ABSTRACT
The noise of the power transformer consists of numerous phenomena’s that are related to vibrations of transformer core and windings as origins and secondary sources like tank, radiators or enclosures. The final noise radiation is caused by the secondary sources vibrations however study on the origin of transformer vibrations results in more efficient noise optimization in the final design. The work that is presented shows advanced vibroacoustic analysis of the transformers winding which is, beside core, the main source of noise in power transformers. Load current in the windings of transformers generates electromagnetic forces which act in both axial and radial directions in the windings. In consequence harmonic vibrations are generated, and the fundamental harmonics dominate the vibration spectrum. The technique of measuring those vibrations on energized winding in air but also immersed in transformer oil is presented and analyzed. Measurement result on real object are also valuable input for numerical model validation where modifications can be introduced and tested.

Keywords: transformer noise, laser scanning vibrometry

1. INTRODUCTION
For the end user, the aim of transformer working in power system is to convert electrical energy in a possible lossless manner. In reality, energy conversion in transformer is however accompanied by many side effects that reduce the performance and profitability of the device. Environmental impact is one of the negative results whose limitation is nowadays an important aspect. A well-known effect, almost inherently related to the work of the transformer, is a hum noise. The transformer noise is mainly caused by physical phenomena occurring in the core and windings. Two operating conditions can be generally distinguished when power transformer is running in the power grid, namely: load and no-load conditions. Both are strictly followed by the noise generation: not loaded power transformer emits mainly the noise caused by magnetostriction of the magnetic core, in the load condition – vibration in the winding dominate [1,2]. Load and no-load noise of the transformer is strictly harmonic, however, the subsequent operating mode differs by its frequency spectrum as well as dominant frequency. The exemplary noise spectra at the load conditions for a power transformer is shown in /1.

The active part of the power transformer, which is oil-immersed in majority of cases, is the source of vibration but the final location where the noise radiates from is the transformer tank. Improper mechanical design of transformer, especially transformer tank, can induce local structural resonances and consequently enhance the hum noise radiation. In the R&D approach, the reliable identification of the sources of noise and vibration is required, in particular if, the sound attenuation is expected as a consequence of the effective design improvement.

Only few studies on transformer vibration measurements using laser Doppler vibrometer have been found. Mizokami Masto [3] focus on transformer core vibrations and distinguishes vibration level between core limb and core yoke for comparison. Jing Zheng [4] approaches the aspect in more complex way including the study on disk type winding vibration however for in-plane direction only what in consequence does not give the complete information of the winding behavior but interpretation of in-plane vector contribution of the radial winding vibration.

Measurement results and analysis presented in this paper are performed using 3D vibrometer.

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technology where vibration can be described in all three directions and consequently the radial winding vibration is obtained.

2. MEASUREMENT TECHNIQUE

2.1 Laser Doppler Vibrometry

One of the best possible measurement technique to identify vibration pattern of a structure as well as its operational deflection shape is Scanning Laser Doppler Vibrometry (LDV), which is a powerful tool for direct measurements of vibration velocity. The LDV technique bases on frequency change between the emitted and reflected laser beam, which is commonly known as Doppler effect and due to very high frequency of the laser light (~400 THz) the accuracy of measurement is ultimate. The LDV measurement is contactless and therefore the tested part remains not influenced during the measurement but what is more important, it allows to perform safe measurement session on power product such as transformer that is energized with high voltage during the test. Eventually, the vibration of device can be measured directly during its operation, either on test facility or onsite and the vibration pattern information is much more reliable. Moreover, the laser vibrometer gives opportunity to perform continuous 3D scanning, which is highly beneficial since it delivers possibility to combine hundreds or even thousands of measurement points in the three-dimensional pattern of vibration. Contrary to that, when measuring vibration with standard accelerometers one must not only take into account the load situation of the transformer but it is also time-consuming to receive high resolution of the vibration patterns. For the situation with oil submerged winding the advantages over classic measurements are even more clearly seen, but even when measuring in air the accuracy the measurement point is defined is sufficient to measure individual cable turns and disks in the winding model.

2.2 Measurement setup

The winding model was tested in two operation configurations, in the air with three scanning heads and 3D measurements, second was oil immersed (Figure 1) with only one scanning head and consequently 1D measurement. The winding in both cases was hanging on elastic suspension and was supplied with voltage of 200 Hz frequency. The measurement points have been grouped to distinguish cable and clamping plates vibrations.

3. TRANSFORMER WINDING VIBRATION

The winding model was tested in two operation condition in air and submerged in transformer oil in transparent polycarbonate box. In both conditions the power supply had the same parameters 650V/29A/200Hz. To avoid any influences on modal parameters form the mounting the winding was hanging on elastic ropes. Measurement points were divided onto two groups; on clamping plate and on cable directly. Clamping plate vibration results answers the question how much vibration is transferred further to the active part construction through mechanical connections, winding disc vibration shows the vibration that is further transferred to the transformer oil.
3.1 Winding vibration in air

Figure 2 shows measurement points during ‘in air’ configuration, on the left one winding cable are marked and on the right on clamping plates. For this configuration 3D vibration measurement was applied with three separate scanning heads, the in-plane direction (X, Y) is marked on below figure, the out of plane (Z) is towards the scanning head.

![Figure 2 – Measurement point on tested winding, cable and clamping plates grouped, measurement in air](image)

Vibration spectrum of the cable disc show dominant frequency at 400Hz. The peak at 400 Hz have rather evenly distributed directions towards all directions.

![Figure 3 – Vibration velocity spectrum in x, y, z directions for cable, in air](image)

Vibration spectrum of the clamping plates show dominant frequency at 400Hz and increased value in Y direction at 800 Hz. For both harmonic frequencies the Y direction is dominating which relates to compression movement in between the plates.

![Figure 4 – Vibration velocity spectrum in x, y, z directions for clamping plate, in air](image)

3.2 Winding vibration submerged in oil

Figure 5 shows measurement points in the ‘oil immersed’ configuration, on the left one cable points are marked and on the right clamping plates. For this configuration only 1D vibration measurement was applied due to reflection problems on the polycarbonate box. The obtained results show us vibration only towards scanning head direction however scanning region is limited though the curvature small.
Figure 5 – Measurement point on tested winding, cable and clamping plates grouped, measurement in oil

Vibration velocity spectrum is similar to the one in air conditions with 400 Hz dominant as the first harmonics and limited value of second harmonic 800 Hz. The values are one order smaller than for the air measurements and are calculated including refractive index for the oil which is 1.4.

Figure 6 – Vibration velocity spectrum in perpendicular directions for cable, in oil

Vibration velocity at 400 Hz for clamping plate is smaller than for cable and the second harmonics 800 Hz almost aligns with the adjacent.

Figure 7 – Vibration velocity spectrum in perpendicular directions for clamping plate, in oil

3.3 Results discussion

Although measurement equipment configuration was different for ‘in air’ measurements – 3D scan and oil immersed – 1D some conclusions can be drawn from the obtained spectrum results. The vibration magnitude changes one order and is smaller when the winding is putted in oil both for cable and for compression plates. Vibration of the cable in Z direction for ‘in air’ conditions are almost four times higher than for the plate, in oil for the cable vibrations are also higher but not that much.

4. NUMERICAL MODELING

4.1 Input for the numerical modeling

The FEA model of the winding was created on the basis of the real test model. As a reference, the model of the winding which vibrates in air was taken. The model was meshed using HyperMesh pre-processor to get the regular mesh. The second order elements C3D20R were used and the total number of elements for the model was more than 1 million in order to reflect the geometry and interactions in small contact areas of the winding as accurately as possible.
Further, the model was exported to the Abaqus software and the Lanczos solver was used to calculate the natural frequencies and mode shapes of the winding. All materials with its mechanical parameters, which occur in the real test model were also implemented in the FE model, namely: pressboard (spacers), elkon – transformer’s plywood (upper and lower plate), steel (connecting rods) and copper (winding).

The whole analysis of the frequency extraction consisted of the static and the frequency step. In the static step, the compression of the winding by steel connecting rods with the force 40kN was simulated. In the frequency step, the natural frequencies were extracted.

4.2 Results of the numerical modeling

The preliminary results are presented in the pictures below. There are some mode shapes of the winding extracted in the frequency step. The upper plate was hidden in some pictures to improve the visualization of the winding movement.

The mode shape which is presented above is connected with the vibrating the upper, lower plate and the top spacer’s ring lying on the winding. The frequency equals to 216.09Hz.
The mode shape which is presented above is connected with the vibrating the upper plate, the top spacer’s ring lying on the winding and the winding. The frequency equals to 350.06Hz.

The go forward plan for the numerical model is to calculate the winding with the wider frequency range 0-800Hz. The main aim of this approach is to see if the frequency modes occur only for the winding.

5. CONCLUSIONS

The work that was presented shows advanced vibroacoustic analysis of the transformers winding which is, beside core, the main source of noise in power transformers. The technique of measuring vibrations on energized winding in air but also immersed in transformer oil was presented and analyzed. The winding model was tested in two measurement configurations, in the air with three scanning heads and 3D measurements and oil immersed with only one scanning head and consequently 1D measurement. Measurement result on real object become valuable input for numerical model validation where modifications can be introduced and tested.

REFERENCES