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NEW METHOD TO OPTIMIZE NO-LOAD NOISE OF POWER TRANSFORMERS BASED ON CORE DESIGN & TRANSFORMER OPERATING CONDITIONS

SUMMARY

This paper introduces a new algorithm to calculate and optimize no-load noise (sound pressure) of power transformers, and to identify iron sheet parameters. The calculation consists of two steps: the **1st step** consists in calculating an initial sound pressure level (A-Evaluation) which has approx. 70 % accuracy within a tolerance interval of ±2dB (A). The **2nd step** consists in estimating the expected deviation from the initial calculation to reach 90 % accuracy in the final results. This deviation could be due to material handling, quality tolerance, core manufacturing, etc.

The optimization process consists of two parts: the **1st part** takes place before choosing a certain iron sheet for calculation to identify the sheet parameters required for computational accuracy ("Sheet Optimization"). The **2nd part** consists in considering a core design with an undesirable sound pressure level in order to reduce it to an acceptable limit. This part takes into account the other limitations such as no-load losses and transformer dimensions ("Design Optimization").

For new iron sheets in the market, there is no measurement history to rely on. However, the algorithm is also capable of identifying the sheet parameters for calculation based on the available algorithm data base and the magnetostriction measurements of the iron sheet manufacturer.

Key words: Sheet parameters, Limitation Factor, Magnetostriction, Noise Factors, 3D Parameter Model.

1. INTRODUCTION

1.1. Past & Present State

The problem of no-load noise of power transformers is discussed only in a very small number of items of transformer literature. In these cases, the problem handling process was focused in most cases on the accuracy of measurements. The estimation of the measured sound level of the core was introduced in analogy to the magnetostriction behavior of the material using empirical parameters.

Using the simulation tools which some software programming companies offer helps to a certain extent. There is no definition of the probability of deviation and the effective parameters inside these tools influence the variation of the sound pressure level to a certain extent. There is no guarantee for the final result. Moreover, in view of the time needed for one simulation case, these tools are not suitable for daily use in transformer manufacturing.

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1.2. Need for a new technology

The acceleration in market and ecological requirements regarding noise restrictions and noise limitation obliges every transformer manufacturer to produce low-noise transformers.

In this paper, a new method is introduced to estimate no-load noise of power transformers (sound pressure) via direct calculation according to the iron sheet type, the core design, and the transformer operating condition. This new technology is capable of providing a 90 % precise result in practically no time and could be used in a simple calculator if the required information is available.

2. THE NEW METHOD

2.1. Calculation

2.1.1. Design influencing factors & iron sheet parameters

For a long period of time, the main determining factors for the sound level in cores has been the flux density and the limb length in analogy to the length variation detected by magnetostriction measurements. Later on, in terms of improvement of the calculation, the core weight was included for practical reasons.

Based on the transformer design, the new algorithm has constructed the whole design factors, which will influence the sound pressure level by 0.3m besides taking into account the flux density, namely:

- Core Volume Factor (V_f)
- Core Weight Factor (G_f)
- Tank Factor (K_f)

The initial value of the sound pressure level (SPL_{ini}) at a distance of 0.3 m is calculated by a function of these factors and the flux density.

$$SPL_{ini}(0.3m) = f(B, V_f, G_f, K_f, P_{1...N}) \qquad \text{dB (A)} \qquad (1)$$

Where

B: Flux Density [T]

$P_{1...N}$: Iron Sheet Parameters

Through the optimization process explained in section 2.2, iron sheet parameters are detected as unique for each iron sheet type. Table I shows an example for different sheet types from different manufacturers.

Table I – Iron Sheet Parameters

Sheet Type	Thickness	P1	P2	P3
Type 1	0.23 mm	28,756	17,734	-3,906
Type 2	0.23 mm	31,189	19,819	-48,789
Type 3	0.23 mm	42.114	21.022	-3.317

It is evident that each iron sheet type has its own sheet parameters, which will be used according to the choice of sheet to determine the final value of the no-load noise of the transformer. However, equation (1) results in a so-called “Initial Value (dB_{ini})” which has a probability of approx. 70 % within a tolerance interval of ±2dB.

To reach a higher accuracy, the calculation should provide a final value which covers the reasons for the deviations (e.g. different sheet coil qualities, core production tolerances, measurement deviations, etc.). By relating these reasons for deviation to the core design and the operating condition, the deviation for each transformer design can be identified precisely.

2.1.2. Limitation factor of deviation

A certain "Deviation OffSet" (DOS) is detected as a function of the operation flux density [T] and a design limitation factor [m] based on core dimensions. This detection is taking place over the 3D surface illustrated in figure 1.

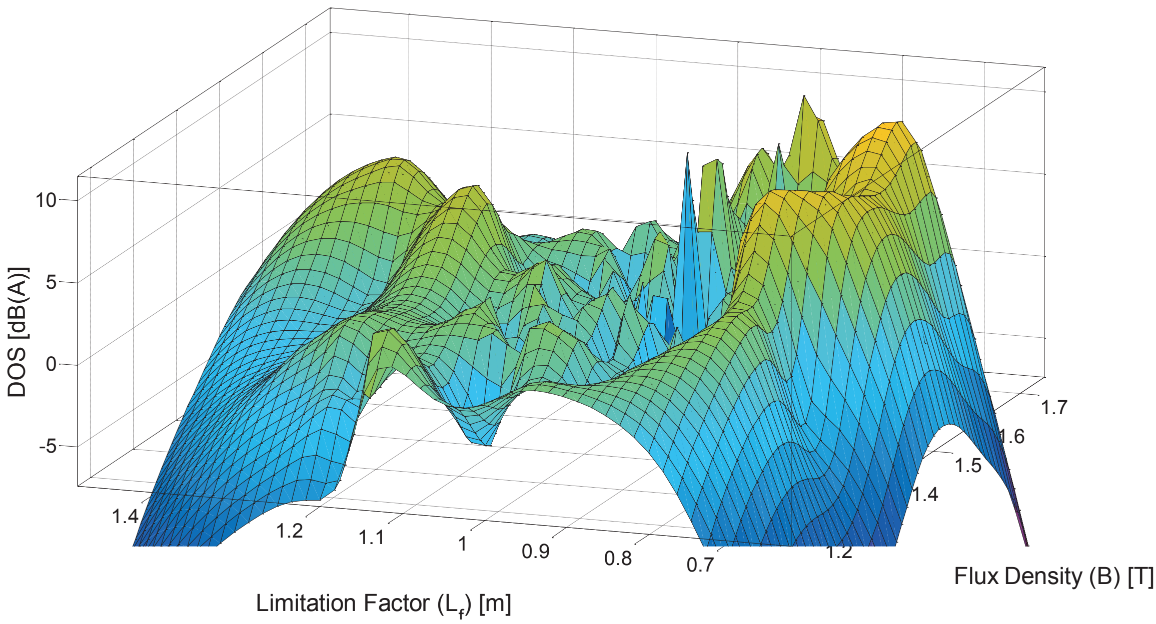

Figure 1 – Deviation surface for a sheet thickness of 0.23 mm

Depending on the value of DOS, a final sound pressure level is recognized as explained in equation (2):

$$SPL_{fin}(0.3m) = SPL_{ini}(0.3m) + DOS \quad \text{dB (A)} \tag{2}$$

$$DOS = f_{surf}(B, L_f) \tag{3}$$

The density and probability functions show the increase in computational accuracy by using the deviation surface. Without including DOS, the probability of deviation within a tolerance of ±2dB amounts to 73.6 % whereby this probability is increased to 91.5 % as shown in figure 2(a, b) if DOS is included.

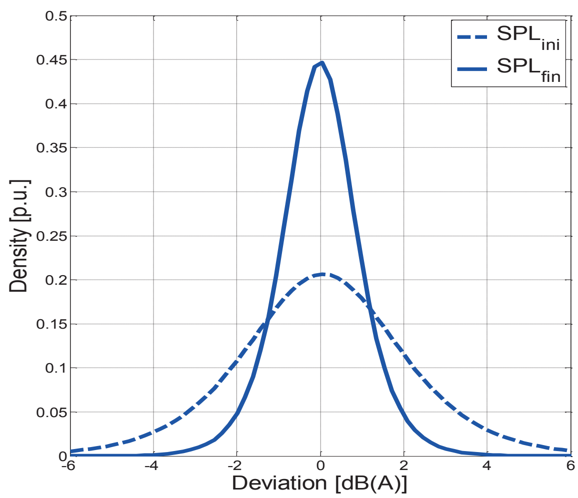

Figure 2a

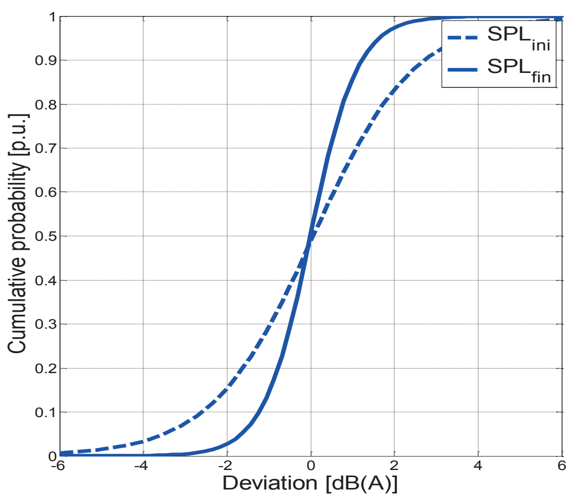

Figure 2b

Figure 2 – Density (2a) and probability (2b) functions of sheet thickness 0.23 mm

2.2. Optimization

2.2.1. Identification of known iron sheet

Depending on the measurement history of the no-load noise of power transformers, the parameters of the iron sheet used in the past for building the cores ("Known Iron Sheet") can be identified. The algorithm uses the available information (measured sound pressure, design factors) to determine the iron sheet parameters, which together with the design factors result in the highest probability of a deviation of ±2dB between the measured and the calculated sound pressure level. The flow chart of figure 3 shows the process of detection of each iron sheet type.

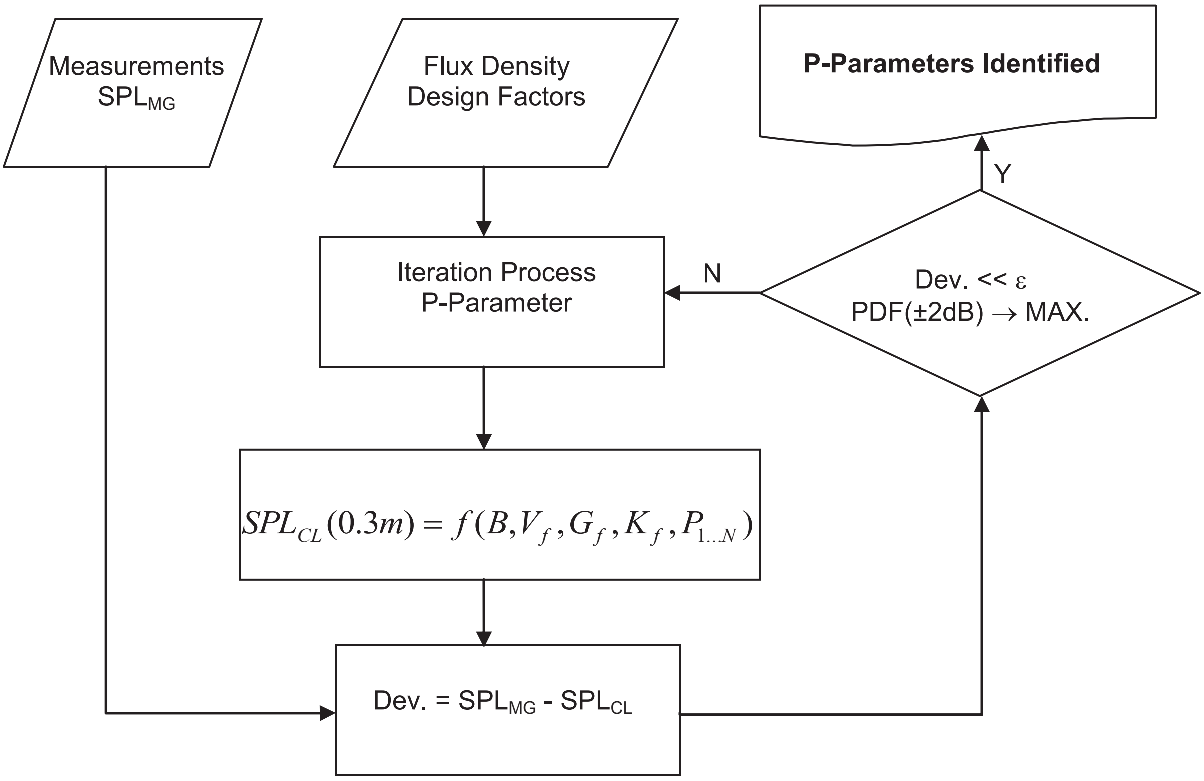

Figure 3 – Flow chart explaining the identification of iron sheet parameters

Where,

SPL_{MG} : Measured sound pressure level of different designs at a distance of 0.3 m.

SPL_{CL} : Calculated sound pressure level based on equation (1) during the iteration process.

PDF : Probability Distribution Function for adjusting the computational accuracy.

Although this process requires a certain extent of measurement history, this history could start from 3 different transformer designs with sound pressure measurements between 1.1 and 1.7T as a starting point for identifying the sheet parameters. However, the implementation of DOS requires at least 50 measurements.

In case of introducing iron sheet types without measurements history ("Unknown Iron Sheet"), i.e. if there is no transformer in which this material is used as a reference, another method is required to identify the sheet parameters, as will be explained in subsection 2.2.3.

2.2.2. Design optimization

According to sound level regulations, which have been subject to rapid changes recently, and because of the introduction of new manufacturers of iron sheet types, there is often a request for a previously manufactured transformer, however with enhanced noise restriction. For example, some customer had ordered a transformer two years ago with a guaranteed sound pressure value of 48 dB (A).

The calculation had provided a value of 46.9 dB(A) with a safety margin of 90 % (10 % risk of violation of that limit). The sound pressure measurement resulted in 46.3 dB(A).

The same customer asked again for the same transformer, however, with a new guaranteed SPL value of 46 dB(A). The target now consists in determining the design factors which result in an SPL reduction to 45 dB(A) with the same safety margin of 90 %. It should be kept in mind that the other limitations (e.g. no-load losses) should not be affected.

The algorithm fixes the value of K_f and tries to optimize the other design factors with the flux density to reach the desired SPL_{fin} = 45 dB(A). **That means reducing the sound level by 2 dB(A)**. The core of that transformer was modified successfully so that SPL reached the required value. The SPL measured at a distance of 0.3 m was 45.6 dB(A). Table II shows the design factors before and after optimization.

Table II – Design Factor Optimization

Design factors	Before optimization	After optimization	Change in %
B	1.573	1.512	-3.88
V_f	-0.0319	-0.0481	-3.66
G_f	-0.5858	-0.5877	-0.44
K_f	-0.415	-0.415	0.00

Even if this process takes no time to obtain these results also graphically as shown in figure 4, this optimization process is performed in critical situations where the use of a specified iron sheet is mandatory (normally origin-dependent). In most cases, another iron sheet from our data base is chosen instead, which is known as a lower noise sheet. However, for cost-saving reasons, it is frequent practice, due to sudden price increases, to change the iron sheet type used previously and to replace it by a cheaper one to keep the transformer price in an acceptable range.

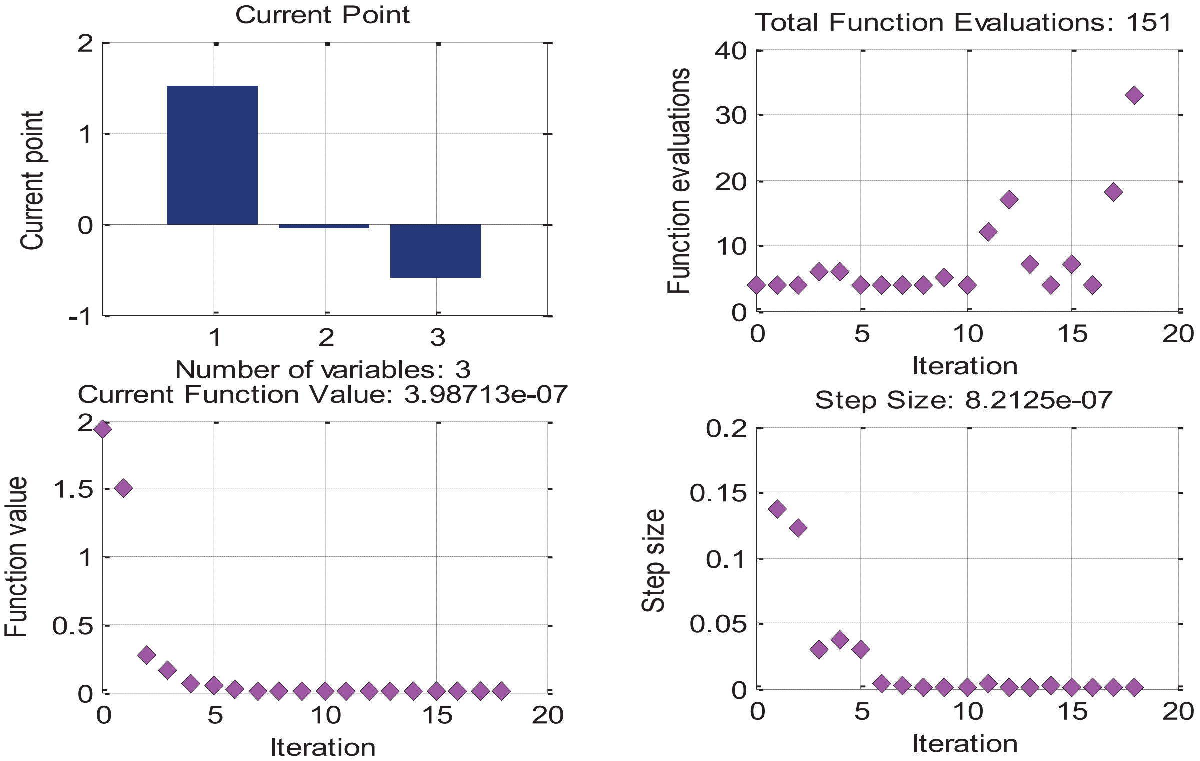

Figure 4 – Graphical illustration of the iteration process during design optimization

2.2.3. Identification of unknown iron sheet using the magnetostriction factor

Iron sheet manufacturers work continuously on improving the quality of their materials regarding both no-load losses and no-load noise. Therefore, almost every year, new iron sheet types are introduced into the transformer market at more attractive prices. Besides, iron sheet manufacturers use to confirm that the new sheet type in question is a low-noise type, based on their magnetostriction measurements.

On the part of transformer manufacturers, it is necessary to identify the sheet parameters in order to realize at least the initial SPL of the entire manufactured core using this new type. This is not possible because there is no measurement history of that new sheet. The information available is:

- Measurement history of Known Iron Sheets,
- Magnetostriction Measurements of Known Iron Sheets and
- Magnetostriction Measurement of Unknown Iron Sheet (new type).

Based on this information, the new algorithm is capable of detecting the iron sheet parameters for the new sheet type. By using the magnetostriction measurements, the algorithm calculates a so-called Magnetostriction Factor (Mf) which is recognized as characteristic value of the sheet. The available history of no-load noise measurements makes it possible to illustrate the 3D-Parameter Surface shown in figure 5 depending on sheet thicknesses and magnetostriction factors.

In case of new sheet types, the magnetostriction factor is determined from the magnetostriction measurements which are made available by the iron sheet manufacturer. Together with the known sheet thickness, the iron sheet parameter is recognized on the 3D-Parameter Surface. Figure 5 shows an example of detecting the volume factor parameter.

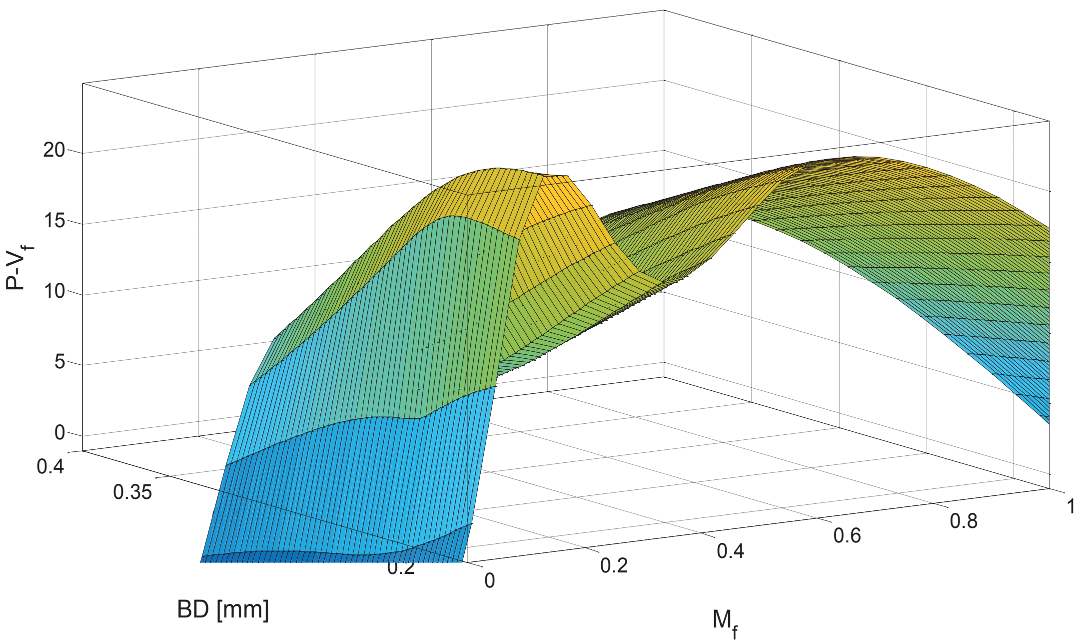

Figure 5 – 3D-Parameter Surface to detect sheet parameter for new types

One should keep in mind that the resulting parameter will construct equation (1), i.e. there is no way to detect DOS unless measurement data is available. Nevertheless, this is a good starting point to have an indication about the core noise performance of a new iron sheet type without having any past history of measurements. Table II shows the results of using two new iron sheets compared to the measurements and guaranteed values.

Table III – Adjusting Sheet Parameters

New Iron Sheet Types	Calculation (SPL_{ini})	Measurement (SPL_{MG})	Deviation
Type 1	53.2 dB(A)	51.9 dB(A)	-1.3 dB
Type 2	46.6 dB(A)	49.2 dB(A)	2.6 dB

3. RESULTS

3.1. Optimization Results

The results of the entire optimization process are clearly shown in figure 6 as an example of quality control based on the probability distribution of the measured deviation. If a higher degree of accuracy is required to avoid exceeding guaranteed values involving penalties, quality B will be preferred to quality A.

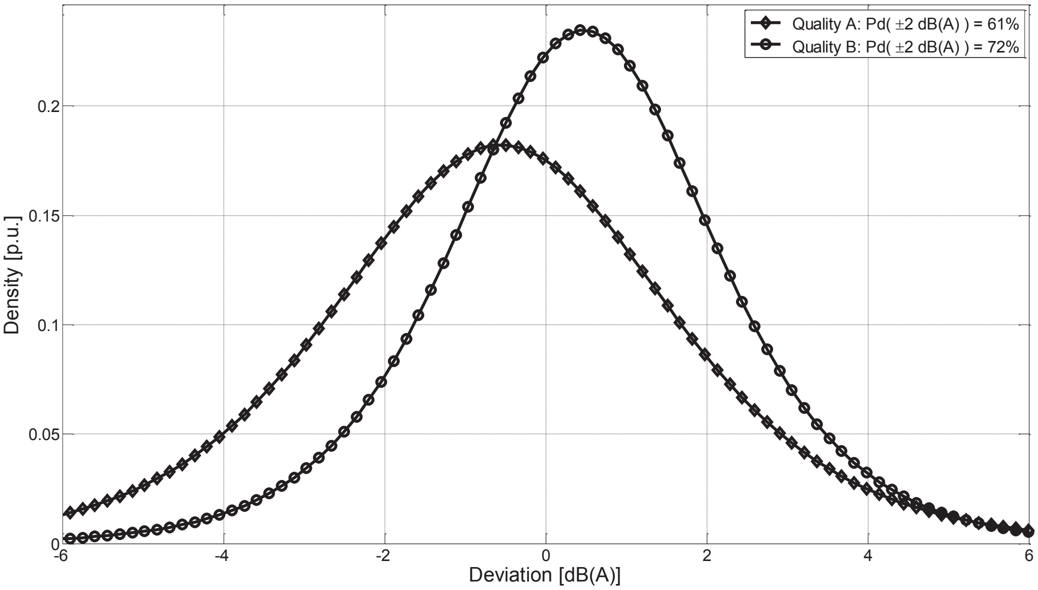

Figure 6 – Using the deviation probability as a measure of material quality

3.2. Practical results

The histogram shown in Figure 7 is the result of using the new algorithm over 2 years. The probability distribution is observed in range ±3 dB(A), because the histogram contains all iron sheet types available at SGB for building the core. It provides a general view about the total scattering between measured and calculated SPL. The mean value (0.06 dB(A)) and the standard deviation (2.07 dB(A)) give a good indication of accuracy and the small range of scatter. The extreme deviating values are a result of new material used or sudden changes of the source quality.

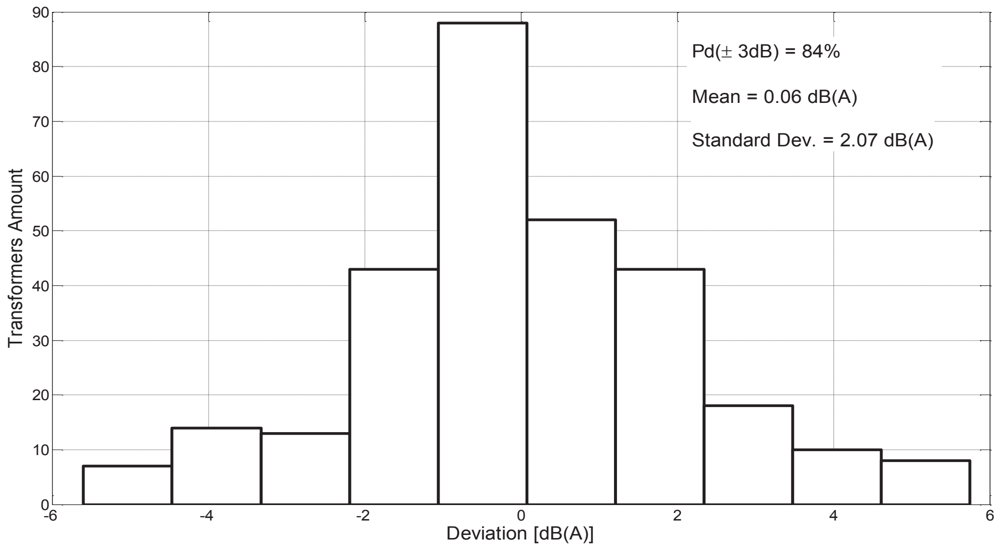

Figure 7 – Histogram of the deviation resulting of using all iron sheet types available

By taking a look on the direct influences of the new method on some of the transformers which were built in the past and have been redesigned over the past 2 years to decrease the deviation between the measured and calculated SPL, one can recognize the savings in material and cost resulting from this progress, due to the high accuracy of the new method as shown in Table IV.

Table IV – Effect of new method on core material savings

Transformer data	Built in	Rebuilt in	Iron savings [kg]
40MVA 115/10.5 kV ONAN/ONAF Guaranteed = 71 dB(A)	2007 Sound Power = 70.9 dB(A)	2011 Sound Power = 68.7 dB(A) Optimized to Sound Power = 70.2 dB(A)	797
25MVA 115/6.3 kV ONAN/ONAF Guaranteed = 66 dB(A)	2007 Sound Power = 65.6 dB(A)	2011 Sound Power = 64.0 dB(A) Optimized to Sound Power = 65.5 dB(A)	299

4. CONCLUSION

The method introduced in this paper permits to optimize the transformer core design under different operating conditions, and market and environmental requirements. Thanks to the high accuracy of the system and the elimination of almost any risk, it is now possible:

- to choose the right quality for each design.
- to have a starting point for new sheets.
- to optimize an existing design for any change in requirements.
- to identify the iron sheets with their magnetostriction characteristic values.
- to avoid in advance any critical deviation offset (DOS).

The good co-operation between SGB and its iron sheet manufacturers has played an important part in reaching that stage of developing a completely self-constructed algorithm which is able to cover all the previous aspects. The available data were separately analyzed based on the operational frequency (50, 60 and 16,667 Hz). However a simple offset might be sufficient to change over between 50 and 60 Hz.

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