MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

Low noise Transformer technology

Dr. Pirnat, Miha[1]
KOLEKTOR ETRA d.o.o.
Šlandrova ulica 10, 1000 Ljubljana

Mag. Tarman, Peter
KOLEKTOR ETRA d.o.o.
Šlandrova ulica 10, 1000 Ljubljana

ABSTRACT

High noise levels have negative effects on people's health and their quality of life in general. Transformer noise is especially undesirable due to its tonal composition. By placing power transformers close to residential areas, a need for low noise transformers arises. Transformer noise is a complex multiphysical problem that needs to be solved, as the demand for low noise transformers grows. In this paper, our comprehensive approach to design and control of transformer noise is presented. The approach is composed of several different activities during the design, production and FAT stages. In design stage, proprietary simulation tools are used to obtain the optimum design from the noise point of view. By using proprietary measurement devices and advanced methods, we are able to ensure that the designed characteristics are achieved in the production stage. Finally, at the FAT stage, noise measurements are performed by using several state-of-art measurement devices, such as the SONAH* and the acoustic intensity measurement systems. Measured data is gathered and used in further development of our design and control approach, which yields noise reductions by 11 and 7 dB at rated voltage and rated current, respectively.
***: statistically optimal near-field acoustical holography**

Keywords: Transformer, Noise, Reduction
I-INCE Classification of Subject Number: 11, 76

1. INTRODUCTION

Noise in residential areas and elsewhere is becoming an increasingly important part of quality of life. Studies [1] show that high noise levels can cause a variety of health problems to people. It is therefore necessary to control and reduce noise levels, where possible.

One of the noise sources in residential areas are also power transformers producing a distinct noise composed of particularly undesirable tonal components. Transformer noise is therefore becoming an increasingly important parameter when an investor is acquiring a new transformer. It is the transformer manufacturer's responsibility to understand and control transformer noise in order to successfully meet the investor's requirements.

[1] miha.pirnat@kolektor.com

Transformer noise is typically divided into three main noise sources: no-load noise, load-noise and auxiliary equipment noise [2]. The nominal no-load noise is present when nominal magnetic flux is established in the magnetic core. The nominal load noise is present when rated current is flowing through the windings. The auxiliary equipment noise is present when pumps, fans or other equipment is running. Due to different physical backgrounds, these three noise sources can be measured individually and then summed in order to obtain the total noise level.

Design and control of transformer noise levels requires a deep understanding of physics behind the noise sources, transformer specific materials, advanced measurement techniques as well as the complete manufacturing process.

In this paper, a general overview is given regarding design and control of transformer no-load and load noise in different stages of transformer production. First, the design stage is considered where a purpose-built software is used to solve multiphysics problems to obtain best low noise transformer designs. Second, the production stage is critical for ensuring low noise levels by avoiding mechanical resonance effects and checking incoming materials. Third, factory acceptance testing and additional special measurements yield accurate noise measurements and other data needed for further simulation software improvements.

2. DESIGN STAGE

Transformers designed for low noise levels undergo a modified design cycle, where additional simulations are made with custom numerical models and purpose-built software TrafoS, which was developed in cooperation with the Faculty of Mechanical Engineering in Ljubljana. Simulations are made for every major design change, until an optimum is reached. The low noise design optimum differs from the standard design one, and can significantly raise the transformer cost.

2.1 No-load noise

The main source of no-load noise is the magnetic core. Due to changing magnetic flux in the electrical steel laminations, a phenomenon called magnetostriction appears [3-5]. This phenomenon causes the electrical steel sheets to change dimensions, as the magnetic flux changes its amplitude. These dimensional changes mechanically excite the magnetic core and cause pressure fluctuations in transformer oil. By propagating through oil, pressure fluctuations hit the transformer tank and cause it to vibrate and radiate sound into the environment.

The TrafoS simulation software enables us to create a finite element model of a complete transformer. First, by entering the magnetic core dimensions, a numerical model of the magnetic core is built by using an advanced two-stage modelling approach [6-8], where beam and link elements are used to model the interlaminar friction between steel laminations, as shown in Figure 1. This yields a physically sound structural model of a magnetic core. The modelling approach is explained in depth and validated in [6].

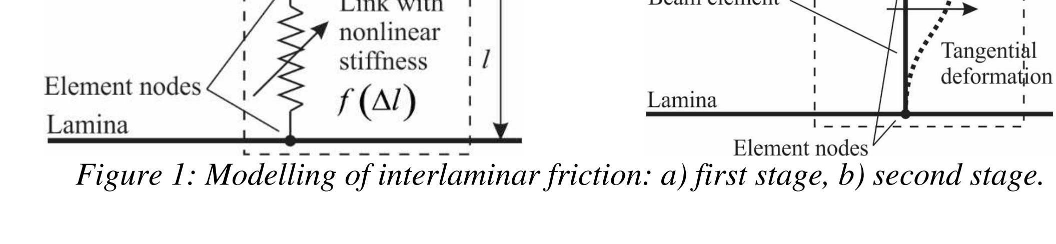

Figure 1: Modelling of interlaminar friction: a) first stage, b) second stage.

The Magnetic core structural model can be used in modal analysis to find its natural frequencies and mode shapes. Figure 2 shows a comparison between a calculated and a measured magnetic core mode shape. A wider comparison between calculated and measured mode shapes can be found in [8], where we compared eight mode shapes for three different magnetic core sizes and found a good agreement.

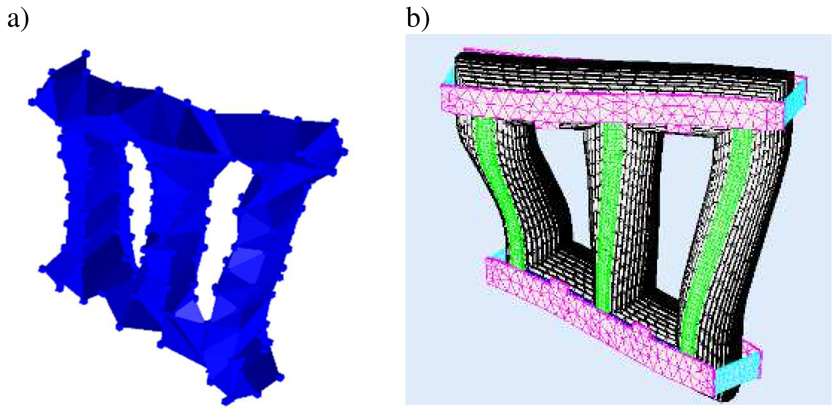

Figure 2: Core mode shape example comparison: a) measured, b) calculated.

By applying magnetostriction to the magnetic core structural model and performing harmonic analysis, a surface displacement field can be calculated at a range of frequencies. The resulting displacement field shown in Figure 3 represents magnetic core vibrations due to magnetostriction with included mechanical resonance effects. This enables us to study different magnetic core designs and avoid mechanical resonances, which can amplify radiated noise levels.

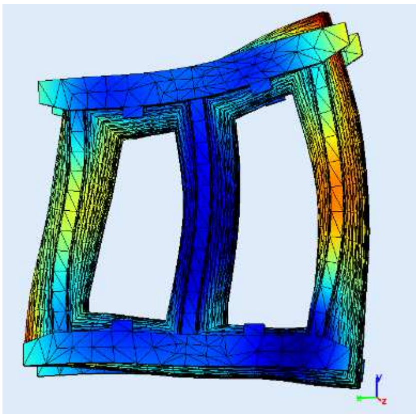

Figure 3: Example of the magnetic core surface displacement field due to magnetostriction.

The magnetic core harmonic analysis results are used as input boundary conditions in the harmonic analysis of a transformer tank filled with oil. In this way, the transformer tank surface displacement field due to magnetic core vibrations can be calculated. An example of the results is shown in Figure 4. The transformer tank used in the analysis is automatically generated from 3D models generated for technical documentation.

a) b)

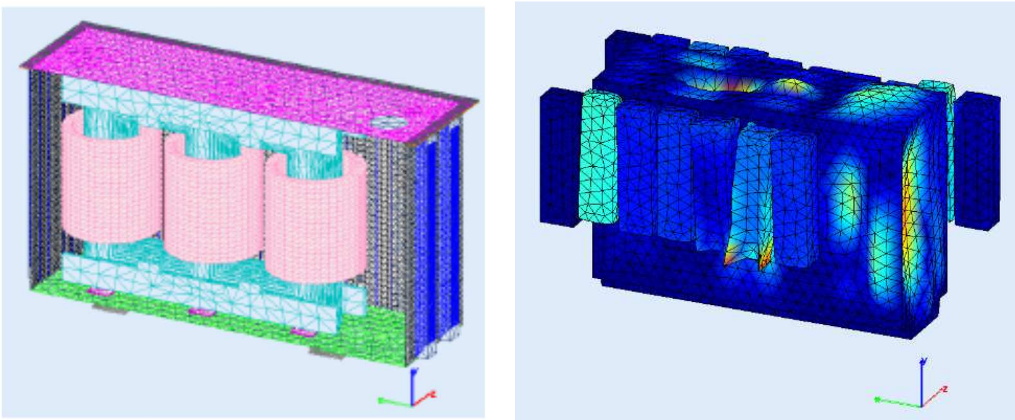

Figure 4: Numerical model of a complete transformer: a) model cross-section, b) harmonic analysis results.

In the final step of TrafoS no-load noise simulation, the transformer tank surface displacement field is used as an input for the boundary element method. The latter is used to calculate the sound pressure field on the transformer tank surface, and in arbitrary surrounding points as shown in Figure 5. The points typically represent locations of standard sound pressure measurements conducted in the in laboratory.

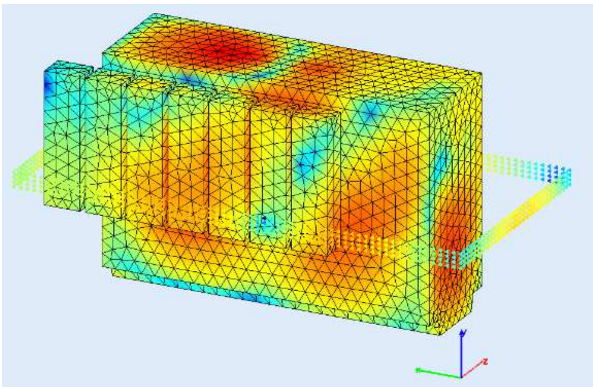

Figure 5: Calculated sound pressure distribution.

2.2 Load noise

Under load conditions, the main source of noise are the current-carrying windings. Due to flowing currents, magnetic forces appear between the conductors. These forces cause the windings to vibrate and generate pressure fluctuations in oil. By propagating through the oil, these pressure fluctuations excite the transformer tank, which in turn radiates sound into the environment.

We have upgraded our numerical approach previously presented in [9] and now use a proprietary 3-step modelling approach in order to obtain load noise sound power level of a transformer. The first step is calculation of magnetic forces between the conductors using 2D axisymmetric electromagnetic model in FEMM [10] software. The 2D FEMM model and calculated stray magnetic field is shown in Figure 6a. An example of the resulting electromagnetic forces is shown in Figure 6b. The forces are shown for 30 winding height segments, where each segment represents cumulative forces within 1/30 of the winding height.

a) b)

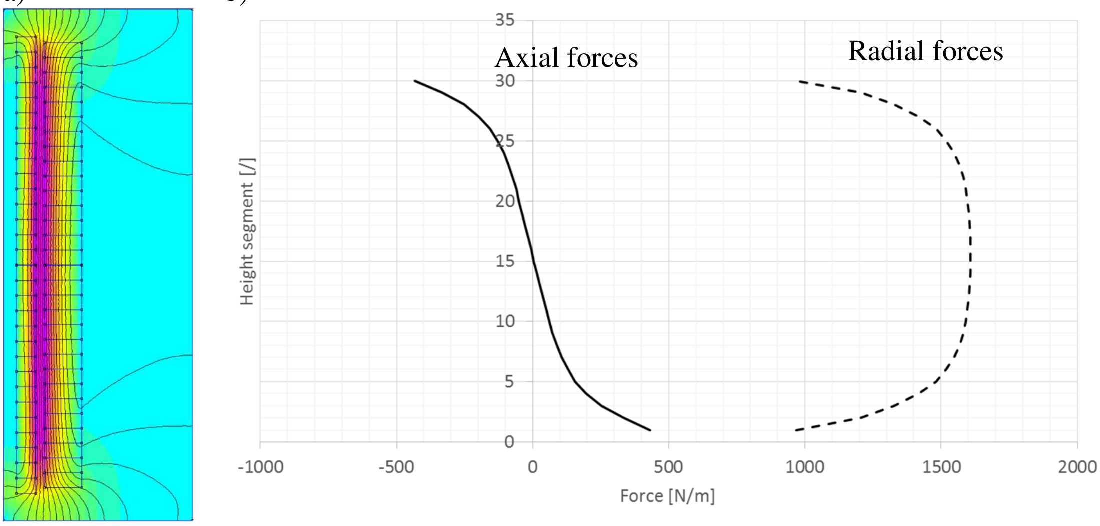

Figure 6: a) Stray magnetic field calculated with FEMM 2D electromagnetic model, b) Resulting axial and radial winding forces.

The second step consists of simplified structural model as shown in Figure 7a, where three-phase transformer is modelled as a single-phase transformer, hence only one set of windings is modelled. This way a significant reduction in model size is achieved. The model incorporates solid-fluid interaction between windings, clamping structure, tank and oil. This enables us to gain an insight into fluid loading of the windings and an unbroken chain of sound pressure transmission from winding surface to tank.

a) b)

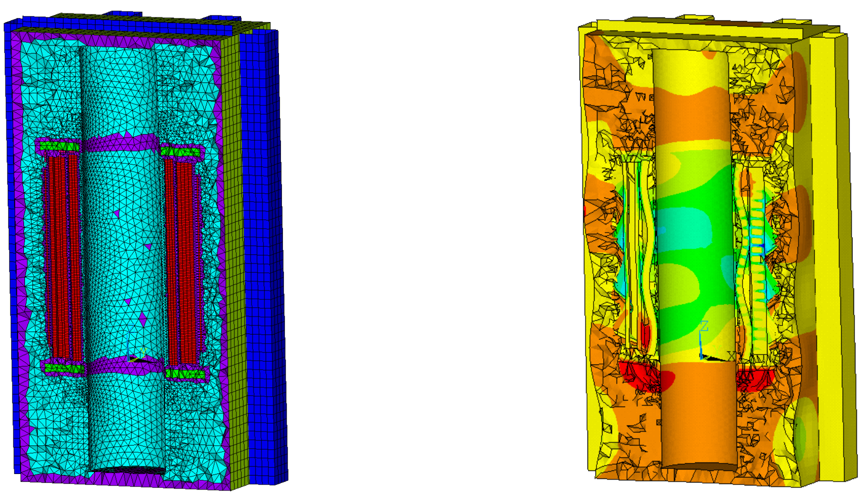

Figure 7: a) Ansys structural model cross-section with solid-fluid interaction, b) Sound pressure distribution and surface displacements at 150 Hz.

By applying magnetic forces to the structural model we can perform a harmonic analysis and obtain transformer tank surface displacements. An example result of harmonic analysis at 150 Hz is shown in Figure 7b.

In the third step a separate analysis is done, where tank surface is placed within a sphere filled with air in order to calculate sound power level of the transformer. Tank surface displacements used in this step are duplicated from previously performed harmonic analysis. An example sound-pressure field at 150 Hz is shown in Figure 8.

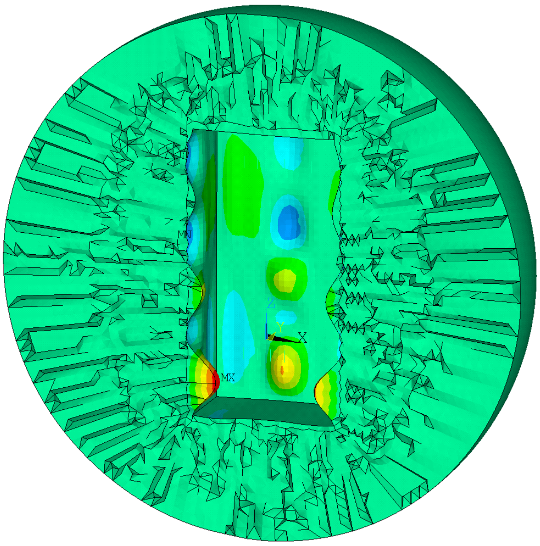

Figure 8: Sound pressure field in tank surroundings at 150 Hz.

3. PRODUCTION STAGE

Once the optimum transformer design is determined and the production process starts in the production facilities, the noise control activities are initiated. These are implemented in order to ensure that the transformer properties determined in the design stage are also achieved in the production stage. Some activities are common for no-load and load noise control, whereas others are noise type specific. Most of noise control activities require additional time, specialized equipment and trained employees, which adds to the overall production time and transformer cost.

Main source of no-load noise is the magnetic core due to the magnetostriction phenomenon. The magnetostriction amplitude is one of the main properties of electrical steel. Measuring it represents a great challenge, and no generally accepted measurement standard exists.

In order to measure magnetostriction amplitudes of incoming electrical steel we use a custom- developed magnetostriction measurement device shown in Figure 9a. The device enables us to perform comparisons between different electrical steel manufacturers and gain valuable data for numerical simulations. A typical measurement result is shown in Figure 9b.

a) b)

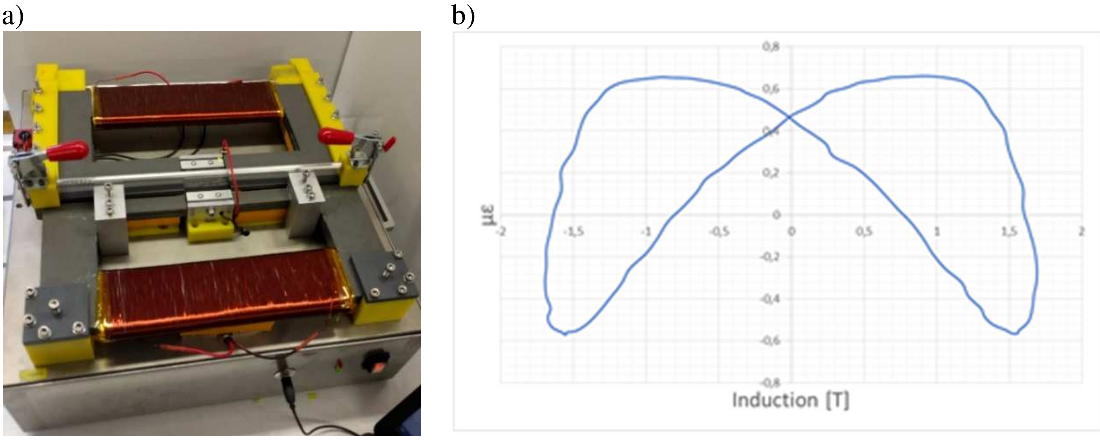

Figure 9: Magnetostriction measurement system: a) device, b) typical magnetostriction curve.

Another activity we perform in order to control no-load noise is mechanical resonance prevention. By using the well-established experimental modal analysis, we obtain modal parameters of magnetic core (Figure 10a) and compare them with the design values. With known excitation frequencies, we can alter modal parameters in a way to prevent possible resonance. This approach is also used with other key transformer components, such as windings (Figure 10b).

a) b)

Figure 10: Experimental modal analysis: a) on magnetic core, b) on windings.

Other activities with regard to noise control include specialized material testing, modified manufacturing procedures, structure-borne noise prevention, etc.

4. FACTORY ACCEPTANCE TEST

Factory acceptance test is one of the final stages of transformer production. As any kind of adjustment in this stage is undesirable and expensive, the design and control of transformer noise must be achieved in previous stages. However, it is crucial to accurately measure what has been achieved. For this purpose, an acoustic intensity measurement is the preferred standard method [11]. If performed correctly, it can be used to calculate the transformer sound power level, which is one of the most informative noise source characteristics.

In order to measure the achieved sound power levels, we use an acoustic intensity measurement system. Furthermore, the SONAH system (Figure 11) is used for noise source localization with an additional set of microphones for other research measurements. Data gathered in this way is used for further improvement of numerical and statistical models.

a) b)

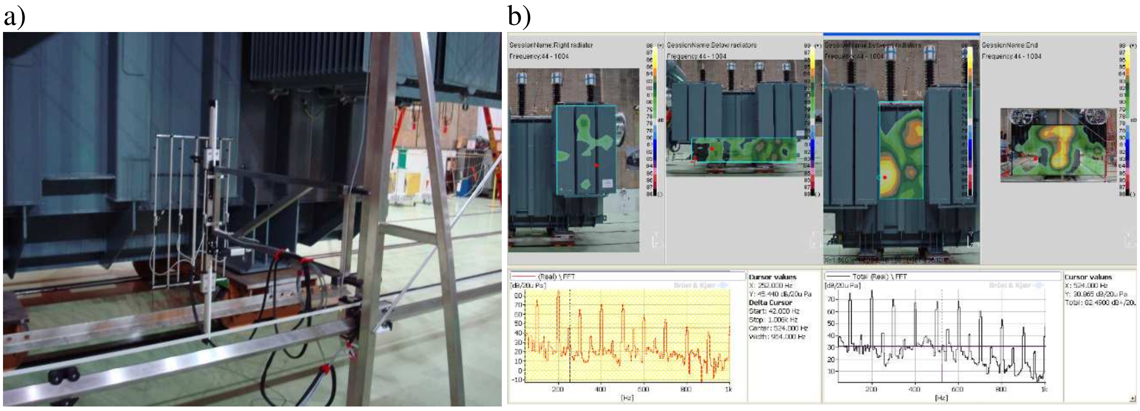

Figure 11: SONAH measurements: a) measurement robot, b) noise source identification.

5. COMPARISON OF STANDARD AND LOW NOISE DESIGN

Implementing noise design and control techniques correctly yields a power transformer with significantly lower noise levels than in a standard design. A comparison of a standard design and low noise design levels is shown in Table 1. The noise reduction is achieved without any additional sound proofing on the transformer tank. It is understandable that values in Table 1 are typical and that the noise reduction can differ from unit to unit.

Table 1: Comparison of standard and low noise design.

Sound power level	Standard design	Low noise design
At rated voltage	X	X – 11 dBA
At rated current	Y	Y – 7 dBA

6. CONCLUSION

A comprehensive approach to design and control of power transformer noise is presented. The approach consists of a number of different activities spread over several stages of transformer production. First, a purpose built simulation software and models are presented, which are used in the design stage for determining an optimum design from the noise point of view. Second, some of the production stage activities are presented, which are necessary to ensure that the designed characteristics are achieved. The experimental modal analysis is needed to obtain modal parameters of key transformer components, and magnetostriction measurements of electrical steel are essential to no-load noise characteristics. Third, information is given about standard noise measurements during the factory acceptance test and other research measurements. These are needed for further simulation software validation and development. Finally a comparison between standard and low noise design is given. By correctly implementing the presented activities, noise reductions by 11 and 7 dB can be achieved at rated voltage and rated current, respectively. The stated noise reductions are typical and can change from unit to unit.

7. REFERENCES

1. G. Leventhall, S. Benton, P. Pelmear, *"A review of published research on low frequency noise and its effects"*, London: Department for Environment, Food and Rural Affairs (2003)

2. E.I. Amoiralis, M.A. Tsili, A.G. Kladas, *"Transformer design and optimization: A literature survey"*, IEEE Transactions on power delivery, 24 (2009), pp. 1999-2024

3. B. Weiser, H. Pfützner, J. Anger, *"Relevance of magnetostriction and forces for the generation of audible noise of transformer cores"*, IEEE Transactions on magnetics, 36 (2000), pp. 3759-3777

4. M. Javorski, J. Slavič, M. Boltežar, *"Frequency characteristics of magnetostriction in electrical steel related to structural vibrations"*, IEEE Transactions on magnetics, 48 (2012), pp. 4727-4734

5. M. Javorski, G. Čepon, J. Slavič, M. Boltežar, *"A generalized magnetostrictive-forces approach to the computation of the magnetostriction-induced vibration of laminated steel structures"*, IEEE Transactions on magnetics, 49 (2013), pp. 5446-5453

6. M. Pirnat, G. Čepon, M. Boltežar, *”Introduction of the linear contact model in the dynamic model of laminated structure dynamics: an experimental and numerical identification”*, Mech. Mach. Theor 464 (2013), pp 144-154

7. G. Čepon, M. Nastran, J. Slavič, M. Boltežar, *“Development of numerical model for computation of power transformer noise”*, 11th international conference on engineering vibration, Ljubljana (2015)

8. M. Pirnat, P. Tarman, M. Nastran, *“A comparison between numerical and experimental modal parameters of transformer core”*, 11th international conference on engineering vibration, Ljubljana (2015)

9. M. Pirnat, G. Čepon, P. Tarman, M. Boltežar, *“Numerical modeling of transformer noise at rated current”*, Proceedings of 4th International Colloquium: Transformer Research and Asset Management, Pula (2017)

10. D. C. Meeker, *“Finite Element Method Magnetics”*, Version 4.2 (28Feb2018 Build), http://www.femm.info

11. IEC 60076-10:2016, *“Power transformers – Part 10: Determination of sound levels”*