Vibroacoustic diagnostics of transformers in a transient state with reduced influence of magnetostriction phenomenon

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In the paper a vibroacoustic method of diagnostics of the mechanical state of an active part of a transformer is presented. The analysis is performed on the signal of bank vibrations in a transient stage of work of an unloaded transformer – during the first few seconds after connecting to the power supply. The method is based on SSM algorithm (Spectral Subtraction Method) reducing the 'disturbing' impact of magnetostriction phenomenon on the measurement. It was concluded that using, in the process of diagnostics of an active part of a transformer unit, only the vibroacoustic method does not provide certain conclusions. Experimental research proved high usefulness of the presented V-SSM method (Vibroacoustic Spectral Subtraction Method) when accompanied by FRA method (Frequency Response Analysis) in winding defect diagnostics.

KEYWORDS: transformer, winding, Vibroacoustic Method, Spectral Subtraction Method

1. Introduction

A pivotal element of diagnostics of an active part of a transformer is examination of vibrations of its construction. In general the vibroacoustic method consists in registering the signal of acceleration of transformer bank vibrations, and numerical analysis of the data obtained in this way. Main mathematical apparatus, used mainly in vibroacoustic studies, is Fourier transform (less often wave transform) [1-3]. Hence the vibroacoustic diagnostics is based on spectrum analysis of vibration acceleration signal, and amplitude spectrum constitutes the basis for conclusions. Whereas the process of the signal registration itself poses no major difficulties – requiring application of accelerometer and digital registration tool – the technology of conducting measurements entails numerous problems to be solved. Main issues, which are of key importance in vibroacoustic diagnostics of transformers, are: impact of the load and supply voltage on the amplitude of bank vibration acceleration, as well as the choice of place for attaching the accelerometer [4, 5]. In line with the guidelines formulated in [6] from 1983, vibroacoustic diagnostics of transformers are conducted on the site of their location and during normal operation. The number of measurement points and their placement on the surface of the bank are selected on the basis of the size of the unit. The signal of vibrations is registered by means of the accelerometer on a portable data storage device and then, in laboratory conditions, frequency descriptors are determined in order to compare them with indicators established as acceptable and limit values [7].

Vibroacoustic analysis is currently undergoing dynamic development, and defining appropriate measurement standards and recommendations seems to be a matter of few years. In truth, the method of vibroacoustic diagnostics was introduced in Poland in 1980s [6], and the vibroacoustic criteria accepted 30 years ago have been used until now. In [7] it was ascertained that vibroacoustic quality indicators should be verified and altered, since in the period of the last few decades, the technology of transformer production has been substantially modernized.

Technological devaluation of the quality criteria applied in vibroacoustic diagnostics of transformer construction, as well as the developments in digital signal processing methods necessitate, along with verification of vibroacoustic quality indicators [7], modernization of analysis methods of a digital signal reflecting vibration acceleration. It is essential that the form of presentation of results of vibroacoustic analysis was unambiguous and clear as well as devoid of unnecessary information. The parameters of digitally registered signal have to be carefully selected so that the application of mathematical tools of digital signal processing (DSP) would not yield additional errors. Similarly to many other diagnostic methods, which are currently being developed, e.g. Frequency Response Analysis (FRA), the vibroacoustic diagnostics does not provide explicit conclusions. It seems that only by applying a few complementary methods, an accurate diagnosis can be reached.

2. Vibroacoustic method V-SSM

The idea of transformer's construction vibrations is based on the analysis of a signal recorded with an accelerometer attached to the tank surface. Inside a transformer electrodynamic and magnetostriction forces influence windings and a core, causing their vibrations. These vibrations, transferred by an insulating liquid, cause vibrations of tank walls.

The reason for core vibrations is magnetostriction, leading to changes of geometrical dimensions of magnetic material located in a magnetic field. The intensity of magnetic field in the core placed inside of a winding depends on a voltage applied to the winding. On the base of Faraday law it was shown in [8] that the change of core length placed in the coil is directly proportional to the square of a momentary value of applied voltage $\Delta L \propto [U_{max} cos(\omega t)]^2$, where ω is pulsation of the voltage. A momentary value of vibrations acceleration caused by magnetostriction equals $a_c(t) = d^2\Delta L/dt^2$ and its basic harmonic frequency is two times bigger than applied voltage frequency.

Vibrations of transformer construction recorded with an accelerometer attached to transformer's tank are a superposition of mentioned above vibrations of a core and windings. The latter are influenced by electrodynamic forces proportional to the square value of a current [8]. Because the force is directly proportional to the acceleration, it can be assumed that vibration acceleration of windings is directly proportional to the square value of the current: $a_w \propto I^2$. With assumption that $I = I_{max}cos(\omega t)$ and knowing that $cos^2\omega t = 0.5(cos2\omega t+1)$, also in this case a frequency of basic vibrations harmonic is twice as big as supplied power frequency, in other words the same as in the case of a core.

Loosening and deformations of windings and core sheets are the direct causes of significant changes in frequency spectrum of recorded vibrations signal. Apart from harmonics with basic frequency 100 Hz (for 50 Hz power supply), the frequency spectrum will contain also other harmonics having various amplitudes. The shape of amplitude spectrum is strictly correlated to the character of mechanical defects in a core and windings.

Most of vibroacoustic methods used for transformers diagnostics is based on the analysis of frequency spectrum of vibrations acceleration in steady state. Analyzed amplitude spectrum is characterized by a large amount of unnecessary information, which makes efficient concluding very difficult. Harmonic frequencies distribution is a representation of a core and windings vibrations and depends on the load current and applied voltage. The large amount of information resulting from spectral analysis makes it impossible to indicate unambiguously the factors which have dominant influence on recorded frequency spectrum.

In a transient stage the recorded signal represents vibrations of both the core and the windings. This is the case of the magnetostriction phenomenon (the primary winding is powered by voltage of amplitude U_{max}) and the current flowing through the primary winding has (initially) very large amplitude, which causes creation of electromagnetic interaction forces between the windings.

It is because the connection of the transformer to the power grid creates the so called surge of magnetizing current. The maximum value of this current depends, among others, on construction qualities of a transformer, combination of binding connections, and also the distance between the magnetizing winding and the core [9]. In some cases, the maximum value of magnetizing current may exceed the value of rated current by a factor of ten or so. Sample curves of momentary values of phase currents at the time of powering an unloaded transformer are shown in Fig. 1.

The assessment of vibrations in a transient state, in the first 10-20 seconds from powering a transformer without any load, may reduce the influence of some factors causing vibrations. The method of tank vibrations assessment in transient state is based on the following assumptions:

1. The influence of magnetostriction phenomena on recorded vibrations is identical for transient and steady states of transformer operation, with assumption that voltage amplitude is constant.
2. The amplitude of magnetizing current in period shorter that 0.5 s from powering the transformer reaches the value several or over ten times higher than nominal currents [9], leading to vibrations of windings caused by electrodynamic forces.

3. In steady state without load the main source of transformer tank vibrations core are vibrations caused by magnetostriction phenomena. Windings vibrations are negligibly low due to the lack of load, in windings there is a magnetizing current having the amplitude considerably lower than nominal current.

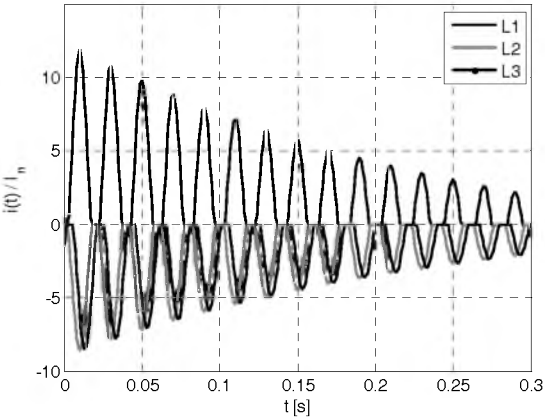


Fig. 1. Curves of absolute momentary values of phase currents at the time of powering an unloaded transformer; I_n – rated current [9]

Fig. 2 presents a general scheme of recording the signal of tank vibration of a transformer in a transient stage.

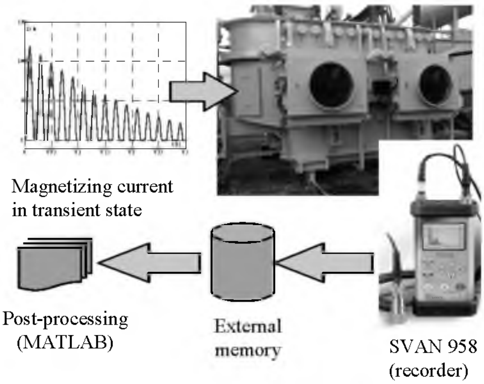


Fig. 2. Flow chart of vibroacoustic diagnostics in a transient state

On powering the transformer, there appears a surge current which causes vibrations of the active part and the tank. The vibrations are measured by the accelerometer, the output signal of which is subsequently recorded by means of the digital recorder. In a final phase, it is subject to mathematical analysis in Matlab environment.

For digital recording of vibrations in experimental studies SVAN958 vibration recorder was used with attached portable data storage device. The recorder can also analyze recorded vibration signals but it was not used for these purposes in this study, but only for recording the vibration signal. The recorded vibration signal was further analyzed in Matlab environment.

In Fig. 3 there is an example of recorded signal of tank vibrations of transformer without load in period approx. 20 s from powering. In the graph showing momentary values of the acceleration (Fig. 3a) and vibrations spectrogram (Fig. 3b), there are visible two ranges of vibrations: the first one from start to approx. 6 ÷ 8 s – vibrations stabilization, and the second one – vibrations with stabilized amplitude.

a)

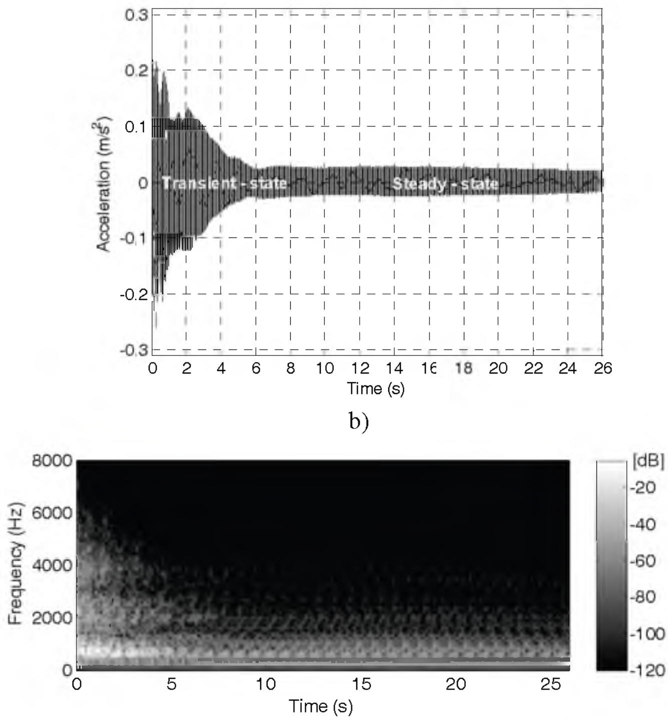


Fig. 3. a) Momentary value of transformer tank vibrations, b) vibrations spectrogram

Because of 'interfering' influence of magnetostriction phenomena on the analysis of transient state may be difficult. For example, problematic might be an accurate assessment of vibrations time caused by transient state. Vibroacoustic comparative diagnostics of windings condition of similar type transformers is also unreliable because core's technical condition of tested transformers might be different which influences the amplitude of vibrations acceleration and the amplitude spectrum in steady state operation without load.

After considering assumption 1 of the presented method it is possible to reduce the influence of magnetostriction phenomena on the recorded vibrations signal. It can be obtained by using a Spectral Subtraction Method – SSM [10]. SSM is one of basic methods used for reduction of interferences having additive character from sound recording and is used in sound engineering. The idea of this method can be described in the simplest realization as following: if recorded discrete signal $y(k)$ is present with additive interference $n(k)$, then:

$$x(k) = y(k) - n(k) \tag{1}$$

is non-interfered signal. In frequency domain:

$$X(e^{j\omega}) = Y(e^{j\omega}) - N(e^{j\omega}) \tag{2}$$

where $X(e^{j\omega})$, $Y(e^{j\omega})$, $N(e^{j\omega})$ are discrete Fourier transforms of signals $x(k)$, $y(k)$ and $n(k)$.

In SSM method equations (1) and (2) are not realized directly, but there are performed calculations based only on amplitude spectra of recorded signal $|Y(e^{j\omega})|$ and estimated interference $|N'(e^{j\omega})|$:

$$\left|X'(e^{j\omega})\right|^{\beta} = \left|Y(e^{j\omega})\right|^{\beta} - a \cdot \left|N'(e^{j\omega})\right|^{\beta} \tag{3}$$

leaving in spectrum $X'(e^{j\omega})$ phase of frequency spectrum $Y(e^{j\omega})$. Coefficient $\beta = 1$ in the case of subtraction in amplitude spectrum domain or $\beta = 2$ in the case of power spectrum. The level of interferences reduction is estimated with coefficient $a \in \langle 0,1 \rangle$. The block diagram of SSM algorithm is shown at Fig. 4.

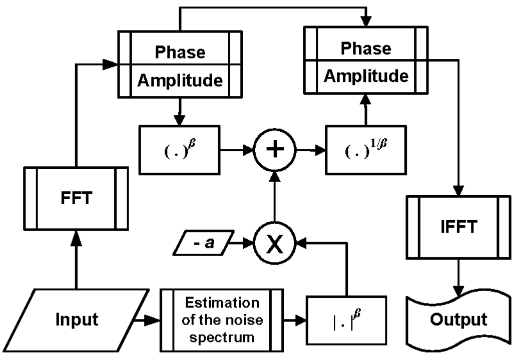
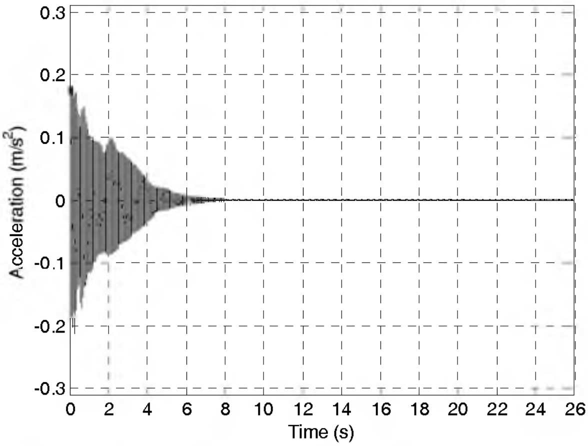


Fig. 4. The algorithm of Spectral Subtraction Method – SSM

In sound engineering the reduction of interferences is achieved by using an estimate of amplitude spectrum from ‘silence’ periods in the recorded signal. The reduction of the magnetostriction based vibrations influence is realized by treating steady state vibrations signal as the additive interference. If in equation (3) $\beta = 1$, $a = 0.1$ and using the signal presented in Fig. 3a, the final result was obtained, shown in Fig. 5: momentary value of transformer tank vibrations acceleration (Fig. 5a) and vibrations spectrogram (Fig. 5b).

a)



b)

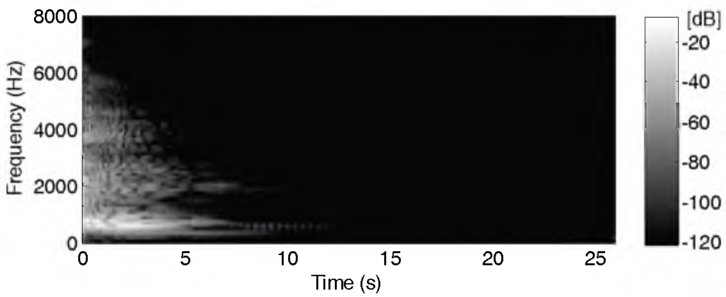


Fig. 5. a) Momentary value of transformer tank vibrations acceleration after reducing magnetostriction phenomena, b) vibrations spectrogram

The value of coefficient a in equation (3) has been determined on the basis of assumption that vibrations amplitude reduction caused by magnetostriction is -40 dB, while value of $\beta = 1$ because the algorithm of spectral subtraction had been realized in signal amplitudes domain.

The application of SSM leads to reduction of magnetostriction based components in the recorded signal. The analysis of such a signal allows assessment of windings and core vibrations influence, resulting from electrodynamic forces, on the transformer's tank vibrations.

3. Experimental results

To find out possibilities of V-SSM diagnostic method there was prepared deformational experiment on a real transformer. It was a unit replaced in distribution company by a new one because of age, however it was in a very good technical condition. Its parameters were: type TONa 800/15, 15/0.4 kV, 800 kVA, year of production 1962. The transformer and its active part are presented in Fig. 6.

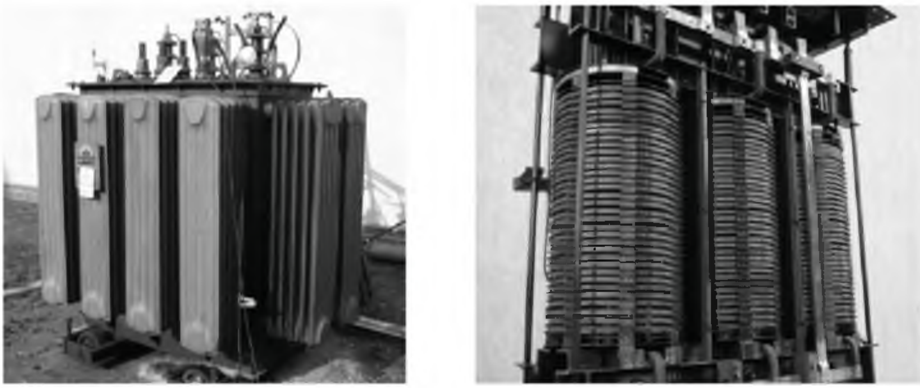


Fig. 6. Transformer used for deformational tests and its active part

The deformational tests were based on introducing controlled deformations to the windings and conducting measurements with FRA and VM methods. Deformations introduced into winding were based on clamping loosening and the axial shift of whole discs. There were three levels of controlled defects:

1. Loosening the winding clamping, without any additional discs displacements – D1.
2. Winding deformed by lowering the single top disc, no clamping as in previous case – D2.
3. Winding deformed by lowering two top disc, no clamping – D3 (Fig. 7).

Fig. 7. Transformer winding with deformation D3 – top two discs lowered to minimum

To perform necessary operations in the windings, it was removed from the transformer with crane and placed in the tank afterwards. For measurement purposes the transformer was completely mounted, with all screws tightened, original oil in the tank and original bushings. Therefore measurements results were not influenced by any factors other than controlled defects.

Vibroacoustic measurements have been taken with accelerometric vibration sensor SVAN 958. During the experiment device SVAN 958 was used as a signal recorder, while mathematical analysis was conducted in MATLAB environment.

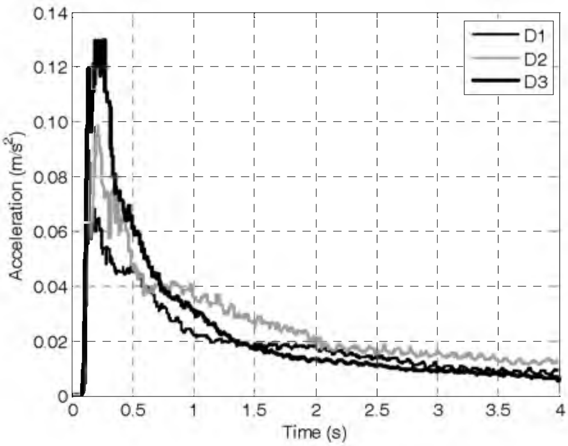


Fig. 8. Stabilization process of tank vibrations for three windings deformations

The accelerometer was mounted on the right side of the tank (on column A), in the middle of its height. For vibroacoustic analysis with SSM algorithm (V-SSM) the first ten seconds of recorded signal were taken into account, starting from powering transformer without any load. Fig. 8 presents stabilization process of vibrations acceleration (envelope [11]) with reduced influence of the magnetostriction.

Performing simulated degradation of windings mechanical condition unambiguously influences the envelope shape of vibrations acceleration signal: by loosening and deforming the winding the amplitude of vibrations increases and the time of transient state vibrations suppression changes. From Fig. 8 it can be concluded that e.g. after time approx. 1 s from powering the transformer the acceleration is 0.022 m/s^2, 0.032 m/s^2 and 0.040 m/s^2, for windings defects D1, D2 and D3 respectively. However it should be noted that even though magnetostriction phenomena have been reduced, in transient state both windings and the core vibrate. Therefore the measurement with V-SSM in real conditions cannot unambiguously determine the mechanical condition of windings only. The obtained results should be verified with FRA method.

The presented experiment proves that V-SSM method is 'sensitive' to the changes in a winding configuration. However, when taking into account the problems expressed in [12, 13] concerning unambiguous interpretations of FRA characteristics, measured in operation conditions, conducting measurements of vibrations in a transient stage along with V-SSM analysis may be crucial for diagnosing the mechanical state of both the windings and the core. In the presented experimental study FRA measurements were conducted, on the basis of which, the possibility of winding deformation could be only be assumed. These were V-SSM measurements that ascertained this assumption.

4. Summary

In the paper the method of vibroacoustic diagnostics of the condition of the active part of large power transformers was presented. The conducted experiments proved that the proposed method is especially useful in diagnosing winding deformations. Considering the current state of research, the method can be applied independently in 'comparative' diagnostics by confronting the measurement results obtained during regular maintenance check-ups.

In addition, the described method was approved by „Energo – Complex" company (Piekary Śląskie) following the tests conducted in their industrial conditions. The method was tested while used together with Frequency Response Analysis (FRA) of transformer. It was concluded that neither method (V-SSM nor FRA), used independently, provides 100 percent accurate diagnosis, yet when used together, the reliability of the diagnosis improves substantially.

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