocnf}} = \ddot{\Upsilon}_{\text{ocnf}} - \Upsilon_{\text{ocnf}} = \widehat{\Psi_{\text{ocnf}}} - L_{11}f_1^2C_{S1}\ 1/f_1 - (\Psi_{\text{ocnf}} - L_{11}C_{s1}). \tag{18}$$

This new physical index will be used to locate and assess the severity of transformer winding short-circuit faults autonomously.

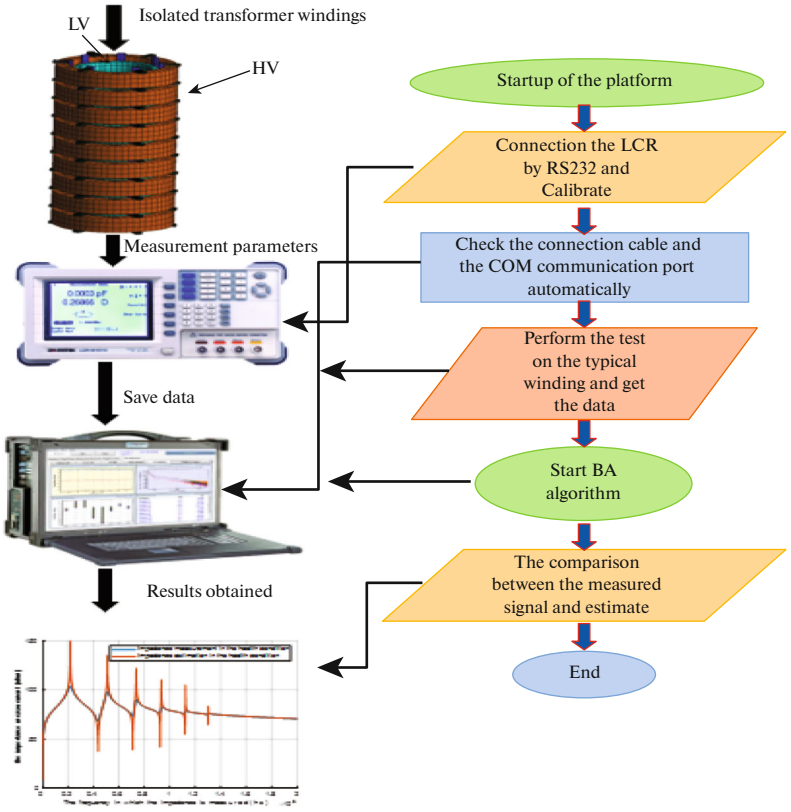


Fig. 3. Block diagram explain the main steps of the platform.

2.4. Block Diagram of the Proposed Approach

The block diagram shown in Fig. 3 summarized the basic steps of the proposed approach, which is composed of: (1) the FRA data acquisition platform autonomously using the LCR meter through MATLAB software, (2) the construction step of the equivalent circuit model of the transformer winding using the FRASMI method by the BA algorithm [11], (3) the winding fault simulation step using the state-space equations of the lumped equivalent model, and (4) the proposed approach to locate and assess the severity of mechanical faults winding (e.g., SC with AD).

3. RESULTS AND DISCUSSIONS

In this research, the lumped equivalent model to a transformer winding was constructed using the frequency response analysis signal morphology interpretation (FRASMI) method by applying the BA algorithm. This method is based on the decomposition of the FR signal into three ranges such as; the low, the medium and the high frequencies, in which, the self and mutual inductances (L_{ii} and M_{ij}), and the shunt and series capacities (C_{s1} and C_{g1}) are determined in the low and high frequencies from the FRA impedance, it is also possible to calculate the turn leakage inductances, capacitances and resistances by using their formulas as represented in the Appendix (ESM_1.Doc). However, the equivalent inductance (L_{eq}) and the equivalent capacitance (C_{eq}) values of the winding are extracted in these two frequency ranges respectively and shown in Table 1.

The estimated parameters of the lumped mutually coupled model using the FRASMI method via the BA algorithm, the self and mutual inductances in mH and the shunt and series capacitances in pF are shown in Table 2. However, the comparison between the measurement impedance of the winding in healthy condition using the LCR meter and that estimated is depicted in Fig. 4.

Table 1. The main measured parameters of the lumped equivalent circuit of the winding

The main parameters of the model	The frequency range in which the parameters measured		
	0 kHz	50 kHz	2 MHz
C_{eq}, pF	–	–	33.11
L_{eq}, mH	–	9.7204	–
R, Ω	2.4	–	–

Table 2. The estimated lumped model parameters

$M_{00} = 0.701$	$M_{01} = 2.329$	$M_{02} = 3.755$	$M_{03} = 5.534$	$M_{04} = 7.468$	$M_{05} = 9.720$	$C_s = 62.42$	$C_g = 18.65$

3.1. Short-Circuit Faults Ssimulation and Interpretation of Transformer Winding

The inductance is the most affected component in failures such as disk deformation, core deformation, and short circuit winding, which is the most influence the amplitude and resonant frequencies of the FRA impedance curve. The second element, which is no less important in determining faults, is the ground capacitances. The strength of the third element use for health inspection of power transformer is the series capacitance. In order to interpret the effect of short-circuit faults on the FRA curve, different fault levels (e.g., SC with 5 to 40%) on different disks were performed on the actual transformer winding. However, Fig. 5a shows the short-circuit faults performed in disk 5 with different levels. From this figure, it can be seen that, the resonant frequencies are shifted to the right as a function of increasing of SC fault levels.

The OCNFs of SC faults performed on different disks of the reel winding with different levels are shown in Table 3. Furthermore, Table 4 shows the OCNFs of the SC realized on two disks of the winding simultaneously with different levels (e.g., 5, 20, 30, and 40%).

3.2. Location and Severity Extent of SC with AD Faults of Transformer Winding

The emergence of AD with SC fault can lead to the fault development on the transformer winding, as it causes a state of imbalance and asymmetry between the winding turns, which affects its parameters. Figure 6 is a winding design that shows how to realize an AD with SC fault between disks 5 and 6. In any way, the axial displacement occurs abundantly at the bottom of the coil, and is expressed by δ. However, Fig. 6 shows the comparison between the measured FRA curves before and after the SC with AD faults with 5 mm AD and 20% of SC.

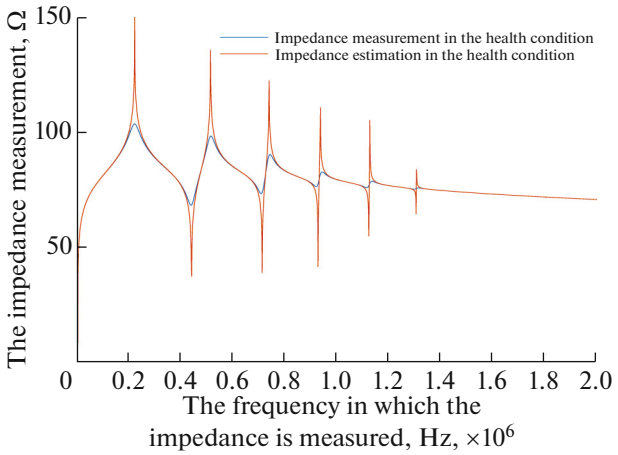


Fig. 4. The FRA fingerprint corresponding to the healthy winding and the impedance estimation in the health condition.

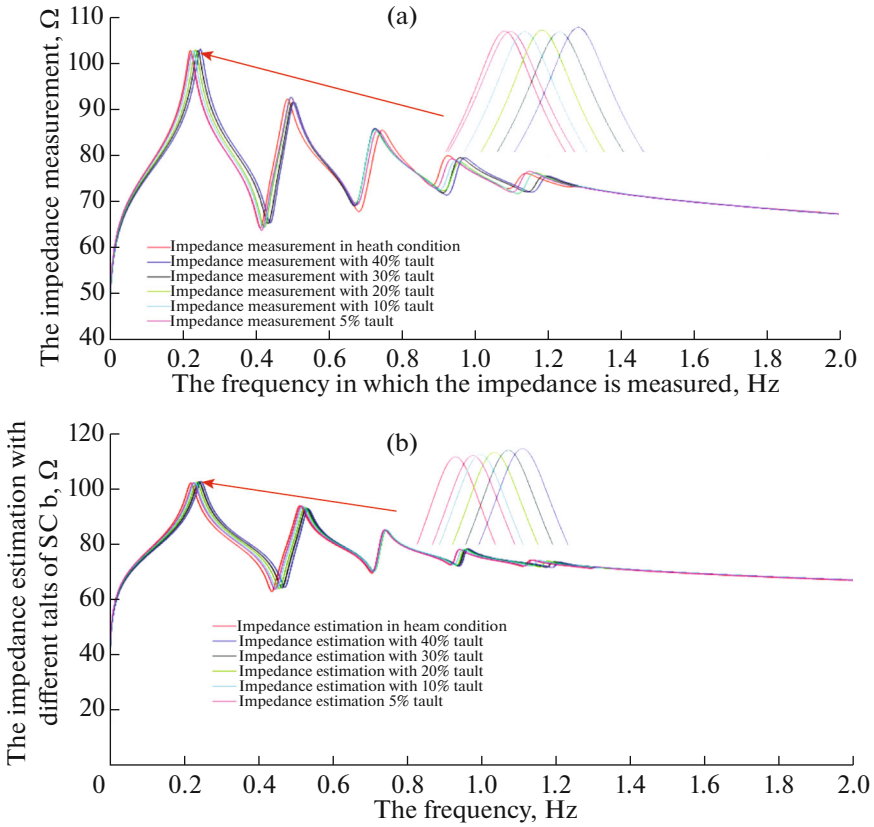


Fig. 5. Short-circuit faults in disk 5 with different levels: (a) reel faults, (b) simulation faults.

3.3. The Change of the Equivalent Inductance as a Function of the Percentage of SC

In this part, have been analysed the variation of ΔL_{eq} in the case of the influence of AD with SC on the model. However, the steps involved for that are: Calculation of $\Delta\Upsilon_{ocnf} = 1.2964$. Then the projection the value obtained of $\Delta\Upsilon_{ocnf}$ on X. By reading on Fig. 7a, the fault has been located between disks 5 and 6, the value obtained of X correspond $\Delta\Upsilon_{ocnf}$ is around 5. Accordingly, conclusion that the fault in the disk 5. Figure 7b below shows the graphical representation of equivalent inductance as a function of short-circuit ratios proportion of 5, 10, 20, 30, and 40% in disk 5, although the displacement ratio δ was taken (5, 8, 14, 17, and 20 mm). The inductance equivalent before and after an AC with SC, respectively, are $L_{eq} = 9.7204$ mH and $\tilde{L}_{eq} = 8.6863$ mH with of 5 mm ratio of AD. The ΔL_{eq} calculated is $\Delta L_{eq} = -1.0341$ mH. By projecting the obtained value on the short-circuit ratio curves in the figure below, the value is between 10 and 20% and approximately 20% where the two lines intersect at the redpoint. In the second example, we have $\Delta L_{eq} = -0.8644$ mH where the SC fault is 5% with an axial displacement of 17 mm.

3.4. Case Study of Axial Displacement with Short-Circuit Consideration with Different Extents of Displacement

The phenomenon has been studied with displacement ratios 5, 8, 14, 17, and 20 mm in the case of short circuit ratios in each disc by 5, 10, 20, 30, and 40%. And as previously mentioned, which was summarized

Table 3. The open circuit natural frequencies of SC faults with different levels in different disk

	No. disks	OCNFs (kHz) of SC in one disk					ΔL_{eq}, mH
		1st	2nd	3rd	4th	5th	
5%	3	225	494	742	945	1145	–0.367
20%	5	236	499	727	959	1166	–0.882

Table 4. OCNFs (kHz) of SC faults in two disks simultaneously with different levels

	No. disks	OCNFs (kHz) of SC in two disks					ΔL_{eq}, mH
		1st	2nd	3rd	4th	5th	
20%	4 and 5	248	506	753	976	1180	−1.508
40% (3) 30% (4)	3 and 4	250	533	818	981	1154	−2.532

Table 5. Results of axial displacement with short-circuit consideration for different disks winding

AD with SC	OCNFs, kHz					Δc_g, pf	ΔL_{eq}, mH	δ, mm	$\Delta\Upsilon_{ocnf}$	degree of SC
	1st	2nd	3rd	4th	5th					
D5–D6	244	504	706	907	1125	2.4	−0.0011	8 mm	1.7949	20%
	236	506	682	868	1108	5.6	−0.8644	17 mm	4.2381	5%
D2–D3	227	495	765	886	1135	3.7	−0.0014	14 mm	1.2844	20%

in Table 5, to measure the parameters of the winding before the occurrence of the malfunction and after its occurrence, then calculate the difference each time, in order to know the extent of displacement and the location of displacement on one side and on the other hand, to show the extent of the ratios of the short circuit.

6. CONCLUSIONS

The first healthiest method ever to find out the correctness of the electrical transformer winding is the analysis of the frequency response (FRA). The analysis of the FRA spectral is an appreciable help to distinguish the extent of alarm generated by AD with SC consideration. This paper first exposure a new method of modelling the transformer winding concerning a short circuit fault in turns in the winding. This approximation is valid as long as n_i is small in front of 1, is used to analyse and synthesize how the model behaves when n_i varies. The simulations that have been presented in this paper assist in the evaluation and interpretation of FRA measurement when a short-circuit occurs by introducing various SC fault ratios: 5, 10, 20, 30, and 40%. The results obtained illustrate that the SC faults in the power transformer winding has been repercussions on the FRA response. Moreover, the proposed calculation of $\Delta\Upsilon_{ocnf}$ and ΔL_{eq} allow better access to detailed information on the characteristics of the AD with SC consideration. Introducing a relationship that combines two faults conditions in electrical transformer winding will be a comprehensive, multi-monitoring solution by determining the location and percentage of the damage is a global solution to diagnostic this problem.

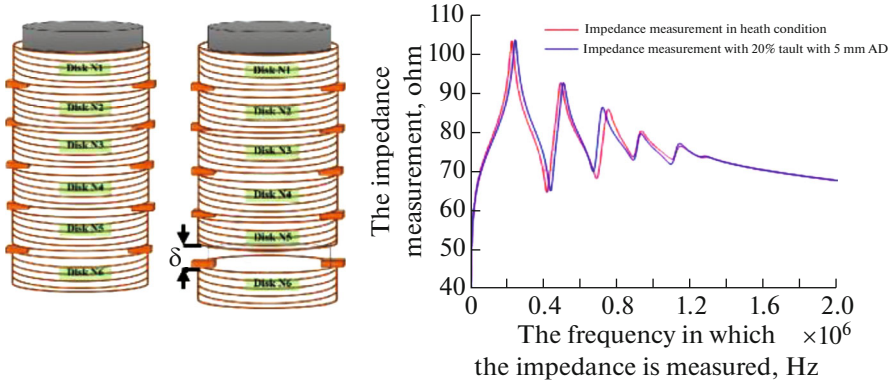


Fig. 6. Example of the winding design before and after the occurrence of AD with SC faults in disk 5.

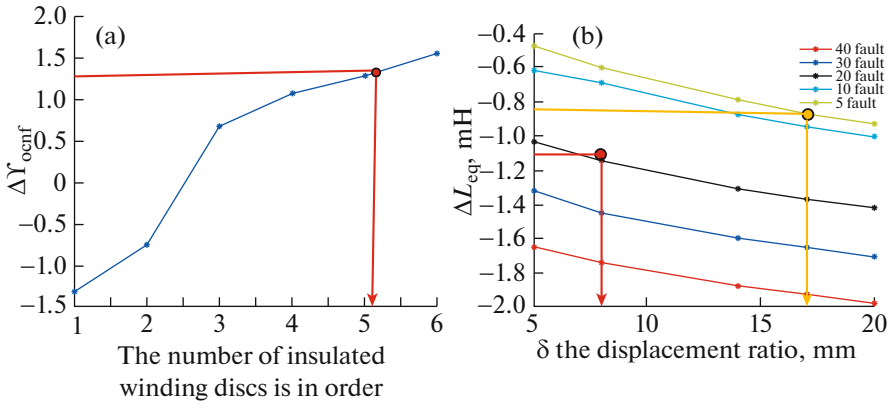


Fig. 7. The change of the equivalent induction in terms of the displacement range in the case of different ratios of SC.

APPENDIX

ANALYTICAL FORMULATIONS

The simulation of the frequency response of transformers windings depend on their structure, were that are formed meshes of RLC elements. In most practical air-core inductances are multi-layered cylindrical coils, and the capacitance is based on geometrical and energy considerations.

Self-Inductance

In the most general case, the self-inductance can be given from the first Maxwell's equations, it is always a positive quantity. The self-inductance depends on the geometry of the circuit and the magnetic properties of the medium in which it is immersed. The intensity of the current which circulates in the coil creates a magnetic field B [14, 15]

$$\oint \vec{E} * \overrightarrow{d_s} = -\frac{d\Phi}{dt} = -\frac{d}{dt}\int\int (\vec{B} * \vec{n}) * dA = -\frac{d}{dt}\oint (\vec{A} * \overrightarrow{d_s}). \quad (1)$$

Le flux total can be given as follow:

$$\Phi = \int\int (\vec{B} * \vec{n}) * dA = \oint (\vec{A} * \overrightarrow{d_s}) = L * I. \quad (2)$$

For a circular conductor, the flux through the loop is expressed by:

$$\Phi = \Phi_{\text{outer}} = \oint_{C2}\left[\frac{\mu_0 * I}{4\pi}\oint_{C1}\frac{\overrightarrow{d_{s1}}}{r}\right] * \overrightarrow{d_{s2}} = \frac{\mu_0 * I}{4\pi}\oint_{C1}\oint_{C2}\frac{\overrightarrow{d_{s1}} * \overrightarrow{d_{s2}}}{r}. \quad (3)$$

And therefore:

$$L = L_{\text{outer}} = \frac{\mu_0}{4\pi}\oint_1\oint_2\frac{\overrightarrow{d_{s1}} * \overrightarrow{d_{s2}}}{r}, \quad (4)$$

where $\overrightarrow{d_{s1}}$ is unite vector quantity, $\overrightarrow{d_{s2}}$ is unite vector, r is a distance between two elements $\overrightarrow{d_{s1}}$ and $\overrightarrow{d_{s2}}$. For a circular coil the inductance is given by

$$L_i = \mu_0 * R\left(\ln\frac{8 * R}{R_s} - 2\right), \quad (5)$$

where R is the mean radius, R_s is the mean geometric radius.

Mutual Inductance

Mutual induction is a coefficient reflecting the influence of one magnetic circuit on another. The mutual inductance by a filament circuit is given with the following relation:

$$M_{12} = \frac{\mu_0}{4\pi}\int_0^{2\pi}\int_0^{2\pi}\frac{r_1(\alpha_1) * r_2(\alpha_2) * \cos(\alpha_1 - \alpha_2)}{R_{12}(\alpha_1, \alpha_2)}d\alpha_1 d\alpha_2. \quad (6)$$

Series Capacitance

The Following expression use to calculate the series capacitance for whole winding:

$$C_s = \frac{1}{n_t - 1} C_s', \tag{7}$$

where n_t number of turns.

Shunt Capacitance

There are three types of shunt capacitance in transformer: capacitance between windings, the capacitance between phases and capacitance to the tank. Where the third type is more interested in this research.

$$C_g = 0.75 * \frac{2\pi\varepsilon_r\varepsilon_0 h'}{\ln\left(\frac{t}{d_0}\right)}. \tag{8}$$

Resistivities

$$R = \rho * \frac{l}{A}, \tag{9}$$

with ρ is the copper resistivity, l is the winding length, and A is the conductor section. The resistance of each element of the lumped scheme is $r = R/n$, n is the cell number of the lumped equivalent scheme.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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