RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
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VIBRATION MODEL FOR THE DETECTION OF MECHANICAL FAULTS WITHIN WINDINGS AND MAGNETIC CORE OF POWER TRANSFORMERS

Summary of the Doctoral Thesis

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF ENGINEERING SCIENCES

To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on December 19, 2019 at the Faculty of Power and Electrical Engineering of Riga Technical University, 12/1 Azenes Street, Room 212.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Jānis Mārks ……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of an Introduction; 7 Chapters; Conclusions; 59 figures; 33 tables; the total number of pages is 117. The Bibliography contains 103 titles.

TABLE OF CONTENTS

INTRODUCTION

The Topicality of the Work

Power transformers are important components of the electrical system. They have a relatively complex design and consequently can have different types of defects [15], which can threaten the safe operation of the transformer and the power system, as well as the transformer itself can be damaged irreparably.

The sources and locations of these defects are different. One of the possible types of defects are mechanical faults that occur within the windings and magnetic core. In a study in Brazil, faults in windings and magnetic core were the source for 30 % of failures [23]. A study done by CIGRE shows that 19 % of the observed failures were caused by windings and 3 % by magnetic core [21]. However, in Thailand these defects account for 2.03 % of all failures [2]. A research [24] on the classification of defects indicate that 1 % of the causes of defects in the Latvian power system are the windings and magnetic core. Therefore, the defects in windings and magnetic core make up a significant fraction of the total number of failures. Hence, their detection is important to improve the safety of transformers.

Mechanical faults within a transformer are mainly caused by electrodynamic forces in the windings and are difficult to diagnose within the magnetic core due to their location within the geometry of the transformer tank. Access to these locations is complicated since it is necessary to take the transformer for repair and disassemble it. This process is laborious and time consuming and interferes with the operation of the electrical system.

One of the most accurate methods of diagnostics of mechanical faults is vibration diagnostics, which involves recording the characteristics of vibration values on the surface of the transformer tank and further processing this information.

Existing methods are difficult to apply because they cannot determine the location of fault within windings and magnetic core, nor do they provide recommendations for further action to be taken. The SFRA (Sweep Frequency Response Analysis) method can detect mechanical changes in the transformer structure, but they are calculated relative to a situation where the fault had not yet occurred [22]. Furthermore, it is not possible to determine the location of the fault more accurately than the individual transformer phase [1]. Vibration diagnostics provides information of the vibrations generated on the surface of the tank, which includes the harmonics of the vibrations, their amplitudes and spectrum, and provides an indication of a possible mechanical fault [10]. However, it is not possible to obtain information about the vibrations generated in the windings and magnetic core since it is impossible to access them with the required vibration sensor during the transformer operation [18].

The Goal and the Tasks Solved by the Thesis

The aim of this Thesis is to develop a new vibration model to identify the existence and location of mechanical faults within the construction of power transformer windings and magnetic core and to formulate a recommendation for further diagnostics.

The following tasks have been accomplished in order to achieve this aim:

1. Analysis of scientific literature has been done to verify the novelty and authenticity of the developed vibration model.
2. Spatial and easily modifiable power transformer vibration model is developed for the detection of mechanical faults.
3. An algorithm is developed, which uses Newton polynomials to approximate and visualize the results of vibration measurement on transformer tank.
4. Three-dimensional magnetic field modeling of transformer in *COMSOL* software is performed to determine the magnetic field induction and tangential current density values in different operating modes for further calculation of electrodynamic forces.
5. A mathematical model of the mass and spring system is developed by replacing the windings and magnetic core of the transformer with a mass and spring system to simulate the vibrations caused by magnetostrictive mechanical forces and electrodynamic forces.
6. Dynamic genetic algorithm is developed that can perform operations with large populations of individuals in *Matlab* and *Matlab Simulink* software, based on the developed mass and spring system mathematical model, using mutations and a black box principle. An evolution process has been simulated, and comparison is made between the modeled results with measurements in reality.
7. Conclusions are formulated regarding the mechanical faults within the windings and magnetic core, and recommendations about the diagnostics are provided by using fuzzy logic in order to reach a conclusion in case of contradictory results.

Scientific Novelty of the Thesis

The following innovative solutions are created within the Thesis:

- transformer vibration model for mechanical fault detection that is based on black box approach and the application of a dynamic genetic algorithm;
- a mass and spring system capable of modeling the vibrations caused by the electrodynamic forces in windings and by the magnetostrictive effect in magnetic core;
- a modified Newtonian polynomial interpolation method for vibration approximation that eliminates breakpoints in values.

Practical Significance of the Thesis

The developed vibration model can be used as the next step in the processing and analysis of the vibrations results measured on the transformer tank, allowing to do the following:

- to identify the possible mechanical faults in the windings and magnetic core of power transformers, local winding deformation, local short circuits, winding deformation and the reduction of compression level in magnetic core, etc.;
- to find the location of mechanical fault within the boundaries of transformer windings and magnetic core;
- to provide a conclusion regarding further diagnostic tests of the transformer.

Methodology of the Research

Newtonian polynomial and spline methods of approximation are used in the development of the Thesis. Finite element method is used in the creation of the transformer magnetic field model. A dynamic genetic algorithm is used to find the required configuration of the mathematical model of the mass and spring system. Matrix theory is used in mathematical operations with a large number of equation systems. Nearest neighbor search algorithm is used to approximate data values in large multidimensional matrices. A constant step iteration method is used to solve the differential equations.

The Thesis uses *COMSOL* software to perform transformer magnetic field induction and current density calculations, *Matlab* software to construct a dynamic genetic algorithm and apply the approximation methods and *Matlab Simulink* software to perform differential equation system calculations.

Approbation of the Thesis

1. Dynamic Genetic Algorithm in Model for Vibrations of Power Transformer Windings. *EPE 2018 10th International Conference and Exposition on Electrical and Power Engineering*, Romania, Iasi, October 18–19, 2018.
2. Modelling of Vibrations Caused by Magnetostriction in Magnetic Core of Large Power Transformers. *The 58th International Scientific Conference on Power and Electrical Engineering of Riga Technical University*, Latvia, Riga, October 12–13, 2017.
3. Magnetostriction Model of Large Power Transformer Magnetic Core. *The 18th International Symposium on Electromagnetic Fields in Mechatronics, Electrical and Electronic Engineering*, Poland, Lodz, September 14–16, 2017.
4. Application of Vibration Measurements for Detection of Mechanical Faults in Power Transformers. *The 5th International Doctoral School of Energy Conversion and Saving Technologies*, Latvia, Ronisi, May 28–29, 2016.
5. Study of power transformer mechanical faults detection by using vibrodiagnostics. *The 13th International Conference of Young Scientists on Energy Issues (CYSENI)*, Lithuanian Energy Institute, Lithuania, Kaunas, May 26–27, 2016.

Publications

1. **Marks, J.**, Vitolina S., Dirba, J. Magnetostrictive Vibration Model for Evaluation of Mechanical Integrity of Power Transformer Magnetic Core. *Latvian Journal of Physics and Technical Sciences*. Latvia, 2019, No. 3, ISSN 0868-8257, pp. 13–25. DOI: 10.2478/lpts-2019-0016 (indexed in Scopus).
2. **Marks, J.**, Vitolina, S. Dynamic Genetic Algorithm in Model for Vibrations of Power Transformer Windings, *10th International Conference of Exposition on Electrical and Power Engineering*, Romania, 2018, ISBN 978-1-5386-5061-5, pp. 1–6. DOI: 10.1109/ICEPE.2018.8559932 (indexed in IEEEXplore, Scopus).

3. Poiss, G., Vitolina, S., **Marks, J.** Development of Indicators for Technical Condition Indexing of Power Transformers. *Advances in Science, Technology and Engineering Systems Journal*. United States, ISSN 2415-6698, No. 1, pp. 148–154. DOI: 10.25046/aj030118 (indexed in Scopus).
4. **Marks, J.**, Vitolina, S. Modelling of Magnetostriction of Transformer Magnetic Core for Vibration Analysis. *Open Physics*. Germany, 2017, No. 1, ISSN 2391-5471, pp. 803–808. DOI: 10.1515/phys-2017-0094 (indexed in Scopus).
5. **Marks, J.**, Vitolina, S., Liepniece, R. Modelling of Vibrations Caused by Magnetostriction in Magnetic Core of Large Power Transformers. *Proceedings of 58th International Scientific Conference on Power and Electrical Engineering of Riga Technical University*, Latvia, ISBN 978-1-386-3847-7, pp. 1–5. DOI: 10.1109/RTUCON.2017.8124760 (indexed in IEEEXplore, Scopus).
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8. Poiss, G., Vitolina, S., **Marks, J.** Development of Indicator Based on Oil Analysis for Estimating Risk Level of Power Transformers. *Proceedings of 57th International Scientific Conference on Power and Electrical Engineering of Riga Technical University*, Latvia, 2016, ISBN 978-1-5090-3732-2, pp. 273–276. DOI: 10.1109.RTUCON.2016.7763130 (indexed in IEEEXplore, Scopus).
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1. MECHANICAL FAULTS OF POWER TRANSFORMERS AND THEIR DETECTION POSSIBILITIES

1.1. Description of Mechanical Faults of Power Transformers

There are several defects that can occur in transformers during their operating period. These defects can be categorized as follows: thermal, electrical, mechanical, and external.

A study done by CIGRE shows that 19 % of the failures considered were caused by windings and 3 % by magnetic core [21]. In Thailand, these defects account for 2.03 % of all failures [2]. In a study done in Brazil, defects in the windings and magnetic core were responsible for 30 % of transformer failures [23]. The result statistics of the classification of transformer defects in the power system of the Republic of Latvia indicate that 1 % of defects are caused by the windings and magnetic core of the transformer [24]. Therefore, the defects in the windings and magnetic core make up a significant part of the total number of failures.

This Thesis focuses on the mechanical defects of the windings and magnetic core of transformer. Alternating current flows through the windings during the operation of power transformers, and the geometry of windings is propagated by the magnetic field leakage flux. As a result of this process, the windings are subjected to electrodynamic forces.

The vibrations generated by the electrodynamic forces occur only in the windings but are transmitted through the transformer structure, starting from the solid insulation of the transformer to the surface of its tank. The mechanical nature of these vibrations is influenced by the construction design of the transformer, i.e. design dimensions, winding and magnetic core configuration, and transformer operating mode [3], [8], [9].

Magnetic core of the power transformer is made of a material that has a relatively higher magnetic conductivity than other neighboring elements of the transformer. Consequently, electrical steel is used as the material for the transformer magnetic core [17].

The microscopic structure of electrical steel consists of domains each of which has a pronounced magnetic polarization. However, the magnetic polarization of molecules within each domain of electrotechnical steel has one direction [7]. When exposed to a magnetic field, domains react to the presence of a magnetic flux. Those domains whose magnetic polarization direction coincides with the external magnetic field flux direction become physically larger, while the domains of different directions – smaller. Because the size of molecules varies in the longitudinal and transverse directions, the geometry of the material changes when the domains change. This is the magnetostriction process [25]. The magnetic field generated by the transformer changes periodically. Therefore, the magnetic core is subjected to periodic changes in its geometry, which causes its vibrations [11], [26].

Vibrations from the magnetostriction process can, over a long period of time, reduce the strength of the mechanical bracings of the magnetic core. As a result, the amplitude of the vibrations can increase since the magnetic core still changes its dimensions depending on the magnetic induction, but the mechanical strength of its containing structures is reduced.

1.2. Evaluation of Diagnostic Methods for the Detection of Mechanical Faults

Diagnostic methods have been examined to detect mechanical faults in the windings and magnetic core. The results of the study done by CIGRE [20] are summarized in Fig. 1.1. The number of interviewed experts using the corresponding diagnostic method for a given fault is shown in brackets. In order to evaluate whether the methods used by the experts [20] can directly detect the mechanical faults, an additional literature study has been carried out which considers alternative diagnostic methods for the determination of mechanical fault.

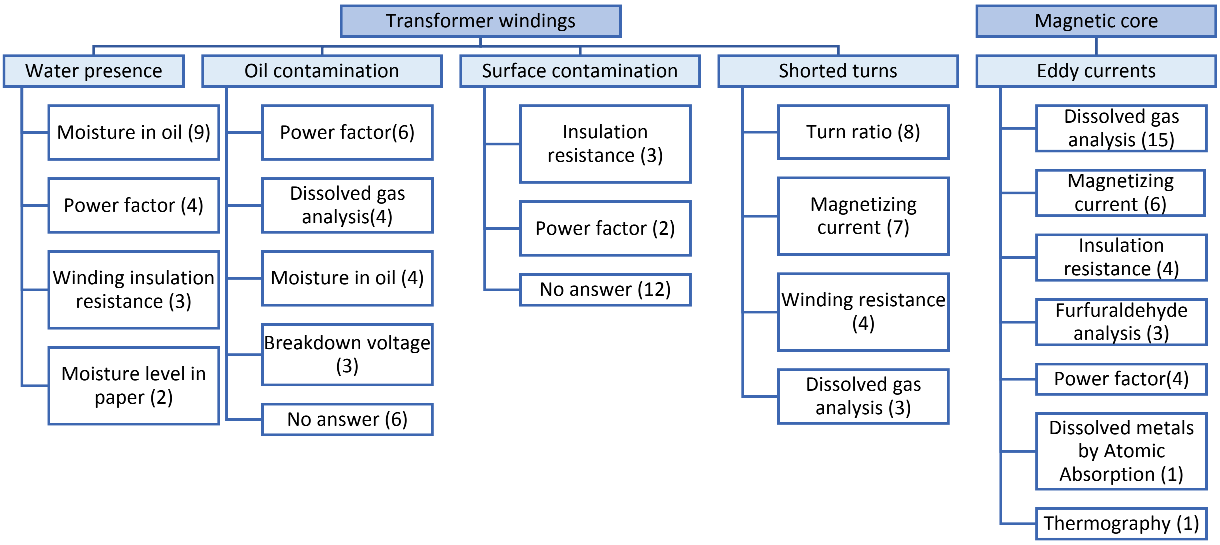


Fig. 1.1. Diagnostic methods for the detection of winding and magnetic core faults.

The evaluation of diagnostic methods shows that indirectly several methods indicate possible mechanical faults in the windings and magnetic core of the transformer. Information on the approximate location and type of fault can be obtained by measuring the vibrations on the surface of the tank. This method is discussed in more detail in Section 1.3.

1.3. Measurements and Evaluation of Vibrations Caused by Transformer

There are several ways to use a vibration sensor to diagnose vibrations generated by the transformer:

- placement of vibration sensors on the surface of the transformer tank;
- incorporation of vibration sensors in the construction design of the windings and magnetic core of transformer;
- positioning of vibration sensors at a certain distance from the surface of the tank.

A widely used approach is to place vibration sensors on the surface of the transformer tank. In this way, it is easy to position the sensors at locations corresponding to different fragments of the windings and magnetic core and to move them easily. However, this approach has a drawback since vibrations generated by the windings and magnetic core are first transmitted through the internal structure, which can change their information [19].

Vibrations can be characterized by any of their three main characteristics – displacement *l*, m, velocity *v*, m/s, and acceleration *a*, m/s^2. Knowing one vibration characteristic allows to obtain the others using mathematical expressions.

Since these mechanical vibrations are first transmitted through the mechanical structure of the transformer, the information about the mechanical condition in the windings and magnetic core can be changed. Therefore, using information about all 3 vibration characteristics, it is possible to obtain more accurate data about the presence of mechanical faults. A specific value can be set for each of the vibration characteristics, exceeding of which may indicate a possible mechanical fault in a particular transformer [29]:

- acceleration $a > 10$ m/s^2;
- velocity $v > 20$ mm/s;
- displacement $l > 100$ μm.

However, there are no universally applicable vibration limits, the exceeding of which leads to the unequivocal conclusion that the transformer in question has a mechanical fault.

It can be concluded from the researched literature and the study of many transformer diagnostic methods that there is no diagnostic method that can uniquely determine the presence and location of mechanical faults in the windings and magnetic core of the transformer.

2. TRANSFORMER VIBRATION MODEL FOR THE DETECTION OF MECHANICAL FAULTS

The developed vibration model is designed to detect mechanical faults in power transformer windings and magnetic core by evaluating measurement results. The operation of the transformer vibration model is intended for cases where the tank surface vibration measurement values are close to or above the set limits (see Section 1.3.).

The developed vibration model uses the black box principle and a dynamic genetic algorithm to simulate vibrations in the windings and the magnetic core. Fuzzy logic is used to form conclusions. As a result, the user receives a conclusion on the respective transformer with recommendations for further diagnostic tests, as well as visualization of the vibrations on the tank surface. The operation of the developed vibration model is illustrated in Fig. 2.1.

The developed vibration model as a result provides 1 of 5 conclusions with appropriate recommendations.

1. **No mechanical fault is suspected in the windings and magnetic core**.
   Recommendation – continue to perform transformer vibration diagnostics without changing test periodicity.
2. **The result is unclear**.
   Recommendation:
   a) vibration measurements on the surface of the tank need to be repeated and used in the developed vibration model to obtain conclusion;
   b) additional testing of the forced-cooling system of the transformer, the base of the transformer tank and possible external sources of vibration is recommended.
3. **Suspicion of a mechanical fault in windings**.
   Recommendation – perform frequency response analysis, determine the value of the turn ratio for each phase, perform a repeated diagnostic of the vibration of tank surface, and perform short-circuit resistance measurements.
4. **Suspicion of a mechanical fault in magnetic core**.
   Recommendation – determine the no-load operation current and magnetic losses, perform a repeated diagnostic of the vibration of tank surface in no-load operation by further examining the relevant region of the magnetic core.
5. **A fault is suspected in the windings and/or magnetic core but cannot be localized**.
   Recommendation – perform a repeated diagnostic of the vibration of tank surface with increased number of measuring points and their coverage region, perform frequency analysis measurements if they have been done before, perform frequency analysis, determine turn ratio value for each phase, perform repeated tank surface vibration diagnostics reducing transformer load and further inspecting the corresponding region of the magnetic core, perform short-circuit resistance measurements and determine no-load operation currents and magnetic losses.

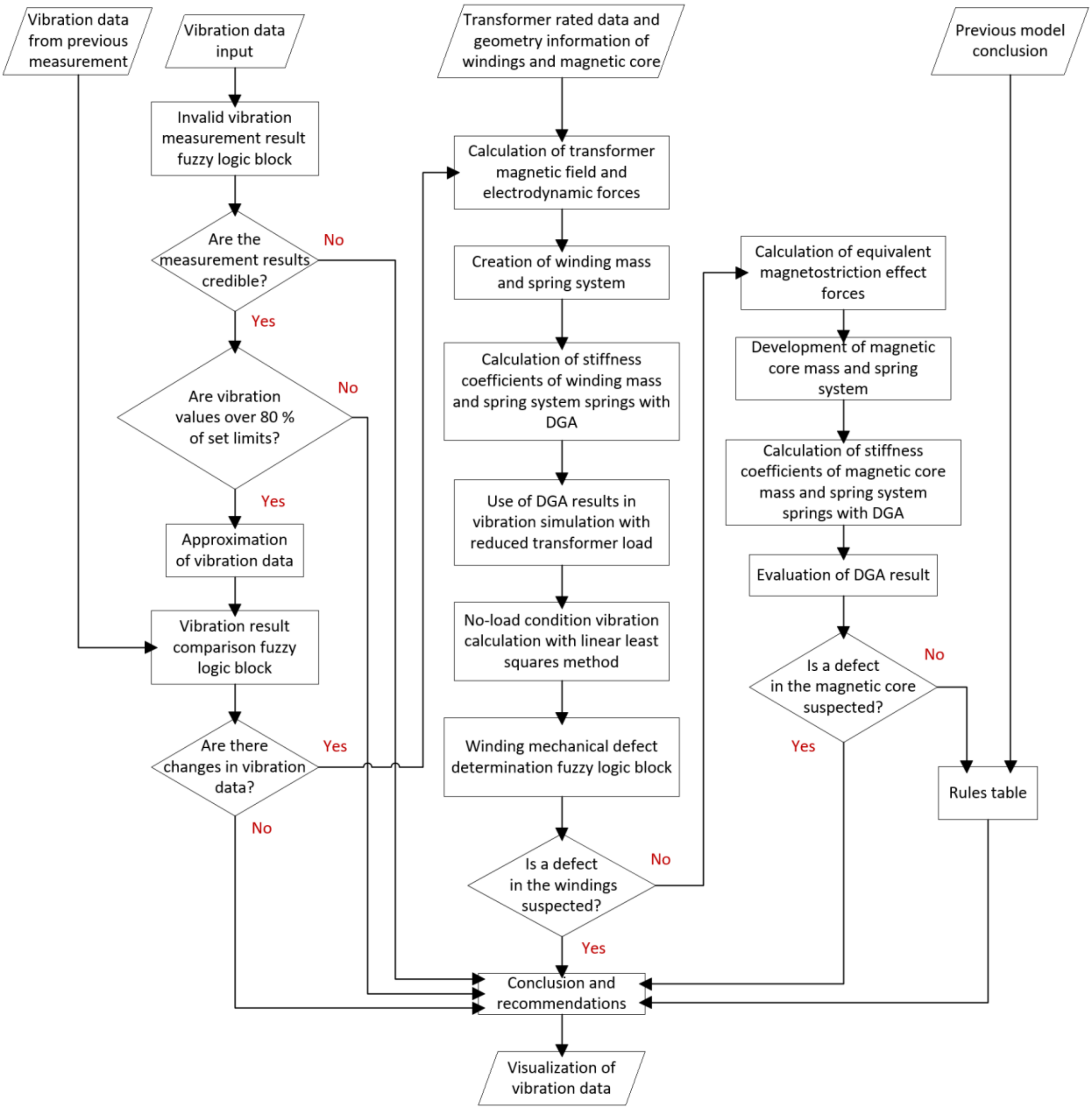


Fig. 2.1. Operation diagram of transformer vibration model.

3. APPROXIMATION AND VISUALIZATION OF VIBRATION MEASUREMENT DATA

Typically, during the measurement of vibrations, the sensors are placed on the surface of the transformer tank in a range of 12 to 150 locations. In order to perform the analysis, it is necessary to obtain a continuous vibration picture on the surface of the tank by applying approximation methods. The number of vibration data points determines which type of approximation method will be used initially (see Fig. 3.1).

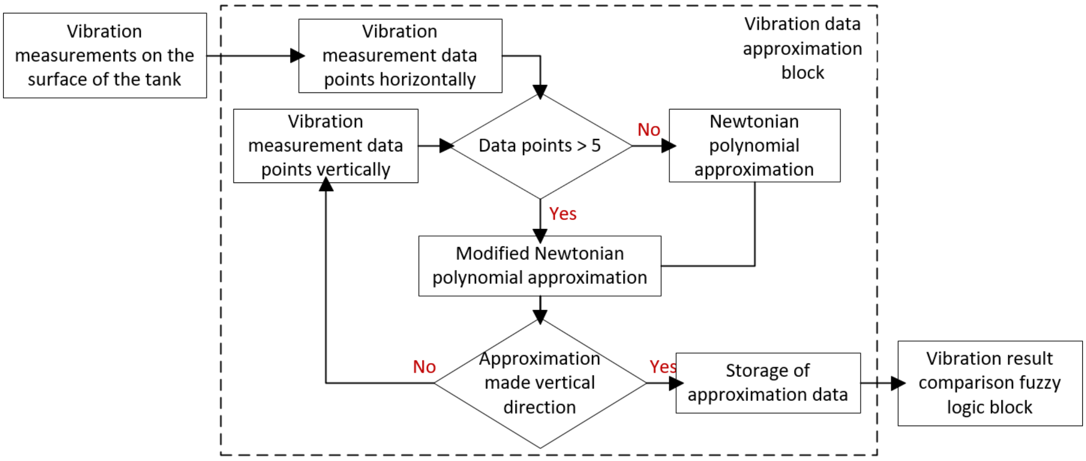


Fig. 3.1. Flow diagram of vibration data approximation block.

In the case of the Newtonian polynomial approximation method, the difference values are calculated, which allows to obtain an approximated value between known data points at certain positions [5], [28]. Expression (3.1) shows the case where 5 known data points are given.

$$\begin{gathered} y_i = a_0 + a_1(x_i - x_1) + a_2(x_i - x_1)(x_i - x_2) \\ +a_3(x_i - x_1)(x_i - x_2)(x_i - x_3) + a_4(x_i - x_1)(x_i - x_2)(x_i - x_3)(x_i - x_4), \end{gathered} \tag{3.1}$$

where y_i – approximated data value at position i;

x_i – position i for approximation between known data points;

a_0, a_1, a_2, a_3, a_4 – polynomial coefficients;

x_1, x_2, x_3, x_4 – positions of known data points.

The Newtonian polynomial approximation becomes more complex as the required highest degree of the polynomial increases. Additionally, approximated values tend to generate local extremes beyond the originally assigned values. Therefore, a modification of the Newtonian polynomial approximation method has been developed and proposed. The modification assumes that the data points are divided into groups of 5 points each, where the starting point of each subsequent group being the end point of the previous group. The number of data sets is given by expression

$$g_{\mathrm{sk}} = \mathrm{rounddown}\left(\frac{x_{\mathrm{sk}} - 2}{2}\right), \tag{3.2}$$

where g_{sk} is the number of approximation groups;

x_{sk} is the number of data points.

As shown in Fig. 3.2, a data approximation point is generated at which the approximation curves form a fracture. To ensure that there is a monotonous change in the amplitude of the vibration values, an additional approximation of the data with different initial groups is performed. The auxiliary data set is positioned so that its midpoint is located at the point of fracture. In this case it is between data points 3 and 7, which in Fig. 3.2 is shown as a green curve.

In order to combine all the results of the approximation into a single curve, a membership function for each approximation group is created with which it is possible to combine the results without significant changes in accuracy. The membership function uses already obtained approximation data from separate sets of data that represent the values obtained at a single position. Depending on the distance from this position to the midpoints of the respective groups used, an approximation value is calculated

$$y_i = \frac{y_{g,i}(x_n - x_i)^2 + y_{g+1,i}(x_i - x_1)^2}{(x_n - x_i)^2 + (x_i - x_1)^2}, \tag{3.3}$$

where $y_{g,i}$ – approximated value of the data from the first group;

$y_{g+1,i}$ – the approximated value of the data from the second group;

x_1 – position value at the beginning of the approximation period of the merger;

x_i – the specific position of the approximation value;

x_n – position value at the end of the approximation period of the merger.

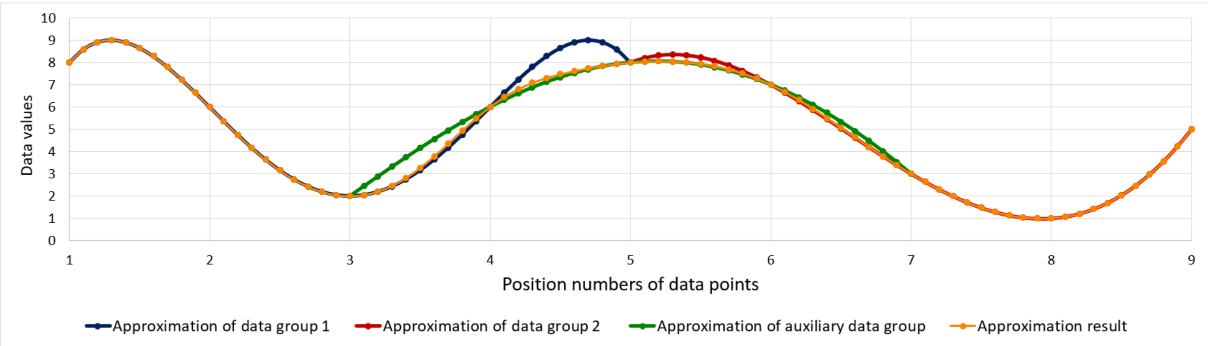


Fig. 3.2. The result of the modified Newtonian polynomial approximation.

Cubic splines are used to verify the proposed modification [6]. Transformer tank surface vibration data for 108 individual measurement cases are compared for the verification purposes. After performing the approximation operations, a global maximum value m_n is found for the modified Newton polynomial method and m_s – for the cubic spline method, and by comparison it is verified that the approximation does not create new vibration epicenters with values exceeding the initially measured values. A comparison of the obtained global maximum values is shown in Table 3.1.

Table 3.1

Results of Verification of Modified Newton Polynomial Approximation Method

Number of cases	Acceleration a, data	Velocity v, data	Displacement l, data
Number of positive cases $(m_n < m_s)$	28	23	24
Number of negative cases $(m_n > m_s)$	8	13	12

As can be seen from the results of the verification, the modified approximation method provides the results of vibration approximation with lower global maximums m_n in most cases. Figure 3.3 illustrates an example of approximation.

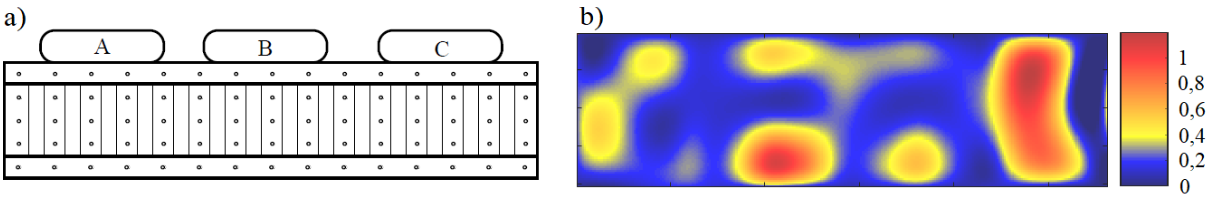


Fig. 3.3. Visualization of approximation of transformer tank surface vibrations:
a) the corresponding location of sensors on the transformer tank; b) approximation of vibrations.

4. CALCULATION OF ELECTRODYNAMIC FORCES AND CHARACTERISTICS OF MAGNETIC FIELD OF TRANSFORMER

4.1. The Necessity of Transformer Magnetic Field Modeling

The presence of a magnetic field in the inner structure of the transformer is the cause of the physical processes that generate vibrations in the windings and magnetic core of the transformer. This is due to the fact that the electrodynamic forces occur when the leakage flux flows through windings [4], but the magnetostriction process occurs due to magnetic field forcing the material of the magnetic core to change its geometric shape [27].

Expression (4.1) represents a function for the calculation of the electrodynamic forces

$$F(t) = B(t) \cdot I(t) \cdot l \cdot \cos(\alpha), \tag{4.1}$$

where $F(t)$ – the generated electrodynamic force, N;

$I(t)$ – calculated tangential values of current at all intersections of finite element mesh, A;

$B(t)$ – the calculated magnetic induction values of the transformer magnetic field model at all intersections of finite element mesh, T;

l – average length of the transformer winding fragment, m;

α – angle between magnetic induction and current value vectors, rad.

Therefore, to obtain the instantaneous value of the electrodynamic forces, it is necessary to model the magnetic induction, the values of current in windings, as well as their vector directions.

4.2. Development of Transformer Magnetic Field Model

In order to calculate the generated magnetic field in the transformer windings, in magnetic core and the surrounding environment and to obtain both the magnetic induction values of this magnetic field and the current density values in the geometry of the transformer windings, several software designed for physical modeling and calculation have been evaluated. They are analyzed on the basis of three different criteria:

- whether it is possible to perform a three-dimensional modeling to obtain the vector values of the magnetic induction needed for the transformer magnetic field model in all spatial axis;
- whether the software can calculate a time-varying magnetic field;
- whether it is possible to export result data for further use of magnetic induction and current density data for the calculation of electrodynamic force values and their vector directions.

Based on the research, *COMSOL* software has been selected because it meets all the criteria and is available at Riga Technical University.

It should be noted that in the process of calculating the magnetic field of a transformer, several assumptions are made, which are designed to produce results without a large number of transformer component characteristics and additional information about them. The assumptions made during the calculation of the transformer magnetic field are:

- all domains created are homogeneous;
- magnetic core and windings are perfectly shaped;
- the magnetic field does not propagate outside the transformer magnetic field model;
- magnetic losses are not considered;
- all voltage level circuits have been converted to a star connection;
- the magnetization curve of the magnetic core is interpolated linearly;
- the transformer magnetic field model does not consider other elements of the transformer design that may cause a magnetic field;
- the material of the magnetic core is isotropic in its modeling plane;
- the electrical circuit of transformer is insulated with perfect insulators.

The *COMSOL* software simulation is set to model a 0.1 second period with an iteration step of 0.0005 seconds. This period is appropriate because it includes a sufficient number of (20) voltage source periods, which creates a permanent regime with already damping transient process. The selected iteration step length provides the required magnetic field magnetic induction values and current density values for the simulated power transformer windings 40 times per source voltage period, and other required variables can then be calculated from these data with the same iteration step size.

5. VIBRATION SIMULATION WITH MASS AND SPRING SYSTEMS

5.1. Mass and Spring System of Windings

Within the developed vibration model for the simulation of transformer winding vibration, a mass and spring system is used. Each mass element of the system has a defined mass, the coefficients of stiffness of adjacent springs and the previously calculated electrodynamic forces are added. This system is then replaced by a differential equation system interacting with a dynamic genetic algorithm that iteratively finds a system configuration that generates the similar vibrations to the values measured on the surface of the transformer tank.

Figure 5.1 shows a visualization of one iteration highlighting a winding segment that is divided into 10 fragments. The numbers from 1 to 10 illustrate the axial distribution of the mass of the windings. This process is performed with both internal and external winding, resulting in 20 mass elements.

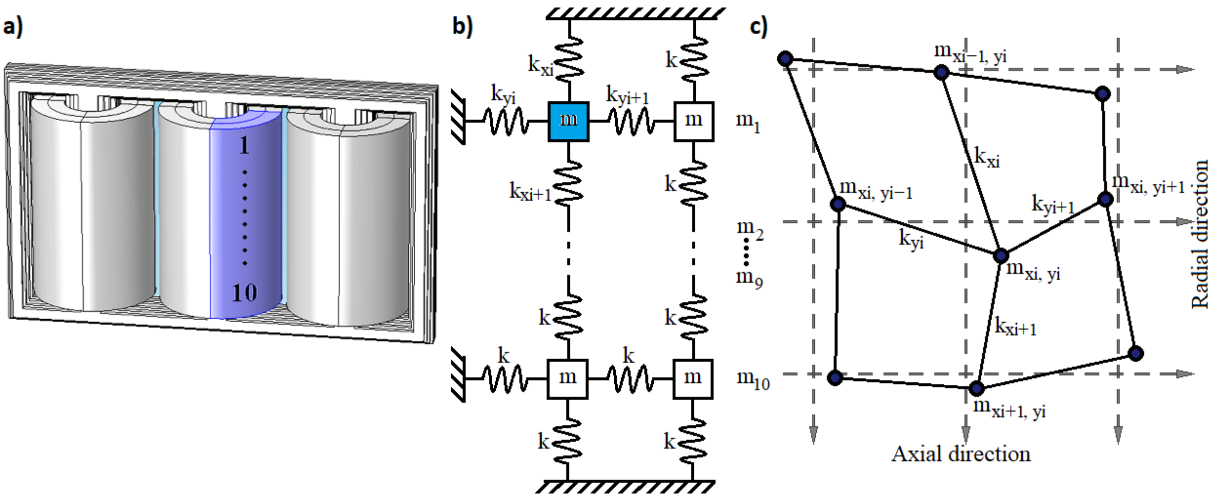


Fig. 5.1. Transformer:

a) winding segment; b) fragment of mass and spring system; c) illustration of 1 mass element.

The motion of the individual mass element $m_{xi,yi}$ and the attached springs are visualized in Fig. 5.1c). Any element of mass and spring system can move in the radial cross-sectional plane of windings when interacting with the attached springs. By creating a system of two differential equations, it is possible to calculate the coordinates of each mass element over a given time interval. This mass movement is expressed as follows:

$$
\begin{aligned}
&m_i \frac{\mathrm{d}^2 x_i}{\mathrm{d}t^2} - k_{xi}(x_{i-1} - x_i) + k_{xi+1}(x_i - x_{i+1}) \\
&-k_{yj}(x_{j-1} - x_j) - k_{yi+1}(x_{j+1} - x_j) = F_{xi}(t), \\
&m_i \frac{\mathrm{d}^2 y_i}{\mathrm{d}t^2} - k_{yj}(y_{j-1} - y_j) + k_{yj+1}(y_j - y_{j+1}) \\
&-k_{xi}(y_{i-1} - y_i) - k_{xi+1}(y_{i+1} - y_i) = F_{yi}(t),
\end{aligned}
\tag{5.1}
$$

where m_i – mass of the mass element, kg;

x_{i-1}; x_i; x_{i+1}… y_{j-1}; y_j; y_{j+1} – position of the mass element, the following and the preceding mass element in radial and axial directions, m;

k_{xi}; k_{xi+1}; k_{yi}; k_{yi+1} – coefficients of spring stiffness in radial and axial directions;

$F_{xi}(t)$; $F_{yi}(t)$ – electrodynamic forces in the radial and axial directions.

The mathematical model of the mass and spring system is implemented in the *Matlab Simulink* software, which allows to transform differential equations into a signal flow diagram, provide results at varying time intervals with variable accuracy and frequency of individual iterations and export variable values to *Matlab* software for further processing and calculation. The entire signal flow scheme is internally connected since the differential equation system for each simulated mass is associated with the adjacent mass differential equation system and mass elements are connected by a single spring. Figure 5.2 illustrates a flowchart diagram of a single mass element in a *Matlab Simulink* environment.

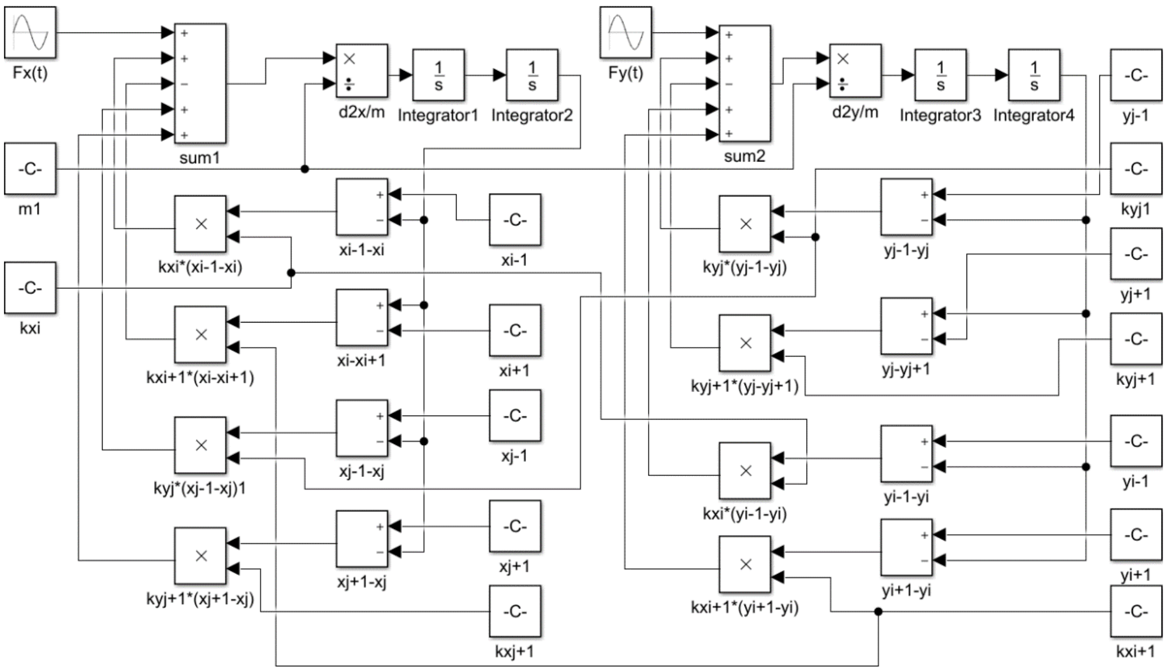


Fig. 5.2. Flowchart of single mass element in *Matlab Simulink* environment [14].

5.2. Mass and Spring System of Magnetic Core

The mass and spring system for modeling vibrations in the magnetic core of power transformer is executed similarly to the windings. A significant difference in the design of mass and spring system of the magnetic core is the added dimension. The replacement of the magnetic core (Fig. 5.3a)) with the mass and spring system is illustrated in Fig. 5.3b).

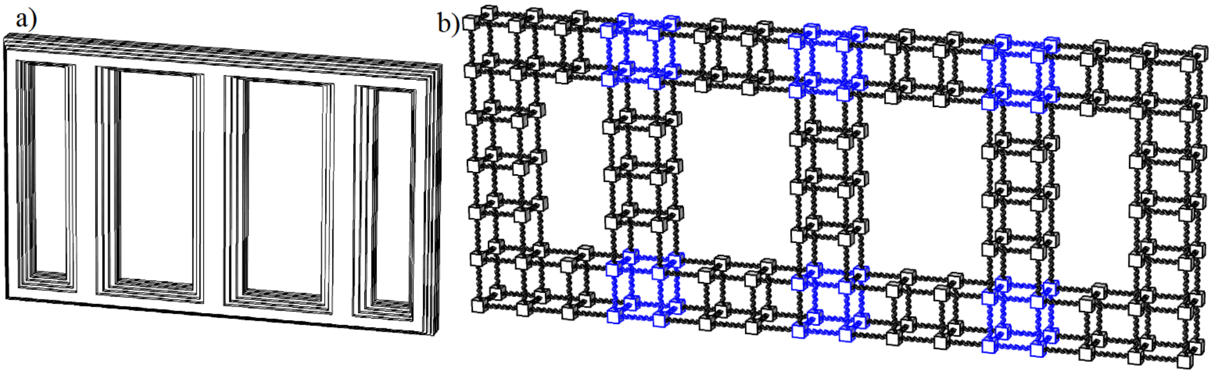


Fig. 5.3. Replacement of a transformer magnetic core with a mass and spring system:
a) construction of the magnetic core; b) replaced mass and spring system.

The colored mass elements and their connecting springs are considered to be rigid objects since in the construction the corresponding points are connected with braces [12]. The motion of each mass element can be expressed as a vector sum of its movements in all space dimensions. These movements are characterized by a system of differential equations:

$$\begin{gathered}
m_i \frac{\mathrm{d}^2 x_i}{\mathrm{d}t^2} + k_{xi}(x_i - x_{i-1}) + k_{xi+1}(x_i - x_{i+1}) + k_{yj}(x_j - x_{j-1}) \\
+k_{yj+1}(x_j - x_{j+1}) + k_{zl}(x_l - x_{l-1}) + k_{zl+1}(x_l - x_{l+1}) = F_{xi}(t) \\
m_j \frac{\mathrm{d}^2 y_j}{\mathrm{d}t^2} + k_{yj}(y_j - y_{j-1}) + k_{yj+1}(y_j - y_{j+1}) + k_{xi}(y_i - y_{i-1}) \\
+k_{xi+1} \cdot (y_i - y_{i+1}) + k_{zl}(y_l - y_{l-1}) + k_{zl+1} \cdot (y_l - y_{l+1}) = F_{yj}(t), \\
m_l \frac{\mathrm{d}^2 z_l}{\mathrm{d}t^2} + k_{zl}(z_l - z_{l-1}) + k_{zl+1}(z_l - z_{l+1}) + k_{xi}(z_i - z_{i-1}) \\
+k_{xi+1}(z_i - z_{i+1}) + k_{yj}(z_j - z_{j-1}) + k_{yj+1}(z_j - z_{j+1}) = F_{zl}(t),
\end{gathered} \tag{5.2}$$

where m_i – mass of the mass element kg;

x_{i-1}; x_i; x_{i+1}… z_{l-1}; z_l; z_{l+1} – the position of the mass element, the following and the preceding mass element in vertical and horizontal directions of the magnetic core in the axis of length, width, height and length of the magnetic core, m;

k_{xi}; k_{xi+1}… k_{zl}; k_{zl+1} – stiffness coefficients in the length, width and height directions;

$F_{xi}(t)$; $F_{yj}(t)$; $F_{zl}(t)$ – electrodynamic forces in the length, width and height directions of the magnetic core.

In order to simulate the magnetostriction effect with this equation system, it is necessary to calculate the equivalent magnetostrictive forces $F_{xi}(t)$, $F_{yj}(t)$ and $F_{zl}(t)$. Young's modulus is applied in order to simulate the deformations caused by magnetostriction effect, calculated as

$$E = \frac{F l_0}{S \Delta l}, \tag{5.3}$$

where F – applied force, N;

l_0 – initial length of the material, m;

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

Δl – length of the material deformation, m.

It is necessary to calculate the system of equations simultaneously for all mass elements of the mass and spring system at each moment of time since the change in the position of adjacent mass elements affects the values of the spring elastic forces on the respective mass element. Therefore, it is necessary to combine the equations of motion of all mass elements into a single system. This is achieved in the *Matlab Simulink* software environment.

The next step of the developed vibration model is to find the configuration of the spring stiffness coefficients of this system, which gives the resulting vibration amplitudes in the radial direction of the outer winding, that are equal to vibrations on the tank surface.

5.3. Dynamic Genetic Algorithm for Determination of Stiffness Coefficients in a Mass and Spring System

The purpose of the developed dynamic genetic algorithm is to find the configuration of the variables that would produce similar results to the vibration measurement data by simulating artificial evolution. This approach is necessary because each spring can have its own individual stiffness coefficient in the mass and spring system. This value can fluctuate over several orders of magnitude and result in a large number of different configurations. Genetic algorithms make it possible to search individual configurations in a large number of possible different cases. Such algorithms operate based on local change and randomization. If a new configuration is found with the better desired result, a greater proportion of subsequent searches occur in this area. It is possible to search results in a logarithmic area of space with relatively similar accuracy in each order by using different types of mutations.

The dynamic genetic algorithm initially generates a population of 100 individuals. Initial generation of individuals creates the first generation of the population. Every individual in the population is the explained flowchart of the signals in *Matlab Simulink* environment. The value of stiffness coefficient of each spring is assigned a random number between 0 and 10^7.

Using the developed dynamic genetic algorithm for winding and magnetic core mass and spring systems, it is possible to find such values of spring stiffness coefficients that the respective mass and spring system generate vibrations corresponding to measurements on the transformer tank surface and interpolated vibration values between these measurement points.

6. APPLICATION OF FUZZY LOGIC FOR RESULT GENERATION OF TRANSFORMER VIBRATION MODEL

The transformer vibration model uses 3 fuzzy logic blocks (see Fig. 6.1), and their main tasks are:

- to search for tank surface vibration measurements, which do not match other diagnostic results for a particular transformer;
- to compare and evaluate two successive diagnostics results of the surface vibration of a single transformer in order to evaluate information about their changes;
- to evaluate the results of the transformer windings in order to determine the need for modeling of the vibrations generated by the magnetostriction effect.

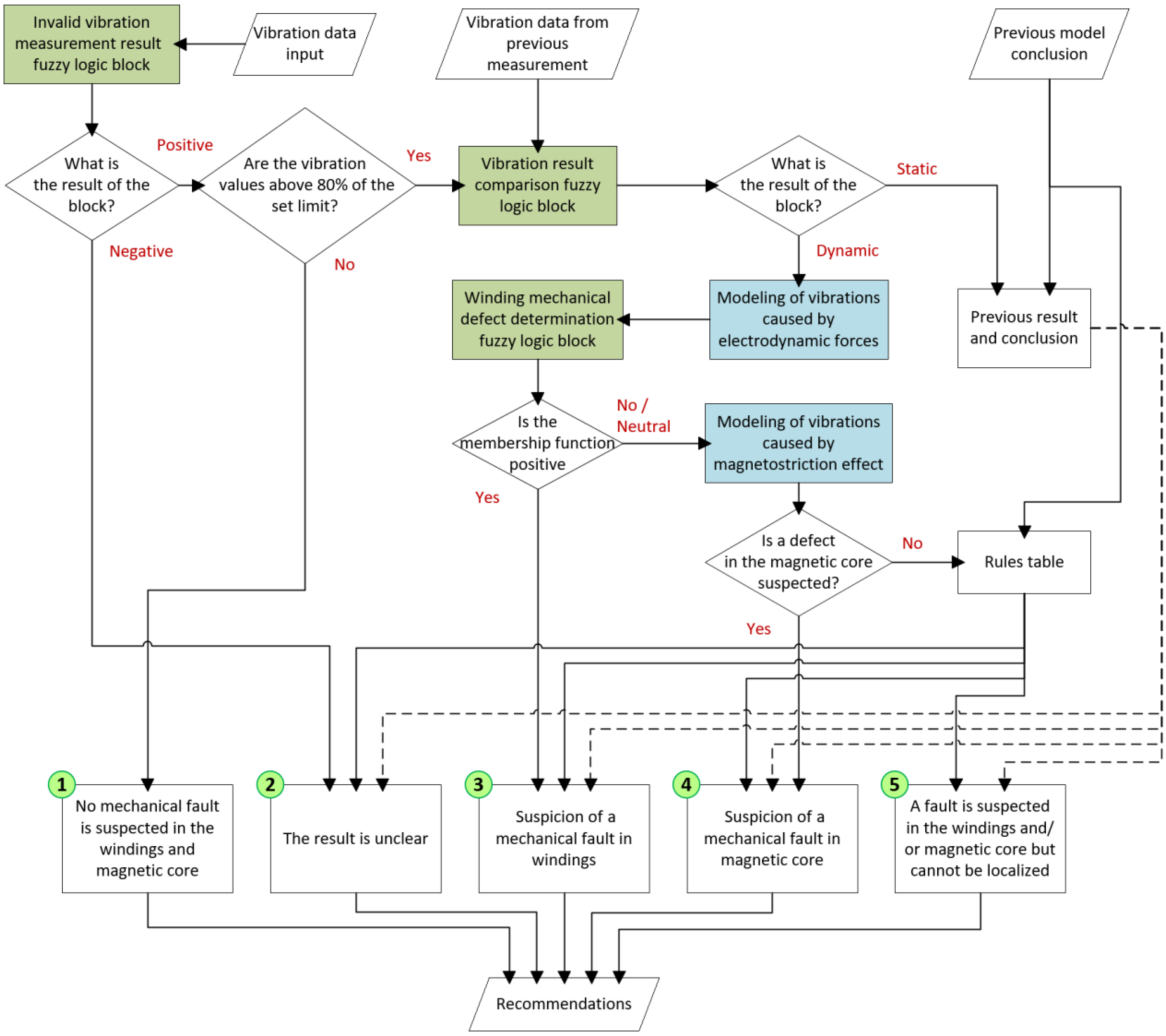


Fig. 6.1. Operation diagram of result generation block of the transformer vibration model.

Invalid vibration measurement result fuzzy logic block uses 4 characteristics. The number of missing measurement points n_{p} and the number of adjacent missing measurement points n_{kp} is also evaluated.

Coefficient $kvb_{\max}$ gives the ratio of the maximum value vb_1 to the second highest value vb_2 of the vibration measurement. Coefficient $kvb_{\min}$ is the ratio to check whether vibration measurements have data points that have an unusually low value due to error. It is necessary to execute this fuzzy logic block separately for each vibration characteristic since the vibration displacement l, the vibration velocity v, and the vibration acceleration a are measured in the diagnostics of the surface vibrations of the transformer tank.

Vibration result comparison fuzzy logic block is designed to compare the results of two consecutive vibration measurements. This is necessary in the case when the increased vibrations have been observed and the evaluation has already been performed, it is not necessary to perform the simulation again since the situation of the respective transformer has not changed.

The characteristics of this fuzzy logic block are kvb_{A}, kvb_{B} un kvb_{C}. Each of them represents the difference of vibration maximum value amplitudes between two measurements in the region of the respective transformer phase on the tank. An example is given in (6.1).

$$kvb_{\mathrm{A}} = \frac{\max(vb_{\mathrm{A2}.\,i}) - \max(vb_{\mathrm{A1}.i})}{\max(vb_{\mathrm{A1}.\,i})}, \%, \tag{6.1}$$

where $vb_{\mathrm{A2}.i}$ is the value of the measurement at the time of last diagnosis of phase A;

$vb_{\mathrm{A1}.i}$ is the value of the measurement at the time of previous diagnosis of phase A.

The last characteristic of this fuzzy logic block is coefficient $kvb_{\mathrm{max.d}}$, which expresses the extent to which the maximum value of the measurement of the vibration amplitudes has changed in proportion to the previous measurement in the rage of the entire measurement.

The winding mechanical fault detection fuzzy logic block is intended to determine which component of the transformer under test is suspected of having a mechanical fault. The fuzzy logic block uses 3 variables: k_a, k_v and k_l, which determine the extent of the characteristic amplitudes of the simulated vibration values for simulations with regularly reduced transformer load coinciding with the values obtained from the no-load operation diagnostic measurement results. The vibration acceleration characteristic k_a is calculated as

$$k_a = \sqrt{\frac{\sum_{i=1}^{n_v} (a_{\mathrm{sl}.\,i} - a_{\mathrm{t}.\,i})^2}{n_v}} \cdot 100, \tag{6.2}$$

where $a_{\mathrm{sl}.i}$ is the value of the acceleration at position i from the load vibration simulation, m/s^2;

$a_{\mathrm{t}.i}$ is the value of the acceleration at position i from the no-load vibration diagnostics, m/s^2;

n_v is the number of vibration acceleration measurement points.

Similarly, characteristics for vibration velocity k_v and vibration displacement k_l are calculated. It should be noted that the values of the modeled vibration amplitudes are initially obtained by simulating the operation of the transformer at full nominal load. This process is then recalculated with the already found stiffness coefficients of the mass and spring system at loads from 100 % to 30 % of the rated power, each time being reduced by 10 %. In this way, the nature of the change in the amplitude of the modeled vibrations is obtained, reducing the load on the transformer. An example of the results is shown in Fig. 7.5.

Afterwards, a linear least squares method [16] is applied to extrapolate the values of the modeled vibration amplitudes in the no-load operation using the calculated vibration values from 100 % to 30 % of the rated power.

It is necessary to find the position of the center of gravity of the graph of the result membership function of this fuzzy logic block, since 3 different results of the fuzzy logic block are possible. The gravity center of the result function is calculated as

$$R_{\mathrm{fuzi}} = \frac{\sum_{i=1}^{n_{\mathrm{it}}} x_{\mathrm{f}.i} y_{\mathrm{f}.i}}{\sum_{i=1}^{n_{\mathrm{it}}} y_{\mathrm{f}.i}}, \tag{6.3}$$

where $x_{\mathrm{f}.i}$ is the value of the i-th argument of the result membership function of fuzzy logic block;

$y_{\mathrm{f}.i}$ is the value of the i-th function value of the result membership function of fuzzy logic block; and

n_{it} is the chosen iteration amount for the result membership function calculation.

In the case of a positive result it is concluded that there is a suspicion of a mechanical fault in the transformer windings, but in the case of a negative result a mechanical fault is suspected in the magnetic core. In the case of a neutral result, it is not directly known which element of the transformer is suspected of having a mechanical fault since there is no clear indication either of the transformer windings or the magnetic core.

The vibrations generated by the magnetostriction effect are modeled in cases where the winding mechanical fault detection fuzzy logic block gives a negative or neutral result [13]. As a result, the stiffness coefficients of the created mass and spring system are found in the simulated geometry of the yokes and rods of magnetic core. Afterwards, each simulated rod or yoke is divided into fragments consisting of 4 mass elements (see Fig. 6.3). Within each fragment there are 2 springs, which are perpendicular to the surface of the transformer tank on which the vibration measurement values were obtained.

The ratio of k_{r} is obtained by dividing the highest of these coefficients by the lowest. The value of this ratio coefficient relative to the values of other fragments of the same magnetic core rod or yoke determines whether a mechanical fault is suspected in the particular fragment.

In cases where transformer winding and magnetic core simulations have already been carried out and these blocks of the developed vibration model cannot be reached unless a mechanical fault in the transformer is suspected, further evaluation using binary logic is provided in the rules table (see Table 6.1).

Table 6.1

Rule Table for Generating a Conclusion

Previous model conclusion	Is the conclusion credible?	The result of winding mechanical fault detection fuzzy logic block	Number of the conclusion (see Section 2)
2	Yes or No	Neutral or negative	2
3	Yes	Neutral or negative	3
3	No	Neutral or negative	2
4	Yes	Neutral or negative	4
4	No	Neutral or negative	2
5	Yes or No	Neutral	5
5	Yes or No	Negative	2
Does not exist	–	Neutral	5
Does not exist	–	Negative	2

7. RESULTS OF TRANSFORMER VIBRATION MODEL

7.1. Calculation Example for One Transformer

The calculation is made for a transformer for which the vibration measurements on the tank surface show values exceeding 80 % of the set limits (see Fig. 7.1).

To ensure the accuracy of the vibration data generated from this transformer, they are all processed with the invalid vibration measurement result fuzzy logic block. 12 vibration data groups are tested as part of this test. In the case of this transformer, the results of all data groups have positive result, which shows that the vibration measurement data is reliable. Consequently, the transformer vibration model arrives to the vibration result comparison fuzzy logic block, which requires an approximation of the vibration values.

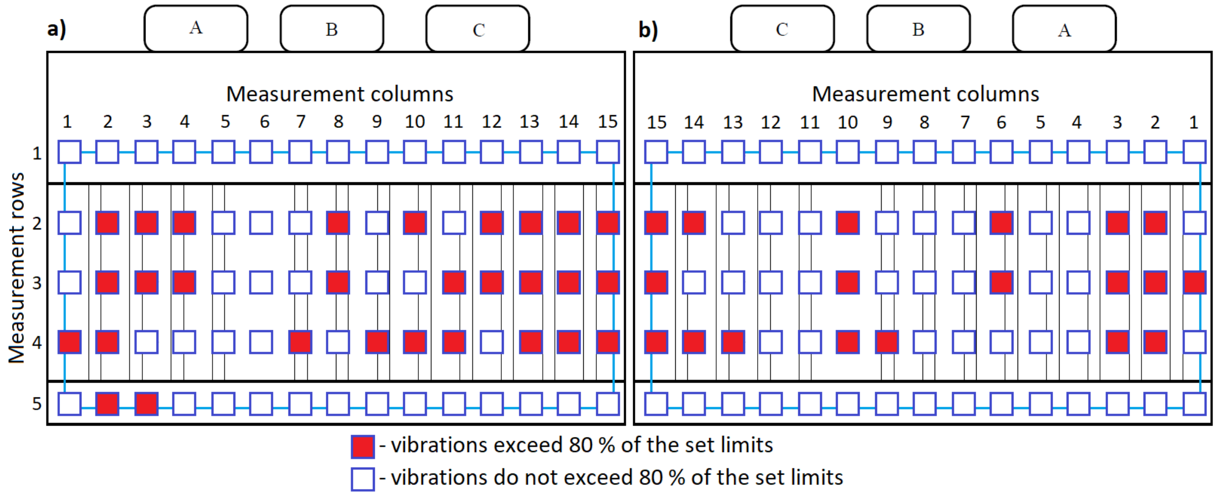


Fig. 7.1. Vibration sensor data displayed on the transformer:
a) the higher voltage side of the tank surface; b) the lower voltage side of the tank surface.

Since the data points in the previous measurement are derived from 4 measurement rows and 12 measurement columns, both the Newtonian polynomial and the modified Newtonian polynomial methods are used. The results of the vibration result comparison fuzzy logic block at both at 100 % load and no-load operation indicate that the vibration values are dynamic. Therefore, it is necessary to perform further operations of the developed vibration model and to perform vibration simulation in the transformer windings.

The operation of the transformer magnetic field electromagnetic force calculation block of the developed vibration model starts with the creation of the geometric model of the windings and magnetic core of the respective transformer and dividing them into fragment elements of the finite element method. After calculating the transformer magnetic field model, the results of the magnetic induction *B* in transformer windings and magnetic core and current density *J* windings are exported to a .txt document for further processing. Precisely, the magnetic field leakage component that crosses the windings of the modeled power transformer is used.

After obtaining the magnetic induction B in the magnetic core and windings and the current density in windings from the transformer magnetic field model, this data is stored transferred to *Microsoft Excel* for storage and then used in *Matlab*. It should be noted that before starting the next block of developed vibration model the values of electrodynamic forces in the fragments of transformer winding segments are calculated.

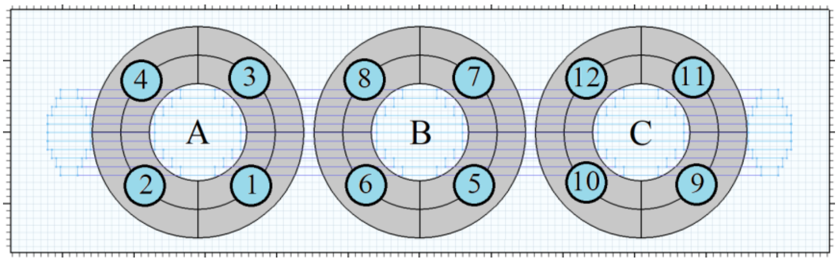


Fig. 7.2. Numbering of transformer winding segments.

In the next step, for each simulation of the winding segment (see Fig. 7.2) a dynamic genetic algorithm is used to find the stiffness coefficients of the mass and spring system.

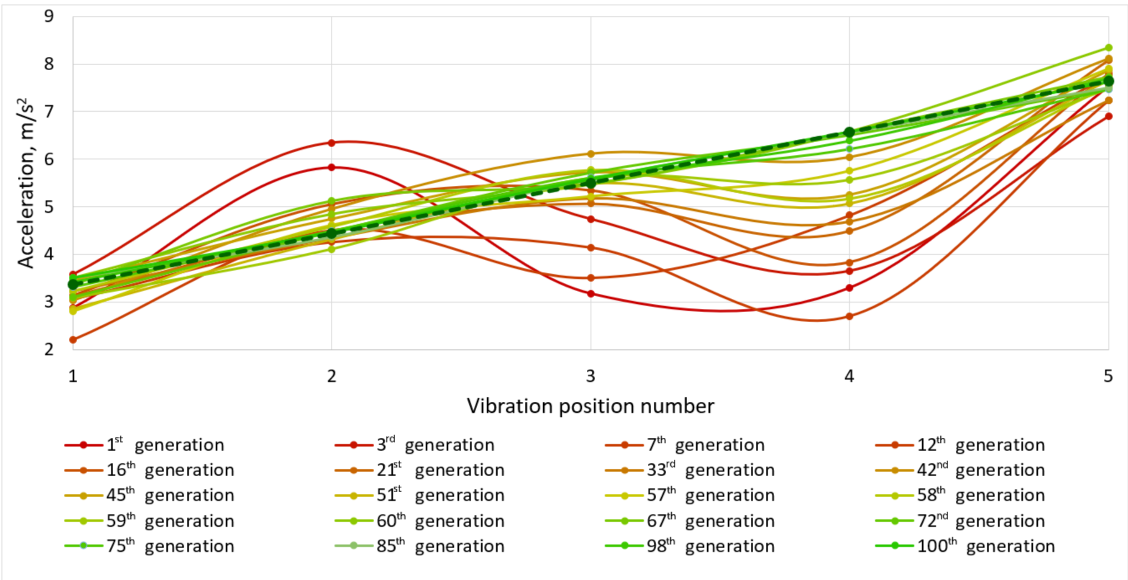


Fig. 7.3. Visualization of results obtained by DGA.

The DGA evolution simulation used to obtain the vibrations generated by each winding segment creates a different number of generations, so their number is variable at each simulation due to their chaotic nature and black box principle. As an example, Fig. 7.3 illustrates the case of the DGA results with 100 simulated generations.

As shown in Fig. 7.3, in the first generations simulated by the DGA the obtained vibration values are of a chaotic nature but tend to the measured vibration values as the number of simulated generations increases. Additionally, it should be noted that the generations illustrated in Fig. 7.3 are chosen because it is these generations that have found mass and spring system configurations that yield better results than their respective previous generation.

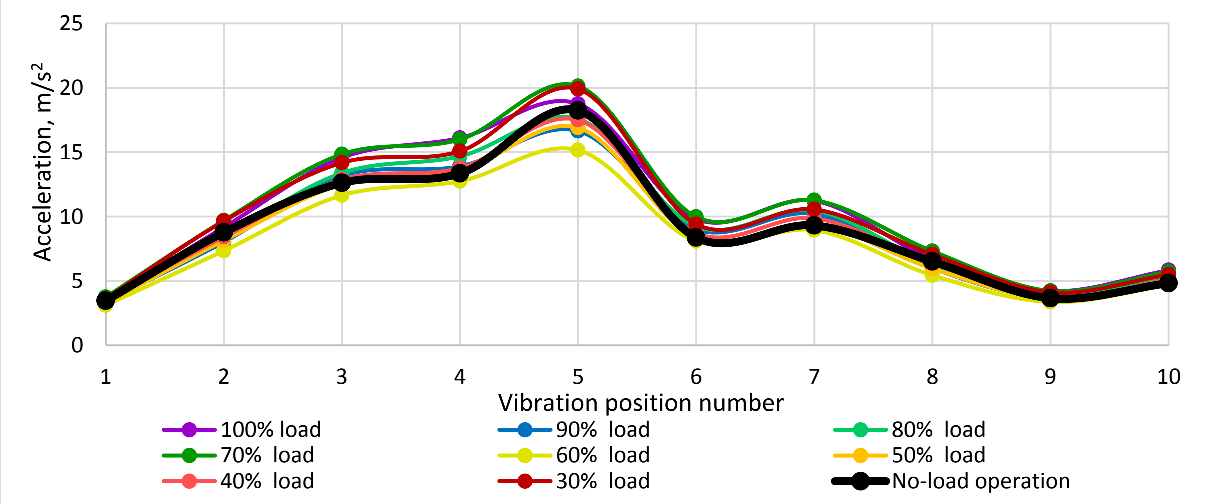


Fig. 7.4. Results of the vibration acceleration of winding segment No. 1 with different transformer load values.

After obtaining the results of the simulation, the next step is to use the obtained stiffness coefficients of the springs for analysis by gradually reducing the transformer load to 30 %. The results obtained for winding segment No. 1 are shown in Fig. 7.4 where the vibration acceleration values of the vibrations generated by winding segment No. 1 change based on the transformer set load in the simulation. Linear least squares method is used to calculate and extrapolate the vibrations produced in no-load operation. In this way, the nature of the total vibration changes at each measurement or approximation point is considered, but exceptions do not result in inconsistent results when the vibration values increase when reducing the transformer load. The results of the least squares method are shown in Table 7.1.

Table 7.1

Results of Linear Least Squares Method for Winding Segment No. 1

Number of measurement point	Vibration characteristics of winding segment No. 1					
	Acceleration, m/s^2		Velocity, mm/s		Displacement, μm	
	Simulation	Measured	Simulation	Measured	Simulation	Measured
1	3.47	2.80	1.86	1.30	7.13	1.40
2	8.77	7.15	8.52	10.44	8.30	16.75
3	12.62	11.11	15.92	17.40	19.58	28.11
4	13.35	14.30	15.96	20.00	20.63	31.50
5	18.24	16.17	5.03	17.15	15.35	25.03
6	8.37	15.50	11.41	12.10	12.65	15.20
7	9.32	11.71	6.59	8.36	5.83	8.84
8	6.52	7.50	4.02	6.00	5.52	5.60
9	3.66	5.53	1.81	4.34	2.93	3.61
10	4.83	5.10	2.48	3.00	5.29	2.10

Table 7.1 shows the summary of the results of winding segment No. 1 as well as other segments of the corresponding transformer windings. These results function as input data in the winding mechanical defect determination fuzzy logic block. The results of this block determine whether a mechanical fault is suspected in the relevant segment of the windings. It should be noted that there are 4 winding segments in the phase of the transformer, each of which can generate its own individual result, but later all these results are combined into one, but the result of each winding segment gives a weight to the total winding result.

This approach produces results for all transformer winding segments and then combines them within each transformer phase. In the case of this transformer, the results of the winding mechanical defect determination fuzzy logic block are shown in Table 7.2.

Table 7.2

Results of the Winding Mechanical Defect Determination Fuzzy Logic Block

Number of winding segments	The corresponding phase of the transformer	Result of fuzzy logic block	Further actions
1–4	A	Neutral	Vibration modeling of magnetic core
5–8	B	Negative	Vibration modeling of magnetic core
9–12	C	Neutral	Vibration modeling of magnetic core

In the case of this transformer, neutral results are obtained in the regions of segments 1–4 and 9–12, and a negative result in the regions of segments 5–8. Therefore, it is required to calculate vibrations caused by magnetostriction effect in the rods of all phases of magnetic core. Additionally, since the magnetic core has a 5-rod design and the vibrations of the transformer tank surface show values on the tank sides that exceed 80 % of the set limits, it is also necessary to simulate and calculate the vibrations generated by these magnetic core construction elements.

The next step is the calculation of the equivalent magnetostriction effect forces, which is performed by the (5.3) by using the magnetic induction B values calculated in the previous steps in the magnetic core of transformer. Then a system of masses and springs is created for both the magnetic core rods of the phases and the rods of the side construction. In the case of this transformer, the mass and spring system of the rod for each phase consists of 20 mass elements interconnected by 84 springs. In the case of side rods, this system consists of 44 mass elements interconnected by 180 springs.

The DGA is then re-applied to find the spring stiffness coefficients that, due to the magnetostriction effect, simulate vibrations that correspond to the no-load operation measurement results and approximate vibration values between them.

Since DGA is using the black box principle, it is necessary to calculate the value of ratio coefficient k_r. The results of this coefficient for the respective transformer are shown in Table. 7.3. The marked ratio coefficient values indicate that these fragments exhibit drastic changes in their mechanical strength. Therefore, the developed vibration model concludes that there is a suspicion of a mechanical fault in magnetic core in the rods of phases A, B and C and in the left side rod, but the result in the right side rod is unclear. The resulting conclusion for each region of the transformer windings and magnetic core with recommendations and visualization of the vibration data is summarized in Fig. 7.5.

It should be noted that the conclusion of the right side rod is obtained using Table 6.4, since there are no previous vibration model results for this region. Therefore, the only row of Table 6.1, corresponding to the situation in this rod, provides conclusion No. 2.

Table 7.3

Ratio Coefficient Results for the Tested Transformer

	Rod of the magnetic core				
	Left side	Phase A	Phase B	Phase C	Right side
Ratio coefficient k_r	1.40	2.66	1.63	2.10	1.01
	1.52	2.15	7.93	21.92	1.03
	2.26	1.81	78.10	14.06	1.45
	3.60	4.44	22.38	5.85	1.19
	1.10	4.78	7.89	1.17	1.25
Conclusion	No. 4	No. 4	No. 4	No. 4	No. 2

Region of the transformer	**Conclusion**	**Recommendations**
Left side	Suspicion of a mechanical fault in magnetic core	Additional testing of the forced-cooling system of the transformer, the base of the transformer tank and possible external sources of vibration is recommended. Determine the no-load operation current and magnetic losses, perform a repeated diagnostic of the vibration of tank surface in no-load operation by further examining the relevant region of the magnetic core.
Phase A	Suspicion of a mechanical fault in magnetic core	
Phase B	Suspicion of a mechanical fault in magnetic core	
Phase C	Suspicion of a mechanical fault in magnetic core	
Right side	The result is unclear	

Visualization of vibration approximation at 100 % load

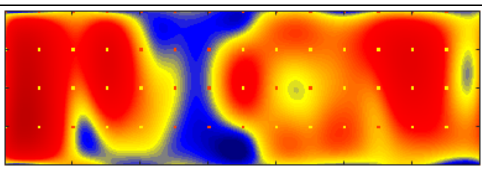
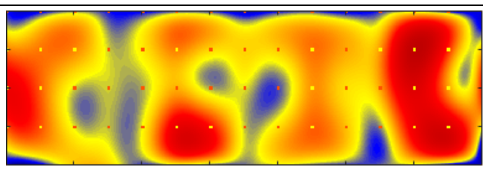
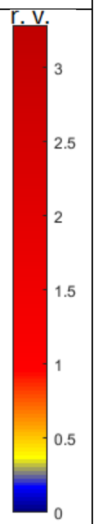
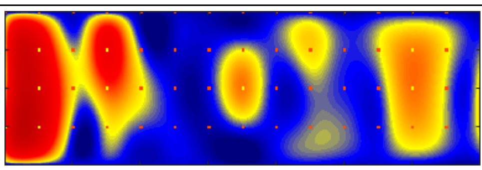
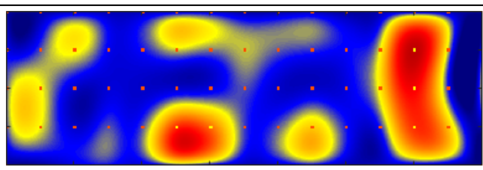
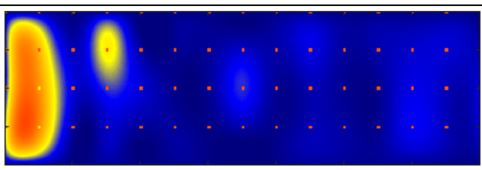
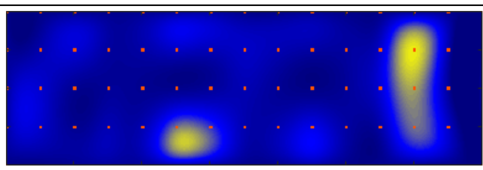
Charac-teristics	**Higher voltage side of transformer tank** **Phases: A B C**	**Lower voltage side of transformer tank** **Phases: C B A**	**Scale**
a, in relative units			
v, in relative units			
l, in relative units			

Fig. 7.5. The results of the calculation example for the respective transformer.

7.2. Results of the Developed Vibration Model

In the framework of the developed vibration model verification, in addition to the transformer discussed above, results are obtained for 4 other transformers with the relevant data of vibration diagnostic results:

- transformer No. 1 – the vibration values exceed 80 % of the set limits in the regions of phases A and B, both at 82 % load and at no-load operation;
- transformer No. 2 – the vibration values exceed 80 % of the set limits in the region of phase A, where the largest vibration values are registered at no-load operation;
- transformer No. 3 – the vibration values do not exceed 80 % of the set limit values in any region of the transformer at both corresponding load and no-load operation;
- transformer No. 4 – the vibration values do not exceed 80 % of the set limit values in any region of the transformer at both corresponding load and no-load operation.

The developed vibration model in the case of transformer No. 1 provides results where there is a suspicion of a mechanical fault in the region of phase A but cannot be localized. This is since the simulation and calculation of vibrations caused both by the windings and the magnetic core do not give a direct indication of the presence of a mechanical fault in this region. However, there is a suspicion of a mechanical fault in the region of phase B, but no mechanical fault is suspected in the region of phase C.

In the case of transformer No. 2, it is concluded that there is a suspicion of a mechanical fault in the region of phase A but cannot be localized. There is no mechanical fault suspected in the regions of phases B and C.

The results of the developed vibration model for transformer No. 3 show that the vibration diagnostic data are credible. Therefore, no vibration of the windings or magnetic core of transformer No. 3 is simulated since there is no reason to suspect a mechanical fault in any of these regions. Thus, for transformer No. 3, in all regions that have been subjected to a vibration diagnostic of the transformer tank surface, it is concluded that no mechanical fault is suspected in the windings and magnetic core.

The results of the developed vibration model for transformer No. 4 in all regions of windings and magnetic core indicate that no mechanical fault is suspected since the vibration diagnostic results are credible, and the values do not exceed 80 % of the set limits.

CONCLUSIONS

1. As a result of the literature analysis it can be concluded that there is no transformer diagnostic method that can directly and unequivocally detect mechanical faults in windings or magnetic core. Furthermore, there is a common feature amongst diagnostic methods used in the industry – there is no universal interpretation of measurement results. In order to solve this problem, a transformer vibration model has been developed. The input data for this model are the vibration measurements on the surface of the tank, and it uses a dynamic genetic algorithm, fuzzy logic, black box principle and a modified Newtonian polynomial approximation method to obtain a conclusion about the existence of a mechanical fault within the windings and magnetic core and provide recommendations for further diagnosis.
2. The operation of the vibration model, irrespective of the position of the sensors on the surface of the tank, is successfully achieved by approximating the vibration values with the Newtonian polynomial method, including a modification of this method for more than 5 sensors in a given direction. The advantages of the modified Newtonian polynomial approximation method are: fewer new local maxima than there are by using cubic spline approximation, and the calculation that does not increase geometrically as with Newtonian polynomial method. It is found that the modified method produces fewer local maxima in 69.44 % of cases when tested with 108 vibration measurements.
3. Vibration simulation performed within the vibration model allows to generate vibration characteristics within the transformer windings, which, when processed in the fuzzy logic unit, allows to obtain a conclusion about a possible mechanical fault in windings, based on the calculations of magnetic field characteristics and electrodynamic forces and the principle of freely interchangeable configuration mass and spring system.
4. A system of masses and springs with freely variable configuration is developed for the simulation of vibrations generated by the rods and yokes of magnetic core. It is based on both literature analysis and acquired experience in vibration simulation within windings that allows to obtain the values of vibration displacement in magnetic core. The evaluation of these vibration values allows to make a conclusion of a possible mechanical fault in magnetic core.
5. A mass and spring system consisting of 20 mass elements and 42 springs for a transformer winding fragment, of 20 mass elements and 84 springs for phase rods, but of 44 mass elements and 180 springs for side rods of a 5-rod magnetic core is created in order to check whether the simulated vibrations correspond to the vibration characteristics measured on the surface of the tank. As a result, the greatest square deviation of the simulated vibrations of transformer windings from the measured values is 2.3 m/s^2 for acceleration, 4.8 mm/s for velocity and 5 μm for displacement, while within magnetic core – 3 μm for displacement in side bars and 1.9 μm for displacement in phase bars.

6. The calculation process for transformer with increased vibration values on the transformer tank, which is presented in the Thesis as a detailed calculation example, allows to conclude that the fuzzy logic blocks for evaluation of the measurement data, comparison of sequential measurement data and obtaining the conclusion work properly, since the most complex possible variant for the fuzzy logic block is obtained. In this variant, the calculated values k_a = 2.7 %; k_v = 4.3 % and k_l = 6.4 % activate all the possible columns of the rule table. Therefore, there is the greatest uncertainty in results, from which the fuzzy logic block obtains 1 particular result.
7. In the framework of the developed vibration model verification, the obtained conclusions for the transformer correlate well with the transformer vibration measurement data. Namely, for 2 transformers with vibration values not exceeding 80 % of the set limits, the vibration model concludes that there is no suspicion of a mechanical fault. However, in the cases of 3 transformers with increased vibration values, the developed vibration model gives an indication of a possible mechanical fault in the windings and/or the magnetic core.

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