CASE STUDY OF SHELL-TYPE POWER TRANSFORMER TANK VIBRATION IN DIFFERENT LOADING CONDITIONS

Marina Griscenko, Renars Vitols, Oskars Simanis
Riga Technical University, Latvia
marina.griscenko@rtu.lv, renars@temeso.lv, oskars@temeso.lv

Abstract. Vibration measurements on power transformer tanks have been used to monitor their technical condition and detect internal failures for already 30 years, but the health grade system for vibration measurements of power transformers has not been yet developed, because constructions of transformers differ significantly. This case study was carried out for a shell-type oil-filled power transformer, which has been in operation since 1995. The unit under study had high vibration on some transformer tank points. This paper addresses the causes of transformer vibration, contribution of windings to transformer tank vibration, vibration spectrum and vibration dependence on cooling oil temperature. To make the experiment both a portable data analyzer and permanent vibration sensors (10 piezo-electric accelerometers sending signals to PC) were used. For the particular transformer vibration in no-load mode occurred to be greater than in loaded mode, which is unusual behavior compared to other researchers' reports. So, it was shown that there is no quantifiable vibration velocity rise on the transformer tank next to the windings in load modes compared to no-load modes. The dominant vibration spectrum frequency was proved to be 100 Hz in all loading conditions. The largest 100 Hz values were registered on the side where the core is not covered by windings - on the sides closer to the shell. The power transformer tank vibration in different loading conditions, specifically, with different cooling oil temperature was also registered and analyzed. Analysis of the experimental data for the particular transformer suggested that there was inverse correlation of tank vibration with the cooling oil temperature – the vibration decreases as the oil temperature increases on some points on the transformer tank next to the cooling pipe.

Keywords: transformer, vibration, condition assessment, shell-type, windings, spectrum.

Introduction

There is a trend in the power system industry to move from traditional time based maintenance of power transformers to a condition based diagnosis procedures [1-3]. As a result individual diagnostic programs for each power transformer are developed [1] and special techniques, accompanying traditional routine tests (e.g., Dissolved Gas Analysis, power factor testing, winding resistance) are researched [3]. Among other special tests, which may be applied, the vibration analysis is used as a tool to help determine the transformer condition [4].

Transformers produce vibroacoustic energy in form of noise and vibrations during operation [5] both in no-load and load conditions, so noise emission and vibration of the transformers in operation is inevitable [6; 7]. Nevertheless, the advantages and limitations of vibration measurements on the power transformer tank are discussed both by industry experts [8-10] and university researchers for almost 30 years [11].

In 2000s research work has been focused on using on-site transformer vibration signal to detect winding looseness [12], while some contemporary researches sum up vibration statistics on-site for the aging electrical equipment being in operation [13; 14]. The former researches are aimed to collect actual values of transformer tank vibration on-site, because extensive pool of data is required to develop the credible "generic health metrics or a health grade system" [13] for power transformers depending on different construction. This case study is supposed to add some knowledge about vibration for aging shell-type power transformers in operation by addressing the winding vibration, spectrum analysis and vibration dependency on the cooling oil temperature.

For the majority of transformers, which are not shell-type, the magnetic core legs are covered with windings, so researchers disagree whether it is possible to distinguish winding and core vibration from measurements on the tank. It is estimated from operation experience that acoustically, winding movement adds 2 dB [6; 7] to the noise value, but there is no same estimation on the exact vibration value. Previous research showed that for more than 85 % of power transformers one could separate contributions of the core and windings vibration by comparing the measurements in no-load and loaded modes, since in no-load mode the electrodynamics forces in windings are practically absent [12]. It is assumed that in loaded mode vibration should rise. This study represents the adverse effect – the vibration velocity decrease on transformer tank next to the windings in load modes compared to no-load modes. Thus, we could agree to industry experts which state that in loaded mode windings vibration fundamental frequency is effectively dwarfed by the much greater 100 Hz fundamental generated by the core, and any variation is in fact attributable to changes in flux density than to variation in the forces in the windings [6; 7]. Nevertheless, researchers agree that the most striking point is the strength of the component at 100 Hz or 120 Hz (twice the normal operating frequency of the transformer), for which [4] suggests the limit of 0.5 ips or ~12.7 mm·s^{-1}, and separate sheets in the core superimpose additional higher frequencies on the main signal frequencies.

The effect of the transformer cooling oil on vibration transmission is also discussed during this study. It was discovered already in 1997 that forces causing the power transformer tank vibration "heavily depend on various operational parameters such as loading current and winding and core temperature" [8]. Indeed, applying voltage to a transformer produces a magnetic flux, or magnetic lines of force in the core, and the degree of flux determines the amount of magnetostriction and hence, the noise level, but since transformer voltages are fixed by system requirements [7], until now attempts to obtain reduction in noise level by the employment of low flux densities proved to be "the most uneconomic" [6], therefore, in this paper the emphasis is put on the temperature level and load.

Materials and methods

The power transformer had the following characteristics – 215MVA, shell-type construction, oil-filled, oil-immersed water cooled, in operation since 1995. The particular transformer is driven by two or one hydropower units, each with 90 MVA synchronous generators, thus it can operate at 50 % load (with one unit) or 100 % load (with both units).

To carry out the measurements both aportable vibration data analyzer and permanent vibration sensors were used. For the permanent system 10 piezo-electric accelerometers sending signals to PC, acquiring and integrating readings through National Instruments' graphic programming language LabVIEW 13.0™ were chosen. The RMS data averaging was used. The vibration acceleration, velocity and displacement were registered, but for the simplicity in this paper only vibration velocity data (mm/s) will be quoted. For the continuous measurement system Butterworth, Bandpass filter of 4th order was applied. From the readings obtained, a continuous spectrum was derived.

Measurements were taken at a height corresponding to 1/4, 1/2 and 3/4 of the transformer tank both on HV (high voltage) and LV (low voltage) sides and the sides close to the shell. Measurements were taken between the tank fins, called "columns" for the purpose of this study. First, measurements were taken at no-load, and then the transformer was loaded in different regimes with different load and temperature. The loading time in each mode was more than one hour, because previous laboratory experiments showed that the temperature of the magnetic core samples increases sharply during the first minutes of magnetizing time and it stabilizes with time [15].

Results and discussion

To detect windings vibration, measurements on columns Nr.3,7,10 of HV and LV side were analyzed as suggested in the previous studies [12] under different cooling oil temperature varying from +27 ºC to +50 ºC. The results are summarized in Table 1.

Table 1

Comparison of vibration velocity in no-load and loaded modes for the points near the windings

Mode	Minimum value, mm·s^{-1}	Maximum value, mm·s^{-1}	Sum of 18 points, mm·s^{-1}	Average value, mm·s^{-1}
No-load +27 ºC	3	15	123	7
No-load +30 ºC	2	19	126	7
No-load +40 ºC	2	23	138	8
No-load +50 ºC	2	22	146	8
Load 50 % +40 ºC	2	26	136	8
Load 50 % +50 ºC	2	31	146	8
Load 100 % +44 ºC	3	27	129	7

From Table 1 the conclusion emerges that the summed value of vibration in full-load mode is actually smaller than in no-load mode with 50 ºC oil temperature.

The measurements next to the shell were analysed separately – transverse vibration created by magneto-motive forces on HV and LV sides closer to the shell during this study reached the maximum value of 46.3 mm·s^{-1}, while longitudinal vibration, (created by magnetostrictive forces and magneto-motive forces [16]) on short transformer sides during this study reached the maximum value of 36.5 mm·s^{-1}.

The expected behavior (increase of vibration in loaded mode [12]) was registered only for the points on the 3rd column on HV transformer side as shown in Fig. 1., while on the LV side, the 7th and 10th column on both transformer sides vibration values were higher in no-load mode as shown in Fig. 2.

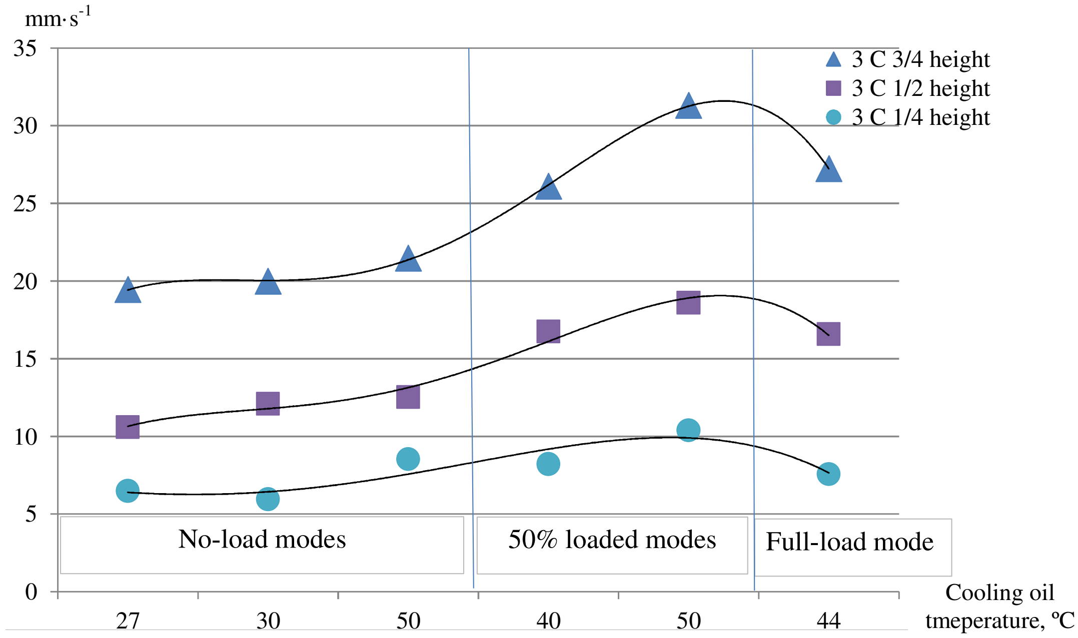

Fig. 1. **Vibration velocity rise in loaded modes for the 3rd column (HV side)**

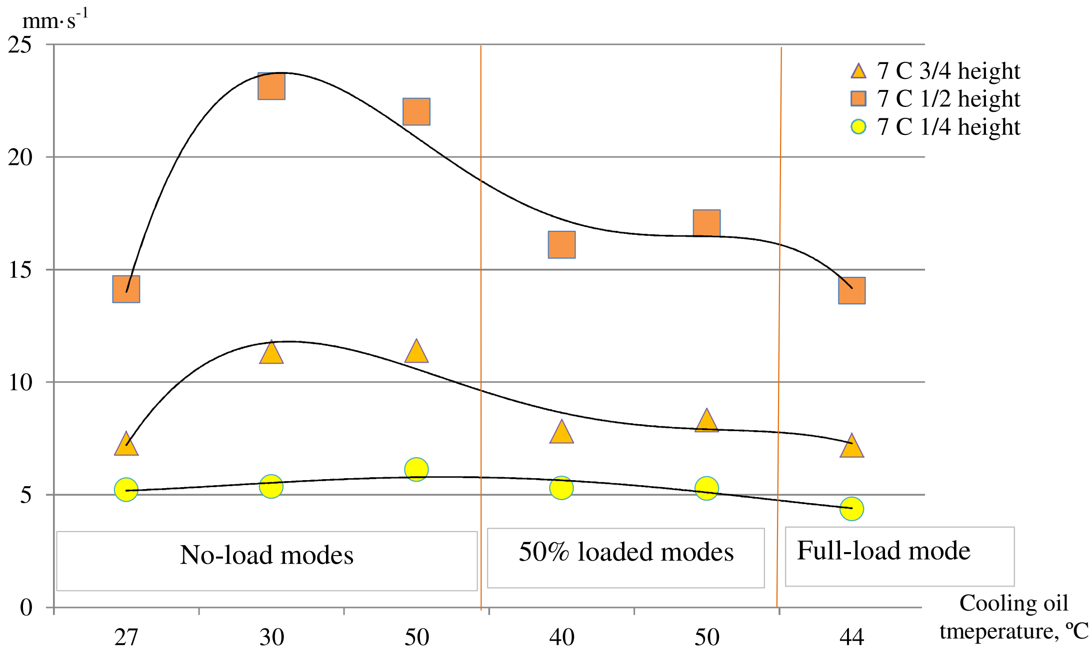

Fig. 2. **Vibration velocity drop in loaded modes for the 7th column (HV side)**

Summing up the results of Table 1, Fig.1.-Fig.2., we could not define a particular quantifiable value, how much winding vibration adds to the total transformer vibration velocity. Instead, one could state that vibration decreases at full load if the transformer does not have winding clamping pressure looseness. For the particular case study this statement appeared to be true, because no winding looseness was actually detected during recent internal inspection.

For the 3rd and 7th column vibration is generally greater at the top of the tank. This could be explained by the large weight of the transformer core and windings (~134.13 tons in total), which depress the transverse vibration of the core at the bottom.

Early studies showed that "there is a significant difference in the amplitude and frequency spectrum of the energization response vibration signals" [8]. For this case study the vibration velocity spectrum at the measurement point close to the shell, presented in Fig.3, shows that 100 Hz harmonic is dominant for the particular transformer in all loading conditions, including no-load mode:

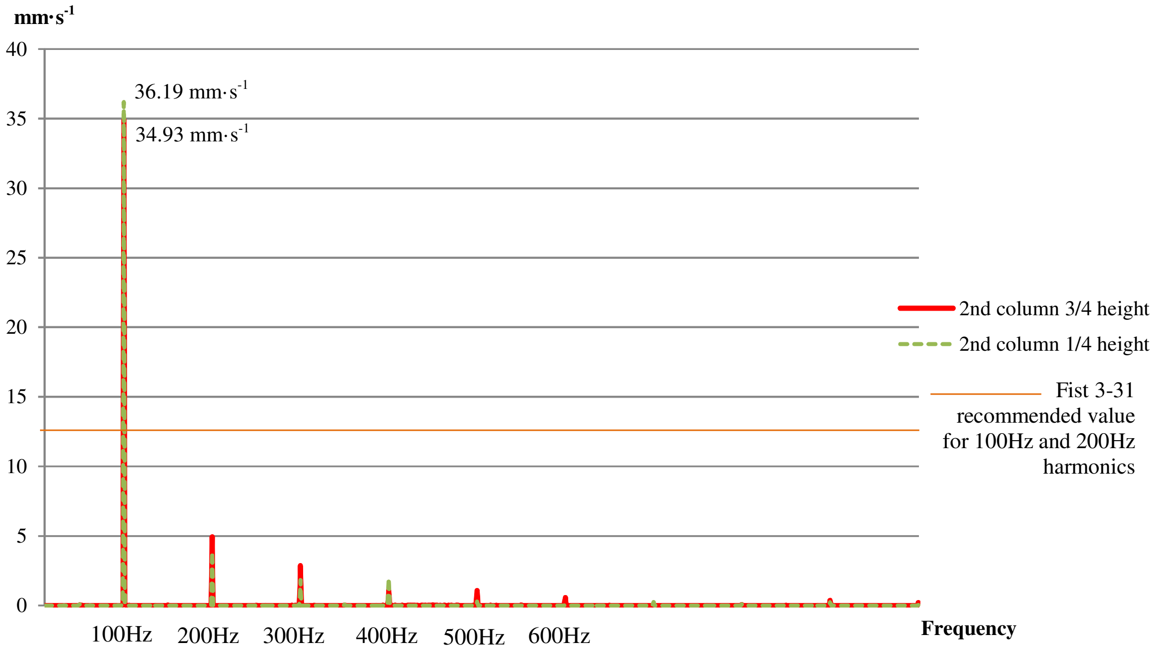

Fig. 3. **Vibration velocity spectrum in no-load mode, shell side**

Since the transformer magnetic core is not symmetrical [7] and magnetostrictive strain is not truly sinusoidal, in the noise spectrum harmonics with 200-700 Hz are introduced [4;7]. The noise spectrum even harmonics (200, 400, 600 Hz) occur from deviation from a square-law magnetostrictive characteristic [4], while odd harmonics (300, 500, 700 Hz) are created by a pseudo-hysteresis effect – the different values of magnetostrictive strain for increasing and decreasing flux densities [4] or in other words – by the saturation of the magnetic core [12]. In early studies spectrum results with dominant harmonics close to 200 Hz and 300 Hz are presented for the transformer "before re-clamping" [8], but during this case study neither of harmonics with 200-700 Hz frequency increased or changed significantly, compared to 100 Hz harmonic. The obtained field-tests results for a transformer with good clamping pressure are close to other researchers' laboratory results for "spectral characterization of vibrations at different regimes of excitation in vacuum tests" [17], where the frequency close to 100 Hz harmonic was also dominant in all loading conditions.

Finally, during the study it was discovered that vibration decreased as the oil temperature increased for some measurement points on HV side next to the cooling oil pipe as shown in Fig. 4.

The inverse correlation was calculated to be strong with the coefficient of determination 75 %, which means that 75 % of vibration at this point could be explained by the oil temperature change, while 25 % remain unexplained.

The different effect was observed at the transformer tank upper level – the greater was the oil temperature, the higher was the vibration. Yet, the later effect could not be viewed as causal relationship, because one cannot distinguish oil and core temperature at transformer tank points which are not close to the cooling pipe.

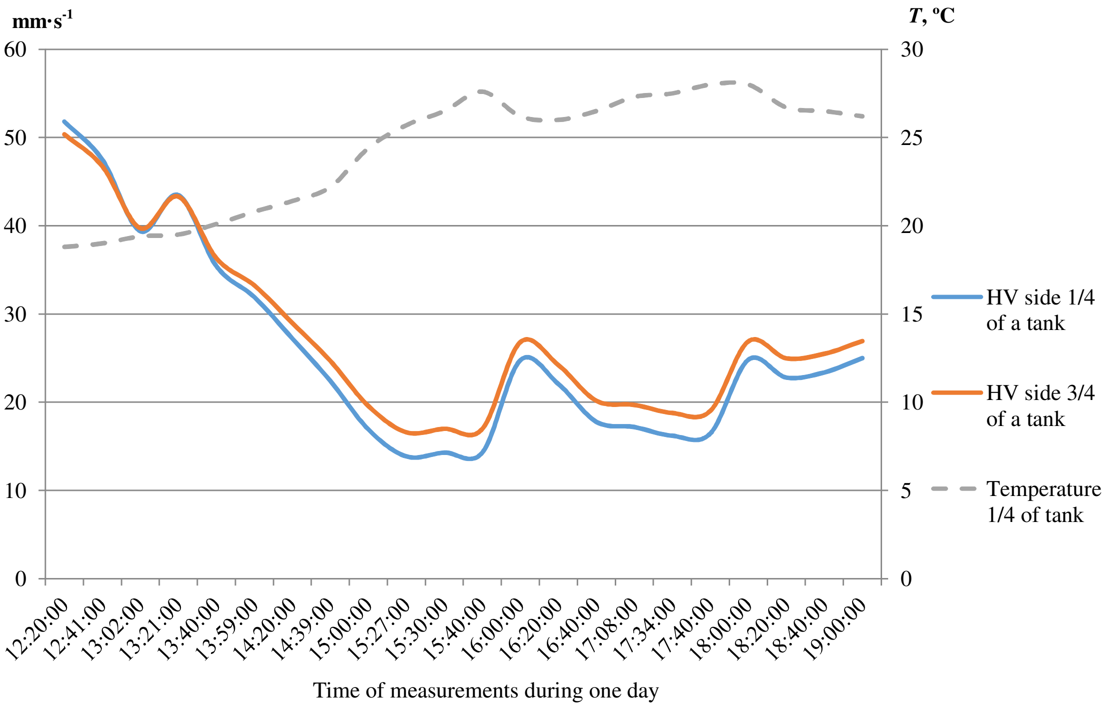

Fig. 4. **Correlation of transformer tank vibration and cooling oil temperature**

Conclusions

1. According to the study results one could make a context specific statement that a transformer with actual vibration velocity on the tank greater than 45 $mm \cdot s^{-1}$ could operate for some years without unexpected outage. The next explorative studies should address the question how long the expected operational life would be.
2. There is no quantifiable vibration velocity rise on the transformer tank next to the windings in load modes compared to no-load modes. Contradictory to previous researches, this study shows that in no-load mode vibration could be greater than in loaded mode. The largest vibration is registered on the side where the core is not covered by windings and there was no significant difference in no-load and loaded mode vibrations.
3. The study showed that vibration on the wall next to the cooling pipe changes as the oil temperature varies for the transformer with oil forced cooling system tank. The following correlation was observed during the study - the lower the oil temperature at the cooling pipe level, the greater the vibration.
4. The provided case study results are true only for the one unit, and more data are needed to generalize the obtained statements, since the constructions and cooling systems of power transformers differ, and so does the expected tank vibration behavior.

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