Simulation-Based Investigation for Local Resonance Frequencies in Power Transformer Core

Ahmed Gamil*, Franz Schatzl and Ali Al-Abadi

Starkstrom-Gerätebau GmbH. Ohmstr. 10, 93055 Regensburg, Germany
E-Mail: ahmed.gamil@sgb-smit.group

Abstract

Core resonance is one of the main phenomena that has always a negative effect on transformer noise level. Because of limitation of measuring the natural frequencies of a core, only few varieties of changing core dimensions are possible. However, using simulation tools is more effective and can help initially to build a suitable model for daily use. Investigating the core in simulation environment as bulk mass simplifies the duty to build a mathematical model to calculate the resonance frequencies based on core dimensions. However, this way is not presenting the reality, that each step of the core has its own shape modes and effective resonances frequencies as well. Considering each step geometry separately will lead to determine the local resonance frequencies and to find a solution for the steps, which have the undesirable resonance frequencies. The target is to find out the effective geometry factors of the step on the resulting resonance frequencies and shape modes. Moreover, the measured frequency spectrums for some tested cores are studied and a correlation between the simulation results and measurements is found. The focus covers core designs for 50 and 60 Hz, and the investigated frequency range lies between 100 and 1400 Hz.

Keywords: transformer core, noise, resonance

Introduction

Energy consumption is continuously increasing, especially in urban regions. Thus, power transformers with ever-increasing nominal power must be developed in parallel. A higher rated power of a transformer usually leads to higher noise level. Due to the increase of the transformers volume, the noise pollution of the adjacent residents increases. Legislation and customer requirements are therefore reinforced to regard transformer noise. Therefore, there is a need to develop ways to reduce the noise of the transformers. The noise generated by the transformer's core is one of the main components of the total radiated noise, and hence, there is a large potential to reduce the total transformer noise by controlling the core noise, [1-3]. The resonance in the core can add a significant contribution on the noise. Therefore, it is required to accurate determining and controlling the core resonance to avoid its occurrence and to mitigate or remove its effect on noise. In the current study, we present a developed simulation-based and experimentally validated model that determines the mechanical behavior of the transformer core. Furthermore, the systematic formulation and practice implementation of the model is presented in this study.

Transformer core

For the creation of the FEM-model, which is used to determine the mechanical behavior, it is important to understand how the core is constructed. The standard 3 phase transformer core consists of two yokes and three limbs. These parts are clamped together by the structural elements of the transformer. The related construction is shown on the left side in figure 1. On the right side of the same figure, the cross section of the transformer core is shown. The core consists of steps which are build from numerous grain-oriented electrical sheets, [1, 4].

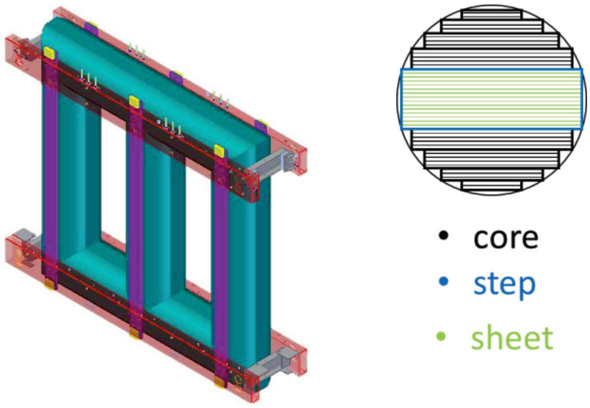

Figure 1: Transformer core

The single sheets are isolated from each other so that the magnetic main flux appears only parallel to the sheets, [1].

Magnetostriction

In addition to the construction of the transformer core, the excitation of the core is crucial for the FEM-model. For simplicity, the core can be considered as an accumulation of molecular magnets. When exciting the molecular magnets, an alternating magnetic flux is generated. As a result, these magnets are reoriented periodically. Due to the reorientation of the molecular magnets a periodic change in the length of the core components arises. This change in length is called magnetostriction. An electrical period results in two maxima with respect to the change in the core length, which is excited at twice the supply frequency. So, for example, an electric 50 Hz transformer vibrates at 100 Hz. In addition to this vibration, the iron core oscillates at the higher harmonics of the main frequency, [6].

Magnetostriction is also dependent on the direction of the magnetic flux. Thus, the magnetostriction component parallel to the magnetic flux $\lambda_{M\parallel}$ has twice amplitude compared to the magnetostriction perpendicular to the magnetic flux $\lambda_{M\perp}$ equation (1), [7].

$$\lambda_{M\perp} = -\frac{1}{2} * \lambda_{M\parallel} \qquad [\frac{\Delta mm}{mm}] \qquad (1)$$

Approach

The approach can be divided into two separate topics. On the one hand, a FEM-model is developed to determines the resonance frequencies of the core. On the other hand, a procedure is performed to evaluate the noise measurements of the no-load tests of transformers which are already tested.

FEM-model

Based on the geometry of the real transformer core, FEM model is created. At this point, some assumptions have to be made to reduce the complexity of the model.

Each individual core step is distinguished from the other steps by geometry. Every core step consists of number of staked sheets that have the same geometry. The staked sheets are excited by the magnetic flux. Because the similar geometry of the sheets and the assumed uniform magnetic flux through the sheets, the magnetostriction of the sheets is at the same frequency. Therefore, it is realistic to consider the bundle of sheets or step a feasible approximation for investigating the resonance. Between the steps, the relative speed between the analyzed sheets of a step and the sheets in the adjacent step is assumed to be very small.

The distinction of the natural frequencies only exists between the steps. However, the internal friction is assumed to prevent any slipping between the steps when vibrating. Nevertheless,

In addition, clamping the yokes perpendicular to the sheets plane is assumed in the elastic region, and hence, will not change the mechanical properties of the sheets insulation material. The existing of the friction between the steps is assumed not to be preventing each step from vibrating independently from other adjutant steps.

In the steps of a transformer core, the dimension perpendicular to the sheet plane is very small in comparison to the dimension in the sheet plane. Because the main magnetic flux takes place in- and out of- the plane of the sheets, the magnetostriction perpendicular to the sheet plane is smaller as due to equation (1). For this reasons, only the deformations parallel to the sheet plane are considered in the model.

The Material used in transformers have different values of the E-modulus in the rolling direction (RD) and in the cross-rolling direction (CRD) [8]. Because, no accurate equivalent material properties of the combined sheets materials are available, another assumption must be made at this point. The material properties in RD and CRD are defined in different areas of the model. In the corners of the core step, which is framed with green triangles in figure 2, the CRD E-modulus is set, whereas the RD E-modulus is set for the remaining of the model. Figure 2 shows a schematic representation of the model which is built based on the previous mentioned assumptions.

The model involves three geometrical parameters as well as the E-modulus in RD and CRD which all influence the resonance frequencies and need to be investigated. For this purpose, the approach of the "design of experiment [9]" is modified and used. Instead of results from experiments, as it usually is, the output of the FEM-simulation are examined with this approach. This makes it possible to analyze the effect of the individual parameters as well as interactions between the parameters. The following dependencies are identified with this approach:

- Increase the BB: natural frequencies increases
- Increase the MA: natural frequencies decreases
- Increase the MSL: natural frequencies decreases
- Increase the E-modulus: natural frequencies increases
- Interactions between BB, MA and MSL
- No interaction between the E-modulus and other parameters

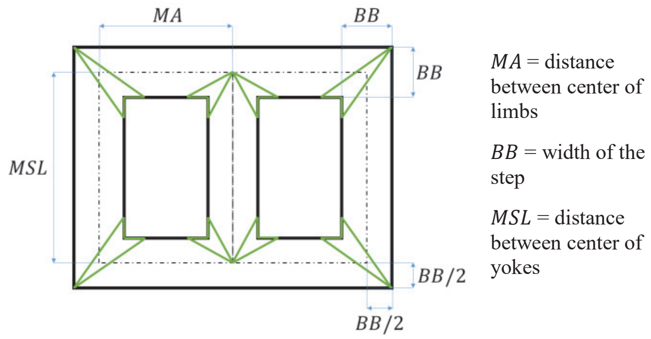

Figure 2: FEM-model

Due to the lack of interaction between the E-modulus and the other parameters, the E-modulus can be considered independent [9]. Equation (2) shows two sets of parameters coupled for investigating the natural frequencies N of the model.

$$N = f(BB, MA, MSL) \circ f(E\text{-}mod(RD, CRD)) \quad [\text{Hz}] \quad (2)$$

Based on this consideration, the influence of each parameter on the core resonance frequencies is determined.

No-load noise measurements

During no-load noise test, transformer core is the main excited component while the windings are not loaded. As a result the frequency spectrum of no-load noise measurements is dominated by the core noise. Evaluation of these frequency spectrums is necessary to find a correlation between core vibration and its noise emission. Figure 3, shows an example of a no-load noise measurement. The considered peaks of the spectrum resulting from the magnetostriction at twice of main supply frequency and its higher harmonics [6].

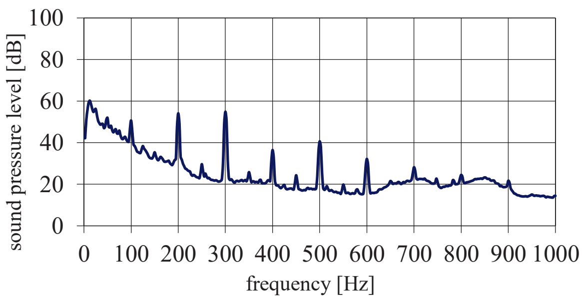

Figure 3: No-load noise measurement example

The first step of the evaluation is to consider the A-weighting [10] of these peaks. In the second step, the A-weighted sound levels $L(f_i)$ are compared to each other. This comparison is presented in equation (3) as a ratio with the exponent Ex as a weighting factor. Thus, Equation (3) provides the probability distribution $w(f_i)$ of a frequency f_i which dominates the noise emission of the investigated core.

$$w(f_i) = 100 * \left(\frac{L(f_i)}{\max(L(f_i))}\right)^{Ex} \qquad [\%] \qquad (3)$$

In the following, Ex is set to the value 15, resulting in the following values for w for the example measurement:

Table 1: Evaluated probability w_i

f_i [Hz]	100	200	300	400	500
$L(f_i)$ [dB(A)]	31,6	43,3	47,8	31,6	37,4
$w(f_i)$ [%]	0,2	22,7	100	0,2	2,5
f_i [Hz]	600	700	800	900	1000
$L(f_i)$ [dB(A)]	30,0	26,8	23,7	21,4	14,4
$w(f_i)$ [%]	0,1	0,0	0,0	0,0	0,0

Results

The approach consists of two parts, the FEM-Model and the no-loss noise measurement. To optimize the transformer core, analysis result of both is gathered. For that, an investigation approach is designed in away. The work flow is shown in figure 4.

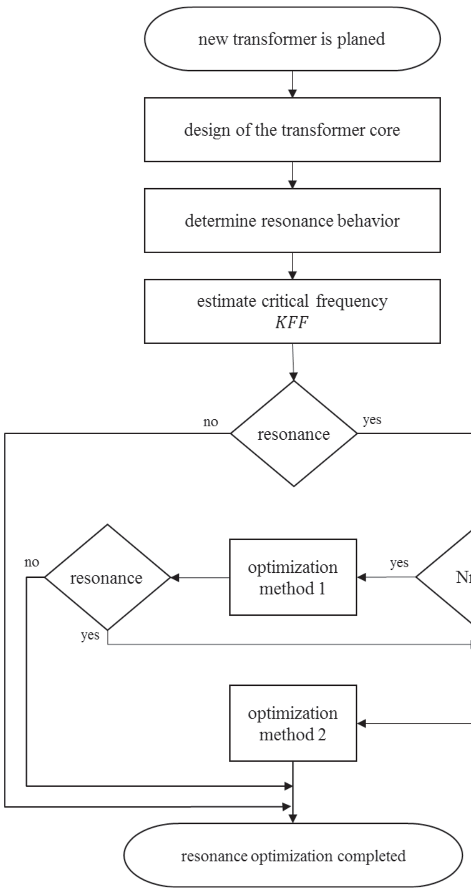

Figure 4: Optimization work flow

For designing a new transformer core, both MA and MSL are fixed, and only the width of the sheets BB changes for each step. For this reason, the output in the parameter study, which is performed from the basis of the selected FEM model, is chosen so that the resonance frequencies are displayed in dependence of BB. The other parameters (MA, MSL and E-modulus in RD and CRD) have constant values. FEM-model is in figure 5, where the natural frequencies that correspond to different mode shapes are presented as a function of sheet width.

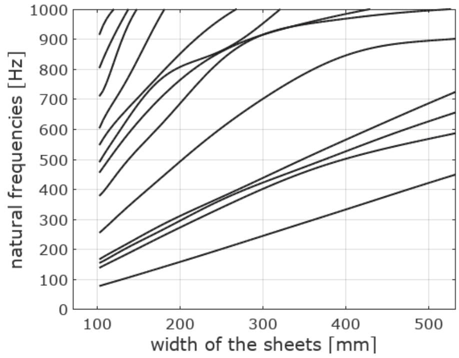

Figure 5: natural frequencies of different mode shapes versus the sheet width BB

The assignment of the lines to the mode shapes is unimportant at this point. The only purpose of this data is to determine the critical width of the each step for resonance.

In order to prevent one step of the core from being excited in resonance, all steps that have a natural frequency at one of the frequencies of the magnetostriction are needed to be changed or replaced. However, since this would affect almost every single step of the core, a possibility must be found to limit these frequencies. For this reason, a method has to be developed in which the dominant frequencies at the generation of noise of a transformer are determined. The first step in the implementation of this method is the evaluation of the no-load tests. The procedure for evaluating the tests is as previously explained. For every frequency f_i the probability $w(f_i)$ is calculated. This procedure is repeated with a large number of noise measurements of different transformer designs.

For a new transformer design, which has no measurement data available, a method is developed to transfer the results of the existing measurements to the new design. For that a factor is developed. This factor KFF is made up of different characteristics that have been found to influence noise generation during no-load tests, equation (4).

$$KFF = fkt(core\text{-}characteristics) \qquad [\text{p.u.}] \qquad (4)$$

The factor KFF is chosen so that the distribution of $w(f_i)$ over the frequencies f_i depends on this factor. Figure 6, shows the different values of $w(f_i)$ for both, a low and a high value of KFF. Thus, for example $w(f_i)$ at high frequencies is relevant only to the high value of KFF.

Now, for a new design of a transformer core this factor must be determined. Subsequently, all transformers that have a similar value at KFF are evaluated and the mean value of the results of these transformers is formed. This mean value can be used to estimate the behaviour of the noise generation of the transformer design. It is possible by this approach to determine the dominant frequencies even for new core designs. It allows to limit the frequencies that are presented in figure 5. Out of this, only a small number of steps are considered to be excited to resonance. Thus, it becomes possible to carry out a specific optimization for the critical steps. Two different optimization methods are possible to eliminate the core resonance:

- Method 1: Optimization of core design
- Method 2: Optimization of single core steps

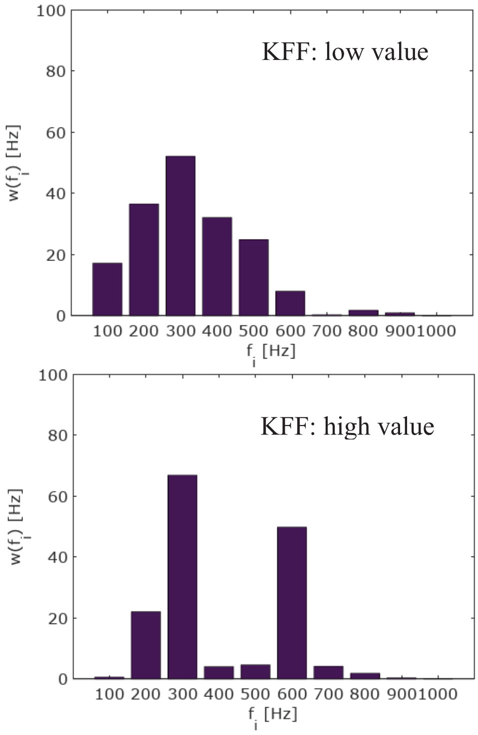

Figure 6: The influence of KFF on $w(f_i)$

The effects of these methods are shown for an example transformer core in figure 7.

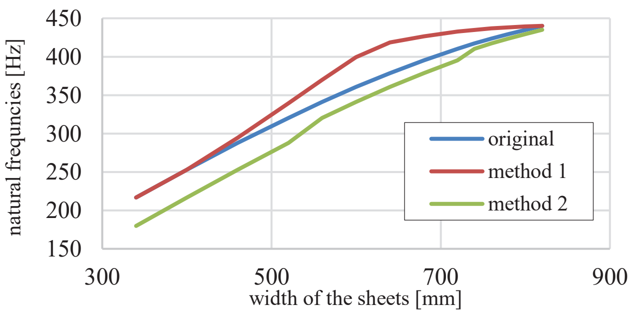

Figure 7: effect of the optimization methods

The effectiveness of these methods depends on the respective step and the parameters of the core. Therefore, it has to be analysed for each individual step and to decide which method has to be used for optimization. The application of these two methods results in different advantages and disadvantages.

Optimization method 1 has following advantages:

- weight reduction
- Cost reduction
- Losses reduction

For these reasons, this method should be used when possible. However, this method is not feasible at some steps of the core, which is why optimization method 2 need be used as an alternative. Method 2, which can affect every single step of the transformer core, has a major disadvantage that is the losses of the transformer could increase. Thus, core resonance optimization and thereby the noise generation often leads to an increase in the losses. A trade-off between noise and loss requires a decision in which direction a transformer should be optimized.

Conclusion

FEM-model is developed to determine the natural frequencies of the individual steps of the transformer core. Based on this model, a parameter study is carried out. It is found that an increase of BB or the E-modulus leads to increase of the natural frequencies. An increase of MA or MSL, on the other hand, leads to decrease of the natural frequencies of the core step model. In addition, a method for evaluating no-load noise measurements is developed. In this method the factor KFF can be used to estimate the critical frequencies for the designed core. By combining these two approaches, it is possible to optimize the transformer core to remove resonances at the main and higher harmonics frequencies. Two different optimization options are developed for this goal. Both options have different effect on core resonances as well as various advantages and disadvantages. Optimizing the core for resonance, and hence, low noise generation often leads to an increase in the losses in the transformer. Therefore a trade-off is required to decide in which direction the transformer should be optimized.

Acknowledgement

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