CYSENI 2016, May 26-27, Kaunas, Lithuania
ISSN 1822-7554, www.cyseni.com

STUDY OF POWER TRANSFORMER MECHANICAL FAULTS DETECTION BY USING VIBRODIAGNOSTICS

Janis Marks
Riga Technical University
12/1 Azenes Street, Riga LV-1048 – Latvia
Phone: +37167089418
Email: janis.marks@rtu.lv

ABSTRACT

Power transformers are important elements of the electrical system and have a high degree of risk since in case of failure the generator connected to the damaged transformer cannot transfer energy to electrical system. Therefore, a generated power deficit may be formed and part of the consumers can be disconnected from power supply.

Power transformers can experience various types of faults that may be potentially dangerous and cause the failure of the device. Various diagnostic methods exist for the detection of these damages. Each of them designed for a specific transformer characteristic. For example, measurement of winding insulation resistance and dissolved gas analysis can be used to detect electrical faults, but thermography is used to identify thermal defects. It should be noted that these widely used methods are not intended to detect mechanical faults. However, one possible approach to detect them is based on analysis of vibration measurements on the surface of transformer tank. This method is discussed in this article.

In order to detect mechanical defects, certain difficulties occur. It is impossible to see what is happening inside the transformer tank without opening it, but vibration analysis can acquire information about transformer windings and core mechanical condition without doing so. This is because vibration sensors are mounted on the transformer tank surface. Consequently, it is possible to analyse the causes of mechanical defects, their location within the transformer's structure and their intensity while transformer is operating.

A case study is provided where data is analysed from a power transformer with increased vibration levels, which is installed in a power plant in Latvia. A method is proposed for graphical analysis of the results of vibration measurements. It allows obtaining more information about vibration amplitudes, their distribution and epicentres, as well as vibration changes within a specified time period caused by the transformer.

Keywords: Power transformers, fault detection, condition monitoring.

1. INTRODUCTION

Alternating current flows in the windings of power transformer while it is working in nominal conditions. This process creates a magnetic field with constantly changing values around the windings. Consequently, this field induces electromotive force in secondary winding of transformer. This force allows the flow of current if the electric circuit of secondary winding is closed. One of determining conditions to provide the operation of transformer is the position of magnetic field within the construction of the transformer. It is necessary for it to flow through every individual loop of secondary winding since this is the part of the magnetic field that induces electromotive force in the secondary winding. For this purpose, magnetic circuits are made of steel consisting of separate strips. This way the magnetic permeability is much higher than the surrounding air or any other dielectric next to it and the position of magnetic field is located utmost through the secondary winding of power transformer. The magnetic circuit cannot be implemented from monolith steel because eddy currents are generated within it. It should be noted that it is impossible for all magnetic flux to flow through the secondary winding since some portion of the magnetic flux will be linked through insulation and other components of the transformer. This component is called leakage flux and a part of it closes through the construction of primary and secondary windings. Therefore, both current conducting windings are positioned within a magnetic field and are exposed to electrodynamic forces proportional to current squared in the given winding. It should be noted that similar forces are acting upon the core of transformer because its material has a characteristic to change dimensions depending on the value and direction of the magnetic field within it. Therefore, electrodynamic forces act upon the transformer and cause vibrations while it is connected to supply of electric energy [1].

Transformer is subject to relatively intense repeating thermal and electrodynamic processes within long-term operation. The result of this is the degeneration of both the insulation condition between transformers windings and the clamping pressure of windings and magnetic core. Over time, the situation can deteriorate and irreversible faults can occur since transformer degenerates through time. It is necessary to carry out transformer diagnostics to avoid these faults. However, the dimensions and construction of large power transformers are non-homogeneous and are not symmetrical. Therefore, certain difficulties occur in order to check the mechanical condition of windings and magnetic core of transformer [2].

Arising vibrations spread within the surrounding space and this process also occurs inside the construction of transformer. The vibrations from windings and magnetic core propagate through the lairs of insulation, constructive components and the tank of transformer. Therefore, it is possible to measure amplitudes and harmonics of vibrations from the surface of transformer with sensors intended for these measurements. However, it is necessary to take in consideration the altered vibration characteristics due to their propagation through the structure of transformer since these vibrations pass through certain parts of transformer and are damped with their kinetic energy distributed throughout a larger space. Additionally, every component of structure has natural frequencies and influences certain harmonics of vibration differently. This also changes the information of vibrations obtained on the surface of transformer. Furthermore, vibrations have a fundamental property of arising in a certain place when they are suppressed in a different region and their paths of spreading are changed. For example, middle three magnetic core segments of five-leg transformer are covered by the primary and secondary windings and vibrations from both the magnetic and electric circuits of transformer bulge mostly in the side segments of the magnetic core since there is relatively low mechanical resistance in these regions. Therefore, the actual mechanic fault can occur in one place but its effects on vibrations generated emerge in a different location since the given distribution path has less resistance. [3, 4, 5].

However, it is possible to estimate the mechanical condition of windings and magnetic core of transformer from measurements taken from the surface of transformer by taking in consideration the uncertainties caused by distribution of vibrations. Therefore, certain standards exit defining the levels of all vibration characteristics (displacement, velocity and acceleration). It is considered that transformer has developed a mechanical fault if these levels are exceeded. However, more precise information cannot be obtained [6].

The objective of this article is to show that it is possible to obtain information about the mechanical condition of windings and magnetic core of transformer with the visualization and approximation of surface vibration of transformer.

A case study is provided where the data of surface vibration of transformer installed in Latvia is viewed, visualization and approximation is performed and corresponding conclusions are made.

2. POWER TRANSFORMER DIAGNOSTIC METHODS USED IN LATVIA

Diagnostic methods used for power transformers in Latvian power plants are shown in Table 1, as well as potentially detectable fault types. The “+” indicates detectable fault types and the “*” indicates the potentially detectable fault types of corresponding methods. Every diagnostics method is intended for a specific transformers element or characteristic. The occurring faults within power transformers can be divided in 3 groups [8] depending on their nature – thermal, electrical and mechanical.

Table 1. Summary of diagnostic methods

Diagnostic methods name	Detectable fault type		
	Mechanical	**Electrical**	**Thermal**
Physical chemical analysis of oil	*	+	+
Chromatographic analysis of oil		+	+
Thermography testing of transformer			+
Vibrodiagnostics	+		
Termination of partial discharge	*	+	
External visual inspection of transformer	+		
Insulation resistance	+	+	+
Dielectric loses		+	
Winding active resistance measurements with direct current		+	+
Detection of short-circuit resistance	+		
No-load losses		+	

Various diagnostic methods for power transformer are used in practice. They differ in their content, provided information and characteristics. They can be applied both when the power transformer is operating and out of service. Single diagnostic method by itself cannot provide information about all possible power transformer faults. Therefore, the most optimal combination of these methods must be found to acquire the data sufficient to evaluate technical condition. As it is shown in Table 1, the mechanical condition of power transformer windings and magnetic core can be evaluated primarily by using vibrodiagnostics. This method allows to collect data about the source of vibrations within power transformers construction, their nature and amplitude. When either windings or magnetic core gradually delaminates, their created vibrations increase with direct proportion [1, 4].

Table 1 also shows that aside from vibrodiagnostics, there are other diagnostic methods, which can detect defects of mechanical nature in power transformer. Winding resistance measurements are one of these methods that allows detecting such faults as burnout of solid insulation, high moisture and water content, and mechanical deformations. These faults have negative effects on the transformers winding insulation and as a result, the insulation deteriorates. However, it is not possible to determine, which of these defects have actually caused the fault. Therefore, in order to clarify this, additional diagnostic methods are required [1, 4].

Another alternative method exists, which is short-circuit resistance detection. Since transformer winding geometric configuration can change as a result of short-circuit this change affects short-circuit resistance and allows to diagnose mechanical faults [9].

3. VIBRATIONS IN POWER TRANSFORMERS

Vibrations data is acquired with sensors on the surface of power transformer tank during vibrodiagnostics. However, this approach alters the original pattern since vibrations originate within transformers windings and magnetic core but afterwards they spread through the internal structure of transformer, reach tank's surface through oil and only then are received by sensors. Fig. 1 shows the graphical interpretation of this process [10].

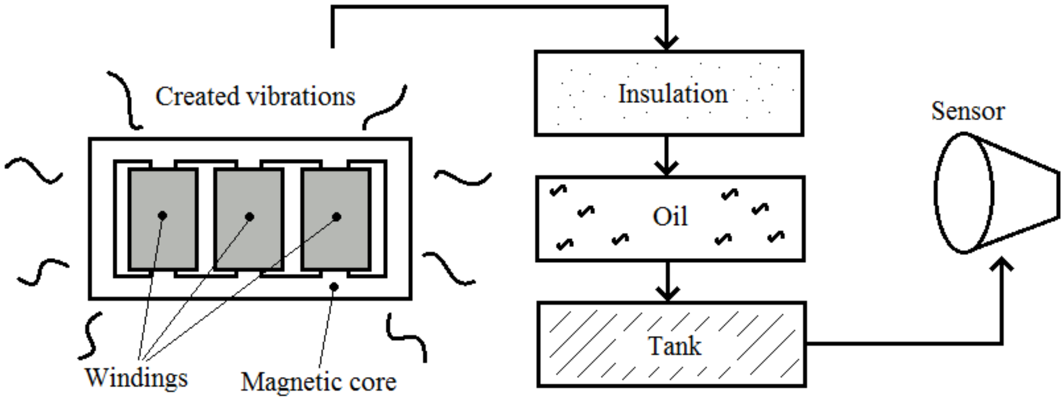

Fig. 1. Transformer vibration distribution

There is a difference between sensor readings on the surface of the tank and originally generated vibrations because their transmission path is relatively long and diverse. This affects both vibration spectrum and combined amplitude. In general vibration data from both inside of transformer or outside of it can be used as input data for detection of mechanical faults since the vibration generation source is the same [3]. But it is difficult to directly acquire information about vibrations of power transformer windings and magnetic core. Therefore, vibrodiagnostic methods use either an expert system (specifically designed software) or rough approximation. Equation 1 shows an example of vibration value change due to transformers structure [11].

$$v_{\tan k,100} = (\alpha + \beta\theta_{to})i^2 + (\gamma + \delta\theta_{to})u^2 \quad (1)$$

where $v_{tank,100}$ is vibration signal amplitude in 100 *Hz* frequency, i and u respectively current and voltage within transformers winding, θ_{to} is the temperature of transformers tank and α, β, γ, δ are coefficients, which are related to the geometry of each individual transformer [11].

Power transformer has other components that generate vibrations such as oil pumps for forced cooling. These devices generate additional vibrations and further negatively affect diagnosis of mechanical condition. However, these vibrations have defined frequency spectrum and can be differed from the main transformer by filtering them [10].

Additionally, the transformer tank can be nonhomogeneous and asymmetric. For this reason, vibrations are received differently in places with varying distances from vibration generation sources. This negative influence is countered by taking into account the position, geometric parameters and respective configuration of transformer tank and other relatively large components within it [3].

Interpretation of the results of vibrodiagnostic test with modelling of vibrations generated in power transformer has a large advantage since it is possible to input all characteristics of transformer tank and other components in the model and acquire more accurate results. The generated results then are compared to situation in reality.

4. SUMMARY OF GRAPHIC INTERPRETATION METHODS OF VIBRATION MEASURMENT RESULTS

In practice there are a large number of power transformer diagnostic methods [7, 11, 12, 13]. A part of these methods use graphic simulations or graphic interpretation of the results and a fraction of them are shown in Table 2. It also displays their comparison, given disparities and the input data *l*, *v*, *a*, (displacement, velocity and acceleration). The methods differ both in the necessary input data and in the obtained information from final results.

Table 2. Comparison of vibrodiagnostic methods

Method	**Input data**					**Necessary software**	**Fault location**
	l	**v**	**a**	**Used harmonics (frequencies)**	**Transformer geometry**		
Vibro-acoustic method	-	-	+	1-10 (100-1000 Hz)	Not needed	Expert system	In transformer windings and magnetic core
Finite element modelling	+	+	+	1-1000 Hz (continuous spectrum)	Is needed	Expert system	In transformer windings and magnetic core
Surface velocity pattern	-	+	-	1 (100 Hz)	Not needed	Expert system	In transformer windings
Vibration sensor network designing	-	+	-	1-20 (100-2000 Hz)	Not needed	Expert system	In transformer windings and magnetic core

Vibro-acoustic method uses specialized software with an expert system and utilizes Fourier transformations to calculate and obtain the necessary results from original vibration data of transformer surface [7].

Both inner and outer structures of a transformer are modelled in finite element method. As the result, natural frequencies are generated and vibrations within the transformer are created. Afterwards, modelled data is compared to vibrations measured in practice, generally approximately 10% difference is obtained [11]. This method is effective since more information is obtained about the processes inside the structure of transformer. However, it can be more complicated to carry out since the method is more complex [11].

The acquisition of velocity pattern on the transformer surface gives information about vibration amplitudes and their changes considering temperature fluctuations within the transformer and around it. The obtained data provides a rough notion about the mechanical condition of the transformer windings, however surface pattern velocity method does not provide information on mechanical condition of other parts of the transformer [12].

The designing of vibration sensor network allows the possibility to adapt it to each individual power transformer. More accurate information can be acquired about vibrations caused by transformer windings and therefore their mechanical condition. It should be noted, that a disadvantage exists since the sensor network is designed for a specific situation and this developed setup will not be as effective and precise if the conditions change. This is explained by the fact that the placement of largest vibration epicentres may change if transformer windings or magnetic core deforms and the configuration of installed sensor network will not correspond optimally to the new situation [13].

5. CASE STUDY

5.1. Problem statement

Results of vibration measurements are analysed for a power transformer installed in a power plant in Latvia as the case study of this article. Increased vibration values have been observed for this transformer during a period of 5 years. The author expresses gratitude to JSC Latvenergo for providing data of vibration measurements for the case study.

Certain difficulties occurred with the processing of the results of vibration measurements with vibrodiagnostic methods analysed in previous chapter of this article because not all necessary information is given within the literature.

- The coefficient for the technical condition using vibro-acoustic method describes the mechanical condition of windings and magnetic core within sectors of transformer. It is calculated by using an expert system [7].
- The software required and mathematical model used for finite element modelling method is not indicated in [11].
- The method of tank surface velocity pattern requires software and a mathematical model to carry out the diagnostic. This software is not specified and model it is not shown in [12].
- The method for vibration sensor network designing selects a specific sensor network for each individual power transformer. It is not possible to do interpretation of data if it is already obtained with a different sensor network [13].

Therefore, there is a necessity for interpretation method of the results of vibration measurements that is freely available and universal enough, and capable of providing the insight about the mechanical faults of transformer windings and magnetic core. Furthermore, the explanations would be available with open code for the operation and expert system of such method.

Table 3 shows the description for proposed method within its current stage of development.

Table 3. Description of the proposed method

Input data					**Necessary software**	**Fault location**
l	**v**	**a**	**Used harmonics (frequencies)**	**Transformer geometry**		
-	+	-	Vibration total value	Sensor relative position on transformers tank	Not needed	In transformer windings and magnetic core

5.2. Proposed method and evaluation of the results

The proposed method uses data of the total values of vibration velocity. It contains all vibration harmonics received from sensors located on the surface of tested power transformer. These sensors can receive frequencies from 10 *Hz* to 1000 *Hz* [14]. Fig. 2 shows the sensor position for this power transformer. Initially, there was only a small amount of sensors but the count was increased due to measured vibrations with high amplitudes. This was carried out in practice. However, this method can be used for different sensor arrangements as well. Measured results are used for data approximation that is carried out with different power polynomials, and approximated values are obtained in places where sensors were not positioned. Then this information is visualized with *Matlab* program and positions with higher vibration values are highlighted. It is possible to analyse vibration characteristics, distribution from main epicentres and intensity by using this method. It should be noted, that the proposed method currently cannot detect whether the cause of higher vibration values in a specific region is the winging or magnetic core within it.

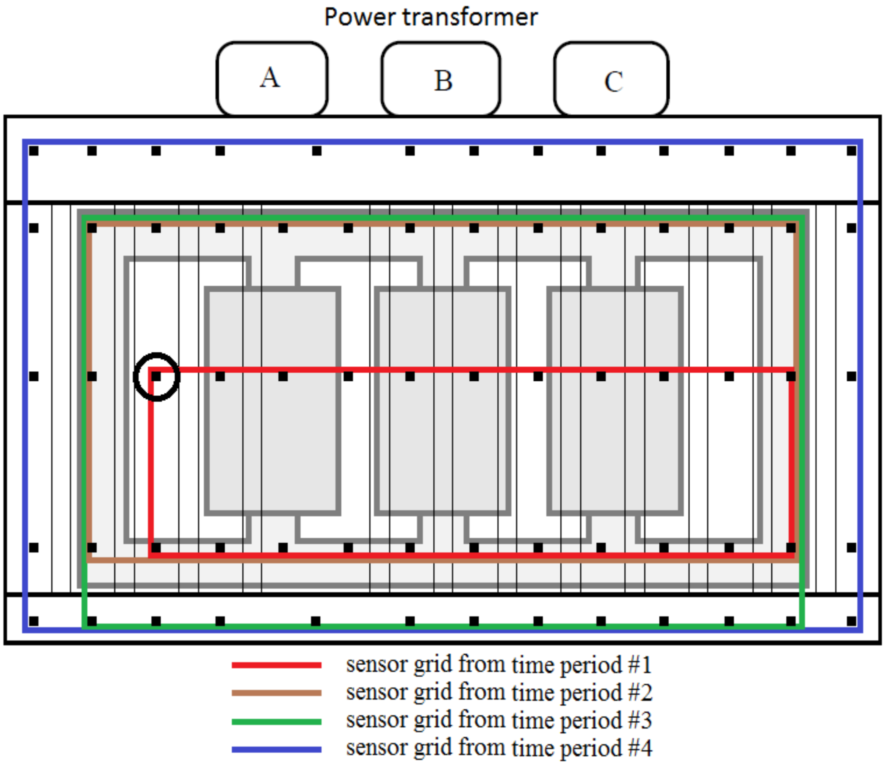

Fig. 2. Sensor grids used vibration measurements in different time periods

Fig. 3 shows with blue colour the results obtained with the proposed graphic interpretation method for one side. Vibration amplitudes with higher values are displayed in red colour. Fig. 3.a shows the approximation results when transformer is operating with no load and Fig. 3.b shows results when transformer is operating with full load. The differences can be explained because there is no current flowing in the secondary winding in no-load operation mode since the secondary electric circuit in not closed. Therefore, electrodynamic forces are not acting upon this winding, and the nature of vibrations caused by the transformer is different.

These results show that vibrations with higher values are generated mostly in phase A winding and the very left side of magnetic core. The highest vibration values overall are in this region of the magnetic core. This can be explained that the tested transformer is five-legged and this construction of magnetic core has this characteristic because the side parts of the magnetic core are not as well fixed in place as the middle sections, which are surrounded by transformers primary and secondary windings.

It should be noted, that there are vibration epicentres with lower values. In most cases they are located respectively against the phases of the transformer. These changes should be taken in consideration because the vibration values are relatively higher.

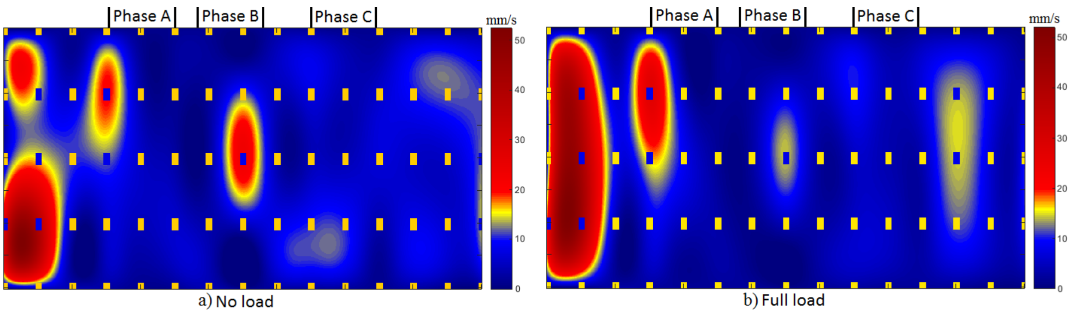

Fig. 3. Graphical interpretation of vibration velocity

CYSENI 2016, May 26-27, Kaunas, Lithuania
ISSN 1822-7554, www.cyseni.com

The proposed method allows the possibility to acquire results of vibration change within time if the data is available from multiple measurements. The black circle in Fig. 2 and Fig. 4 displays the point where the values of vibration amplitude have increased the most. Fig. 5 shows the results from this change. Fig. 4 shows and emphasizes the vibration velocity amplitudes growth within period of 5 years. The position and arrangement of sensor networks was different and it was necessary estimate correct relative position. This procedure allowed combining vibration results from different sensor grids and obtaining vibration change within time. Drastic differences are shown at phase A and the segment of magnetic core on the left of it. This could indicate mechanic faults with the windings and magnetic core of power transformer.

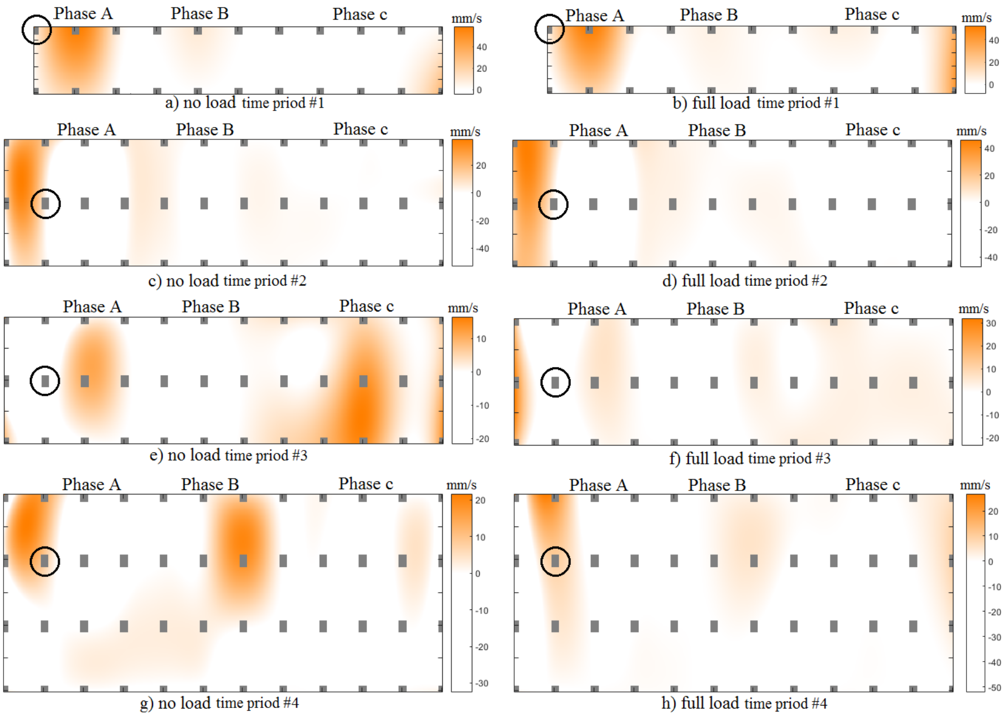

Fig. 4. Results of vibration amplitudes change

Fig. 5 shows the tendency for vibration amplitude to increase in this region. Similar situation is displayed in both no-load and full-load conditions. The decrease in one period of time can be explained because the windings were repressed and their clamping pressures increased in that year.

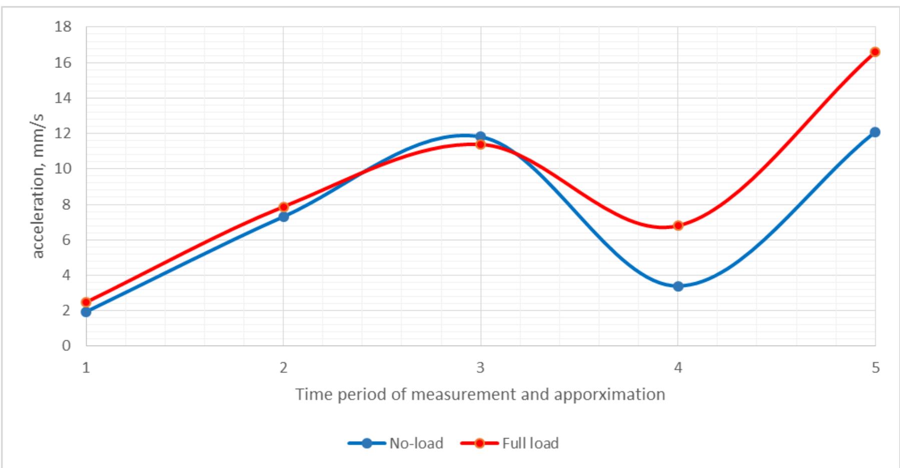

Fig. 5. Vibration change of previously marked point

Acquired results with proposed graphical interpretation method correctly displays maintenance action performed on the tested transformer which allows concluding that evaluation performed with proposed method is technically valid.

6. CONCLUSIONS

The analysis of literature allows concluding that different approaches exist to obtain information about the mechanical condition and possible faults of windings and magnetic core of power transformer. The main approaches are modelling transformer construction considering precise geometric parameters or processing measured vibration data. In both mentioned cases the obtained result has some error from the diagnostic of transformer because it is impossible to carry out approximation or modelling identically to the situation in practice.

The graphic interpretation method of measured vibration data proposed in this paper has the advantage to use data obtained from the surface of transformer tank. It is possible to perform approximation and visualization by using this method. Additionally, this methodology provides the possibility evaluate process for vibration change within time period even if sensor grids are different and to acquire graphic results in positions on the surface of the transformer tank where vibration sensors were not installed.

Improvements are planned for the proposed method by adding information about geometry of the transformer, positions of separate construction elements and their mechanical characteristics when considering vibration transmission.

This is necessary to model vibration distribution from windings and magnetic core to the surface of transformer. That would allow determining the causes of faults within windings or magnetic core.

REFERENCES

1. BETLE M.; TENBOHLEN S. Investigations on vibrations of power transformers. Proceedings of XVII International Symposium on High Voltage Engineering. Hannover: Institute of Power Transmission and High Voltage Technology. 2011 August 22-26.
2. Probabilistic vibration models in the diagnosis of power transformers. Instituto de Investigaciones Electricas. 2011 Link to the internet <http://cdn.intechopen.com/>.
3. Study on transformer tank vibration characteristics in the field and its application. Xi′an Jiaotong University. 2011 Link to the internet <http://pe.org.pl/>.
4. JIN M., PAN J., HUANG H., ZHOU J. Transmission of vibration of a power transformer from the internal structures to the tank. Proceedings of Acoustics 2012. Fremantle: School of Mechanical and Chemical Engineering, The University of Western Australia. 2012 November 21-23.
5. CHIESA N., LOTFI A., HOIDALEN H.K., MORK B., RUI O., OHNSTAD T. Five-leg transformer model for GIC studies. International Conference on Power Systems Transients. Vancouver 2013 July 18-20.
6. *International Electrotechnical Commission.* Geneva, Switzerland, 2001. International standart IEC 60076-10. Link to the internet <https://webstore.iec.ch/preview/info_iec60076-10%7Bed1.0%7Den.pdf>.
7. Vibro-Acoustic Method of Transformer Clamping Pressure Monitoring.
8. PREMALATHA V, SRUTHI S.S., VIKASH M., ILAMPOORNAN M.K. Instrument transformer winding fault analysis using frequency response analysis. ICACCCT 2012. Proceedings of International Conference. Ramanathapuram. 2012 August 23-25.

9. KULKARNI S.V.; KHAPARDE S.A. *Transformer Engineering Design and Practice*. New York: Marcel Dekker, INC 2005. 452 p. ISBN 0-203-97059-4.
10. LI K., XU H., LI Y., ZHOU Y. MA H., LIU J. GONG J. Simulation test method for vibration monitoring research on winding looseness of power transformer POWERCON 2014. Proceedings of 2014 International Conference on Power System Technology. Chengdu: Hohai University. 2014 October 20-22.
11. WANG Y., PAN J., JIN M. Finite element modelling of the vibration of a power transformer. Proceedings of ACOUSTICS 2011. Gold Coast: The University of Western Australia. 2011 November 2-4. Proceedings of 2010 International Conference on Electrical Machines. Rome.
12. HACKL A., HANBERGER P. Investigation of surface velocity pattern of power transformers tanks. Electrical Machines (ICEM). 2010 September 6-8.
13. Diagnostics of mechanical faults in power transformers - vibration sensor network design under vibration uncertainty. 2014 Link to the internet <https://www.phmsociety.org/>.
14. Vibration sensor data and sensor characteristics. Link to the internet <http://www.vicont.ru/vk-310ru.html>.