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MAGNETOSTRICTIVE VIBRATION MODEL FOR EVALUATION OF MECHANICAL INTEGRITY OF POWER TRANSFORMER MAGNETIC CORE

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Magnetostriction process creates vibrations within magnetic core of a power transformer. This effect can cause delamination of magnetic core layers and increase the vibration amplitudes on the surface of transformer tank. In this paper, a magnetostrictive vibration model is proposed for improved evaluation of the mechanical integrity of magnetic core and the finding of possible mechanical defects. This model is based on the simulation of magnetostrictive vibrations by replacing the magnetic core with mass and spring system, and application of a dynamic genetic algorithm in order to find the necessary system configuration. A case study is provided structurally modelling magnetic core in *Matlab* and *Matlab Simulink* with the analysis of simulated vibrations that indicate a possible mechanical defect.

Keywords*: magnetostriction, numerical simulation, transformer cores.*

1. INTRODUCTION

There are numerous different defects that can originate within power transformers during their operation period. These defects can be categorized in the following types:

- Electrical defects – e.g., internal short-circuits between individual winding turns, localized partial discharges;
- Thermal defects – e.g., transformer winding solid insulation degradation, hot spots in transformer windings;
- Mechanical defects – e.g., loosening and displacement of windings, delamination of magnetic core layers.

This paper focuses on mechanical defects within the magnetic core of a power transformer.

There are multiple diagnostic approaches that are designed to detect mechanical defects. Vibroacoustic method uses information from the vibrations registered on the surface of transformer tank. This method is mainly used to diagnose mechanical defects in transformer windings since it determines the existence of a mechanical defect, if vibration amplitude values for a set position are elevated. However, by measuring individual harmonic amplitudes of registered vibrations, this method can diagnose the possibility of a mechanical defect within magnetic core, if the certain harmonic amplitudes are elevated as well, although this approach cannot detect the position and intensity of a mechanical defect [1]. Another power transformer diagnostics method is a sweep frequency response analysis (SFRA). This approach can detect changes within the windings and magnetic core of a power transformer by observing the change for multiple given frequency domains of transformer response [2]. However, by applying this approach, it is not possible to detect the position of mechanical defect beyond a single phase of the transformer as well as the severity of it. Furthermore, this method requires a baseline data information in order to operate.

The aim of this paper is to develop an approach to better evaluate the mechanical integrity of magnetic core of power transformers and to determine whether a possible mechanical defect exists by proposing a magnetostrictive vibration model.

2. MAGNETOSTRICTION EFFECT

In general, the geometrical changes in length caused by magnetostriction occur if the material is composed of microscopic domains that each have their individual magnetic poles. This is true for ferromagnetic materials. If no external magnetic field is applied, the polar direction of these domains is redistributed randomly throughout the given material. However, if an external magnetic field is applied to the given material, the domains begin to alter their magnetic polarity. The result of this reaction is that the domains that originally were aligned with the external field have increased in size and the remaining domains have diminished in size. Figure 1 illustrates the effect of this process. The magnitude of this process is dependent of the strength of the externally applied magnetic field but has a diminishing effect. [3]. The physical effect of the magnetostriction process is the source of vibration generation. This is due to the fact that microscopic domains are not perfect spheres.

Magnetostriction effect is the cause of mechanical movement within the magnetic core of the power transformer and it occurs because this component is made of ferromagnetic material and during the operation of transformer there is a constantly changing magnetic field propagating throughout the magnetic core. This process causes the magnetic core to change its dimensions and emit vibrations [4], [5]. The nature of this movement is periodic and proportional to the primary voltage frequency since the generated magnetic field has also periodically changing values and is induced by the primary voltage [6]. Therefore, magnetic core exhibits vibrations, which are then transmitted through other mechanical elements of the power transformer until they reach the surface of the tank. This is a complicated process because the vibration distribution path has multiple components.

The change in length for the direction aligned with the magnetic field is different from the same effect in perpendicular direction [8], [9]. This is due to the shape of magnetic domains of material and the lamination of magnetic core [10]. The correlation between applied magnetic field strength and the caused deformation is dependent on the material used since the magnetic domains can have different molecular structure and, therefore, geometrical shapes [11], [12].

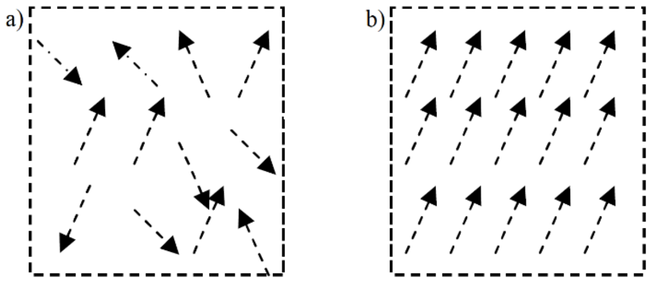

Fig. 1. Magnetic domain alignment (a) with no external magnetic field, (b) with external magnetic field [7].

The negative consequences of magnetostriction effect are emitted noise, which can exceed given limits and delamination of the magnetic core layers over a long period of time of continuous operation [7], [13], [14]. Created vibrations from the magnetic core may overlap the vibrations caused by the windings due to electrodynamic forces and, therefore, make it difficult to detect mechanical defects within it.

2. THE PROPOSED MAGNETOSTRICTIVE VIBRATION MODEL

To detect a mechanical defect and to improve evaluation of vibration measurement data, the authors have developed a power transformer mechanical vibration generation model caused by magnetostriction effect in magnetic core. The flowchart of the proposed model is displayed in Fig. 2 and this vibration simulation approach is interlinked with the previous research for winding mechanical defect detection [15].

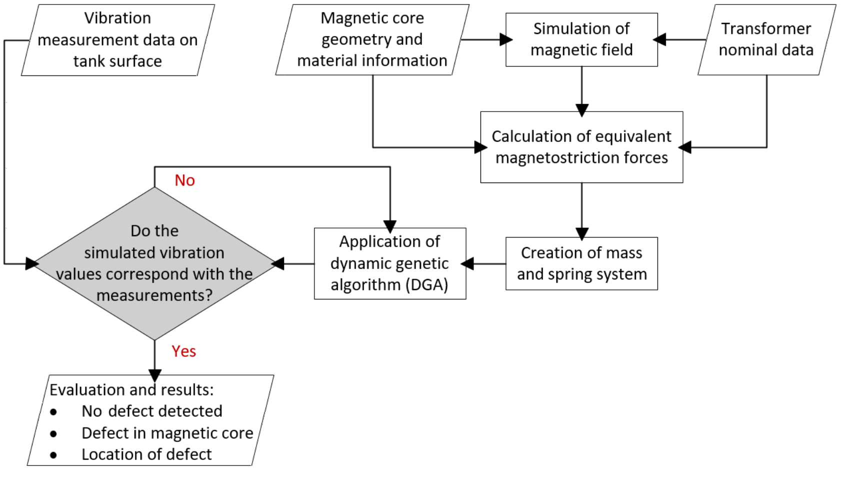

Fig. 2. Evaluation of mechanical integrity of magnetic core by magnetostrictive vibration model.

The proposed model is based on the replacement of magnetic core with mass and spring system that is moved by equivalent forces of magnetostriction effect. Furthermore, the model applies a dynamic genetic algorithm (DGA) in order to find the correct spring stiffness coefficients to create a configuration of coefficients for the mass and spring system that is capable of producing vibrations corresponding to the measurements of vibration total value on tank surface. The equivalent forces required to move this system are calculated by using the magnetostriction deformations and the Young's modulus of the magnetic core material.

Figure 3 illustrates how the magnetic core is replaced with a system of mass elements connected internally with springs. The alignments of springs are constructed in order to have each individual mass element connected with 6 springs, 2 springs for each dimension axis. This is required since all mass elements need to be capable of movements in any direction. This is achieved by combining the movements in each dimension axis as part of superposition.

It should be noted that all existing springs are not visible in Fig. 3. The hidden springs connect mass elements of magnetic core outer boundaries to other elements of the transformer structure. These structural fragments are assumed to be stationary and do not create vibrations of their own. Furthermore, the mass elements displayed in gray tone are defined as stationary as well since these regions of magnetic core have better fastenings and, therefore, do not exhibit vibrations caused by magnetostriction with equal intensity. Corresponding positions of vibration sensors providing vibration total value measurement data on tank surface are displayed in dashed pattern. Furthermore, this replacement approach is applicable to any form of magnetic core as well as to power transformers with different rated power.

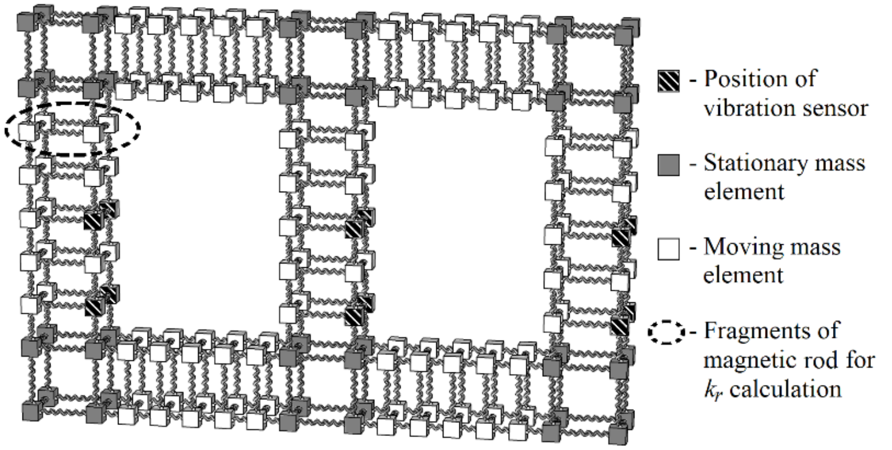

Fig. 3. Magnetic core representation as mass and spring system.

When magnetostriction effect exerts a force upon a given mass element, the surrounding springs create a force in the opposite direction. However, the new equilibrium point in space for this mass element has changed, thus, movement occurs as a result to this change. Therefore, by applying a periodic force on the mass element, vibrations are generated. Figure 4 illustrates the movement of a single mass element in vertical axis and the resulting forces acting upon it as a result.

For this mass and spring system to operate, it is necessary to generate forces caused by a magnetostriction effect. A simple movement of mass element due to magnetostriction does not suffice since this process does not have a single vectoral direction. This is because the change in mass element length due to magnetostriction in a single axis will not move the centre of mass but expand or contract the element itself. However, the sides of the mass element will change their position. Therefore, deformations caused by magnetostriction cannot be expressed as forces that produce a movement of the whole mass element.

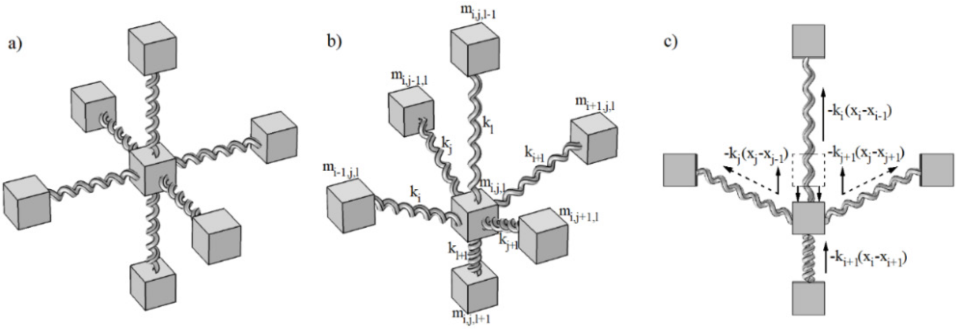

Fig. 4. (a) Mass element connection with neighbouring elements, (b) spring deformation due to element movement and (c) the acting elastic forces upon the displaced mass element.

For this reason, it is proposed to use Young's modulus of the magnetic core material in order to acquire forces that produce equivalent overall mass element movement as a magnetostriction effect.

Equation (1) describes the calculation of Young's modulus

$$E = \frac{F \cdot l_0}{S \cdot \Delta l}, \tag{1}$$

where F applied force, N;

l_0 initial length of the material, m;

S surface area, where the force is applied, m^2;

Δl deformation length of the material, m.

The change in length Δl of magnetic core due to magnetostriction can be expressed as a function based on the magnetic induction value of the externally applied magnetic field [16]. This function is usually represented as a magnetostriction graph that illustrates the correlation between magnetic induction values and caused change in length for electrical steel both in direction aligned to the magnetic induction vector and perpendicular to it [17]. However, due to the nature of these graphs being symmetric, the correlation between magnetic induction and deformation can be approximated and expressed as functions, displayed in equations (2) and (3)

$$\Delta l_d = \frac{346.23 \cdot B^6 - 1410.6 \cdot B^4 - 420.71 \cdot B^2 - 79.301}{10^9} \quad (2)$$

$$\Delta l_p = \frac{-86.659 \cdot B^6 + 84.198 \cdot B^4 - 2027.6 \cdot B^2 - 105.9}{10^9}, \quad (3)$$

where Δl_d material length change in parallel direction, m;
Δl_p material length change in perpendicular direction, m;
B magnetic induction, T.

Thus, the change in magnetic core dimensions is based on the magnetic induction value and direction at any part of the entire geometry of the magnetic core. This process creates difficulties to model the entire magnetic core as a single solid material since the values and direction of magnetic induction are different in any part of the magnetic core geometry and are changing throughout time. Therefore, it is possible to calculate the applied force to a mass element since all other variables of equation (1) can be acquired. This is possible because the initial dimensions of the mass element are defined. Therefore, both surface area S and initial length l_0 are known. The deformation values Δl_d and Δl_p can be calculated by using magnetostriction functions described in equations (2) and (3), and the values of Young's modulus for electrical steel are known and displayed in Table 1.

Table 1

Young's Modulus Absolute and Relative Values of Electrical Steel [18], [19]

Direction	*E* value, Pa	Relative *E* value to steel, %
Parallel to magnetic field	$157 \cdot 10^9$	78.5
Perpendicular to magnetic field	$104 \cdot 10^9$	52
Perpendicular to lamination	$176 \cdot 10^9$	88

Therefore, it is possible to calculate the equivalent forces to a magnetostriction effect in both parallel and perpendicular directions to all axial components of a magnetic induction vectoral value by using equation (1) and expressing the force value F from it. Together there are three force values for one magnetic induction axial component since the effect of magnetostriction exists in all three axial directions. Therefore, it is necessary to add all force values in a single direction from all three magnetic induction axial components to obtain the values of $F_{xi}(t)$, $F_{yj}(t)$ and $F_{zl}(t)$ required in equations (4), (5) and (6) that describe the movement of each mass element in three dimensions by applying Newton's second law of motion and the effect of stiffness coefficients of systems springs

$$m_i \cdot \frac{d^2 x_i}{dt^2} - k_{xi} \cdot \left(x_{i-1} - \frac{x_i}{2}\right) - k_{xi+1} \cdot \left(x_{i+1} - \frac{x_i}{2}\right) - k_{yj} \cdot \left(x_{j-1} - x_j\right)$$
$$-k_{yi+1} \cdot \left(x_{j+1} - x_j\right) - k_{zl} \cdot (x_{l-1} - x_l) - k_{zl+1} \cdot (x_{l+1} - x_l) = F_{xi}(t) \quad (4)$$

$$m_j \cdot \frac{d^2 y_j}{dt^2} - k_{yj} \cdot \left(y_{j-1} - \frac{y_j}{2}\right) - k_{yi+1} \cdot \left(y_{j+1} - \frac{y_j}{2}\right) - k_{xi} \cdot (y_{i-1} - y_i)$$
$$-k_{xi+1} \cdot (y_{i+1} - y_i) - k_{zl} \cdot (y_{l-1} - y_l) - k_{zl+1} \cdot (y_{l+1} - y_l) = F_{yj}(t) \quad (5)$$

$$m_l \cdot \frac{d^2 x_l}{dt^2} - k_{zl} \cdot \left(x_{l-1} - \frac{x_l}{2}\right) - k_{zl+1} \cdot \left(x_{l+1} - \frac{x_l}{2}\right) - k_{yj} \cdot \left(x_{j-1} - x_j\right)$$
$$-k_{yi+1} \cdot \left(x_{j+1} - x_j\right) - k_{xi} \cdot (x_{i-1} - x_i) - k_{xi+1} \cdot (x_{i+1} - x_i) = F_{xi}(t)\,, \quad (6)$$

where m_i; m_j; m_l mass of the corresponding element, kg;

$k_i \ldots k_{l+1}$ stiffness coefficient of springs in corresponding position;

$x_{i-1} \ldots x_{l+1}$; $y_{i-1} \ldots y_{l+1}$; $z_{i-1} \ldots z_{l+1}$ position of the centre of mass element in corresponding position and direction, m;

$F_{xi}(t)$; $F_{yj}(t)$; $F_{zl}(t)$ applied force to the mass element in corresponding direction, m.

By applying equations (4), (5) and (6) to the mass and spring system, it is possible to calculate the position, speed and acceleration of each mass element. However, the model needs to find mass element movements that generate vibrations equal to those measured on the tank surface of the transformer. Therefore, the stiffness coefficients of the springs must be adjusted. The possible number of combinations of stiffness coefficients for the springs is too large to compute all the possibilities since only applying integer values between 10^4 and 10^7 with a system of 84 springs has in total approximately 9.194^{587} individual combinations. Therefore, it is impossible to use a brute force approach and, thus, dynamic genetic algorithm (DGA) is applied.

The DGA creates a randomized combination of spring stiffness coefficients and calculates the generated vibration values. This process simulates a single individual of a population of possibilities. For DGA to be able to find an acceptable result, multiple individuals must be simulated. They create a population for a single generation of configuration evolution. After all individuals are simulated and their vibration results calculated, the individuals are sorted based on their vibration results corresponding to the required values. This difference between calculated and measured vibration values is the fitness function of the DGA. Then, a random number of individuals are deleted and reproduced by the surviving ones. However, the new individuals have randomized changes to their structure – mutations. Both the deletion and reproduction processes are partly randomized. However, there is a gradient approach used as based in the previous research [15]. The better the fitness function of an individual compared to the corresponding population, the smaller the change of this individual to be deleted and larger the change of reproduction form of this individual. Therefore, this process improves the fitness function of each generation of population and simulates evolution.

Over multiple generations, the fitness function becomes acceptable and the calculated vibration values correspond to the measured values. Therefore, the internal stiffness coefficient structure is obtained for the mass and spring system to generate the required vibration values. This process is performed to vibration values for both sides of each magnetic core rod or yoke. Afterwards, the stiffness coefficients of the generated system's internal structure are compared to search for differences, and ratio coefficient k_r is calculated as $k_r = k_{rmax}/k_{rmin}$, i.e., a result from dividing the largest value stiffness coefficient k_{rmax} by the smallest value stiffness coefficient k_{rmin} of a given fragment of magnetic core. Each fragment consists of 4 mass elements forming a square grid with the length of it aligned with measured vibration direction. Figure 3 displays these fragments as horizontal layers of mass elements in the structure of each rod.

The value of k_r shows if the stiffness coefficients of springs aligned with the vibration direction and positioned next to each other differ. High value of k_r shows evidence of a possible mechanical fault within this fragment of magnetic core since the mechanical integrity of this component is lowered and it exhibits loose structural components. However, k_r value close or equal to 1 signifies that corresponding stiffness coefficients represent a homogenous structure with no relatively loose elements, thus, there is no evidence of a mechanical defect.

3. CASE STUDY

A power transformer is used as a case study in order to confirm that the proposed magnetostrictive vibration model is operating as intended. Figure 5 displays the measured vibration visualization to the corresponding positions on the tank surface of the selected transformer in no-load operation. Lower part of phase A at high voltage side indicates elevated vibration displacement amplitudes that are marked in a darker tone. Furthermore, there are areas on the magnetic core, with no tone coding added where vibration measurements were not taken.

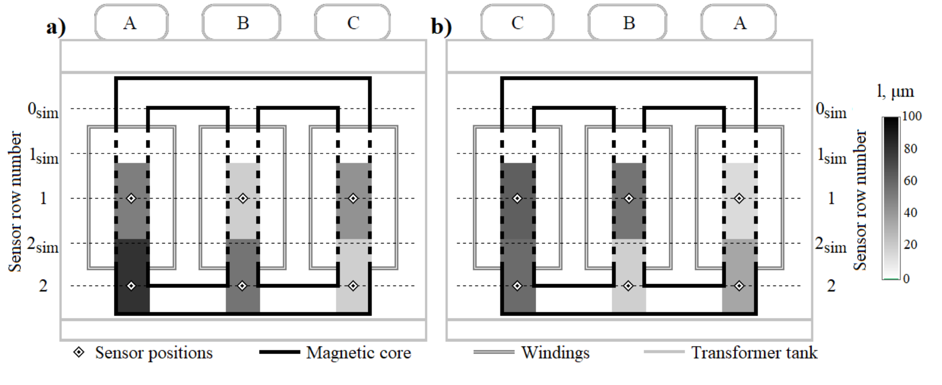

Fig. 5. Measured vibration visualization to their corresponding positions for (a) high voltage side and (b) low voltage side.

For this case study, *Matlab* and *Matlab Simulink* software is used to create the proposed magnetostrictive vibration model. Each of the magnetic core rods is replaced with a mass and spring system consisting of 20 individual mass elements internally connected with 84 springs. The visualization of this approach is displayed in Fig. 3. Equations (4), (5), and (6) are created as signal feedback loops. Each of the 20 mass elements have a feedback loop for the calculation of position and movement in a single direction. Therefore, 3 equation replacements with this approach simulate mass element movement within three-dimensional space. Figure 6 displays a single feedback loop. The initial input parameters are as follows:

- the equivalent magnetostrictive forces, *F(x)t1* block;
- mass of the element, *m1* block;
- spring stiffness coefficients surrounding the element, all blocks starting with the letter "*k*".

It should be noted that all feedback loops simulating magnetostrictive vibrations are connected since the position of neighbouring mass elements impact the movement of the original mass element.

In this case study, DGA generated an evolution that consisted of a population of 500 individuals over 80 generations for each of the magnetic core rods. The generated result has good conformity with the vibration values measured on the surface of the transformer tank since the calculated RMS error total value is 2.04 % across all simulated vibration positions in all magnetic core rods. Figure 7 illustrates the graphical interpretation of this comparison, where dashed lines indicate vibration measurement results and continuous lines – simulated vibration results.

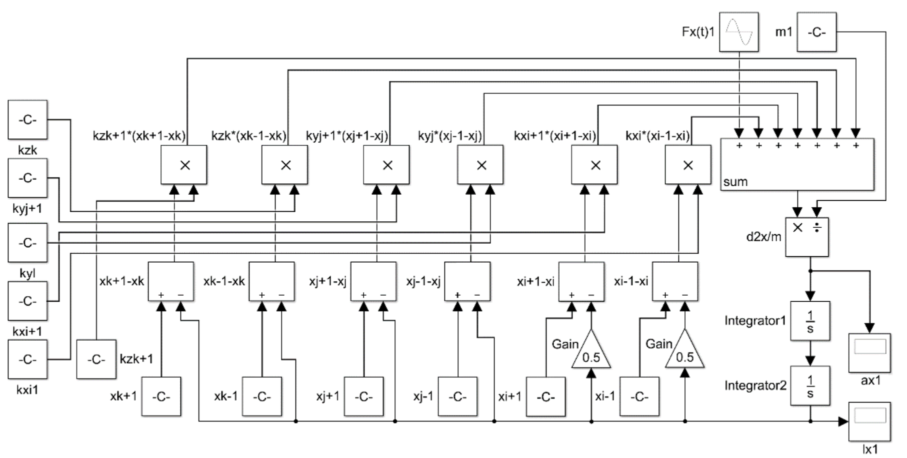

Fig. 6. Mass element movement calculation block for a single dimension, *Matlab Simulink*.

It should be noted that the original vibration measurements are limited to the magnetic core rod middle and lower regions. However, the proposed model created and extrapolated results for the unknown positions as well. These vibration displacement amplitude values at the top of the magnetic core rod have the corresponding nature to the values at lower structure sectors since they are within the range of the same magnitude of amplitudes.

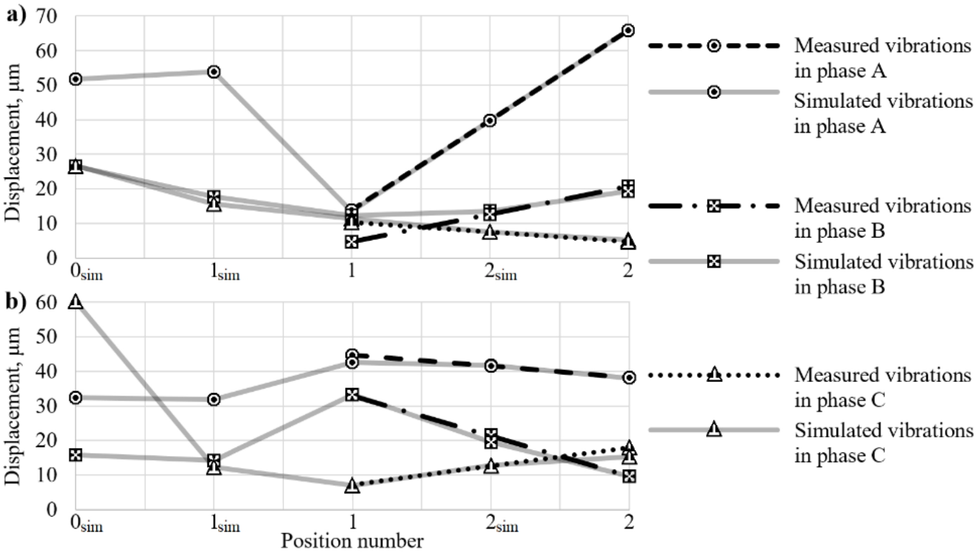

Fig. 7. Simulated and measured vibration values for (a) high voltage side and (b) low voltage side.

Afterwards, the values of ratio coefficient k_r are calculated as described in Section 3. Table 2 shows the acquired results throughout all magnetic core rods at every measured sensor row corresponding to sensor row number 1 and 2, as well as interpolated results between the sensor rows marked as 2_{sim} and extrapolated results located at the top regions of rods named 0_{sim} and 1_{sim}.

Table 2

Calculated Resulting Values of k_r

Row no.	Values of k_r		
	Phase A	Phase B	Phase C
$_{0si}$m	1	4	5
1_{sim}	102	2	1
1	4	1	3
2_{sim}	3	2	2
2	27	12	1

The values of k_r for phase C exhibit typical structural behaviour consistently diminishing towards upper fragments of rod. However, increased values of k_r can be observed both at upper and lower regions of the rod of phase A, as well as at the lower region of phase B. That indicates decreased mechanical integrity in this area of magnetic core since the vibration simulation results show that there are fragments within these rods that have loose structural components.

4. CONCLUSIONS

The proposed magnetostrictive vibration model investigates replacing the magnetic core of a power transformer with a mass and spring system and applying a dynamic genetic algorithm in order to create a black box of numerous spring stiffness coefficients to simulate vibrations corresponding to the vibration measurements made on a tank surface.

The obtained stiffness coefficients of the mass and spring system are used to evaluate if there is a defect within the magnetic core.

The power transformer for the case study was selected since there were mechanical defects found during the diagnostics process. Implementation of the proposed model indicated that there was evidence of mechanical defects within magnetic core rods of phases A and B, thus confirming that the proposed magnetostrictive vibration model was operating as intended.

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MAGNETOSTRIKTĪVU VIBRĀCIJU MODELIS SPĒKA TRANSFORMATORU MAGNĒTVADA MEHĀNISKĀS IZTURĪBAS NOVĒRTĒŠANAI

J. Mārks, S.Vītoliņa, J. Dirba

K o p s a v i l k u m s

Izpētīta magnetostrikcijas efekta ietekme uz lieljaudas transformatoru magnētvadu, radot tā presējuma atslābšanu ekspluatācijas laikā. Lai uzlabotu magnētvada mehāniskās izturības novērtēšanu un vibrāciju mērījumu rezultātu uz transformatora tvertnes virsmas interpretāciju, ir piedāvāts magnetostrikcijas radīto vibrāciju ģenerēšanas modelis. Modelis paredz magnētvadu aizstāt ar masu un atsperu sistēmu, kurā iekšējo masu elementu kustību ģenerē magnetostrikcijas efektam ekvivalenti spēki, kā arī ir pielietots dinamisks ģenētiskais algoritms, lai atrastu pareizu modelētās masu un atsperu sistēmas konfigurāciju. Gadījuma izpētes iegūtie rezultāti rada aizdomas par iespējamu mehānisku defektu esamību modelētā transformatora magnētvadā.

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