Developing an Accurate Load Noise Formula for Power Transformers

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Developing an Accurate Load Noise Formula for Power Transformers

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Abstract **-- A thorough investigation of the design parameters influencing the load noise generated by power transformers is performed. The investigation is done through evaluating the calculated noise by using an advanced vibro-acoustic model and benchmarking it against measured sound levels of transformers with different ratings and designs. The design parameters are weighted based on their level of influence on the generated noise and are used to drive a detailed load noise formula (d-LNF). The d-LNF is further developed by weighting the most relevant parameters to drive a simplified LNF. Both formulas have proven their reliability in calculating the load noise and therefore, they have been used in the daily designs to optimize for low noise transformers. However, the advantage of the LNF is that it can be easily exchanged between transformer manufacturers and utilities as it involves the main electrical design data without details about the designs of winding, shields, tank and insulations.**

Index Terms**—Load noise, Short-circuit test, Sound power level, Power transformers, Vibro-acoustic.**

I. INTRODUCTION

With the increase of the demand for energy, due to the increase in population and economic development, all power grid sectors (generation, transmission and distribution) are accordingly expanding. Power transformers as vital components within the power sectors are increasing in number and rating to fulfill the energy demand. Parallel to that, inhabited areas are continuously expanding, and hence, are closer in proximity to power stations. The noise emitted by power transformers, therefore, is becoming an issue.

Controlling and/or mitigating the generated noise by power transformers during normal and extreme operating conditions is important. Enormous efforts are utilized by manufacturers to achieve low noise transformer designs. The noise emitted by a transformer in operation consists of a no-load and load part. No-load noise can be measured during factory acceptance tests (FAT) with an open circuit test, which will magnetize the core and yet produce the core or no-load noise. Load noise can be measured with a short circuit test during FAT in which one winding will be shorted and the short circuit voltage will be applied to the other winding to circulate the rated current through the windings and yet produce the winding noise (load noise). The operation noise, however, is the logarithmic summation of both load and no-load noise. The trend in the power industry is to guarantee a no-load and operation noise level of a transformer.

With the increase of power transformer ratings and the decrease of no-load noise due to the improvement in core steel, the load noise is becoming more dominant in comparison to no-load noise. The design of the winding is an important parameter on the generation of load noise as the load noise is generated by the winding itself. However, the connection of the winding to other components of the active part by using different clamping structures can have a significant effect on the generated noise. The tank of a power transformer is a bulk of mass that can amplify or de-amplify the structure-borne sound wave during transmission process. Different materials of tank shields are normally used to control the stray flux and prevent it from penetrating the tank. Nevertheless, improper shield design can lead to increase of the generated noise due to amplifying the tank vibrations and/or exciting the tank resonance [1].

Many design parameters relevant to load noise are still unknown. According to standards [2], [3] the load sound power level is calculated as $\mathrm{Lwa} = 39 + 18\log 10(S_r/\mathrm{MVA})$. This formula, which was first presented by Reiplinger [4], predicts the load noise as a function of transformer rated power S_r but does not account for the winding design, clamping and the electromagnetic forces in the winding, shields and tank walls. Comparing the sound levels calculated by the formula with measurements of a wide range of power ratings shows a deviation of 5-10 dB, and therefore, different manufacturers proposed to add 10 dB to envelop all the measured data [5]. This indicates that in addition to the rated power, other parameters are important contributors on the generated load noise and need to be investigated. In order to investigate the parameters influencing the load noise generation in power transformers, an advanced vibro-acoustic model was developed [6]. The model solves the dynamic response of the transformer winding set under the periodic electromagnetic forces.

In the current study the vibro-acoustic model presented in [6] has been further developed to include the contribution of other transformer parts on the total generated noise in addition to the winding set. The included parts such as; clamping-structure, tank and shields are mechanically, acoustically and/or electromagnetically coupled to the winding during operation. The acoustical part of the vibro-acoustic model calculates the radiated sound by integrating the averaged vibration components over the exposed area of each single conductor of the winding. The investigation is performed through evaluating the calculated sound levels by using the developed vibro-acoustic model and benchmarking against measured sound levels of transformers with different power ratings and designs. The design parameters are weighted based on their level of influence on the generated sound and are used to drive a detailed Load Noise Formula (d-LNF). The d-LNF is developed further by accounting the most relevant parameters only to derive a Load Noise

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Formula (LNF). Both d-LNF and LNF have proven their reliability in calculating the sound level and therefore, it has been used in the daily designs to optimize for low noise transformers.

II. MODELLING

The developed vibro-acoustic model handles multi-winding arrangements with different winding designs and clamping rings. The model solves for the vibration frequency response function (FRF) of the three vibration components (axial, radial and tangential). The winding vibration is mainly calculated by axial, radial and tangential models which are describing the vibration response in the respective coordinate system. The inputs for the model are the winding geometries, the electro-magnetic force per element, and the effective material properties.

The axial dynamic response of power transformer winding is mathematically modelled with a set of physical assumptions and boundary conditions. The geometrical structure of the winding consists of stranded or solid copper insulated with craft paper and axially stacked or spaced with radial key spacers and/or radially with axial sticks. Each conductor in the winding is setup as a mass-spring-damper system. Each axial element (conductor or disk) represents a mass. The stiffness is the equivalent of the conductor material, insulation and spacer. In general, windings are only axially coupled via an upper and lower clamping ring.

The equation of motion (EOM) in multi-degree of freedom (MDOF) of the mass-spring-damper system for the winding elements and the clamping rings is represented by applying Newton's second law of motion and Hook's low in a matrix form. Applying the steady state solution of the EOM in the frequency domain, the vibration FRF at any desired element is calculated.

The radial and tangential vibrations are modelled by assuming the winding conductors as elastic rings with zero sliding between stacked rings. The radial and tangential vibrations FRF of the rings under periodic loading are calculated.

The acoustic part of the vibro-acoustic model calculates the radiated sound by integrating the three-dimension vibration components over the exposed area of each single conductor of the winding.

The vibro-acoustic model calculates the natural frequencies, mode shapes and the generated noise per winding set. It is capable to distinguish between different design parameters such as,

- Electromagnetic forces
- Winding types (Disk, helical or layer),
- Winding geometry,
- Cooling duct layout (number and orientation),
- Radial and axial magnetic gaps,
- Multi winding arrangements (including tap positions),
- Winding and insulation material properties.

Additional to the previously mentioned parameters, the model involves tank and shield designs as they are mechanically, acoustically and/or electromagnetically coupled to the winding during load operation. Furthermore, the clamping pressure, as an effective parameter on the generated noise [6], is inserted in the model as a function per winding type.

III. DERIVATION OF THE DETAILED LOAD NOISE FORMULA

The design parameters are weighted based on their level of influence on the generated noise of a wide range of transformers with different designs and ratings. This is done by analyzing the trends between the vibro-acoustic model and measured sound levels. The investigated design parameters are as follows:

A. *Rated power*

The rated power S_r is expressed as,

$$S_r = I^2 Z \quad [MVA] \tag{1}$$

The rated power correlates to the rated current square I^2 which is directly proportional to the electromagnetic forces in the winding. Thus, the rated power is the most effective parameter for the load noise. This is the reason why Reiplinger's formula is working. However, the accuracy is not enough as it will be shown later. The base impedance Z has only information of the rated current and rated voltage.

B. *Short circuit impedance*

The short circuit impedance ($u_k\%$) is found to affect the load noise with same level as the rated power. The physical interpretation of the high influence of the $u_k\%$ is as follow.

For power transformers the reactance X is dominant over the resistance R. Therefore, the complex power is equal to the reactive power, and the base impedance Z is equal to the reactance X.

The short circuit impedance u_k is the percentage leakage reactance $\%X$,

$$u_k = \%X = \frac{X}{Z}100 = \frac{IX}{V}100 \tag{2}$$

The reactance X of power transformer during short circuit operation, which refers to the primary winding is,

$$X = \frac{V^2}{S_r}\frac{u_k}{100} \quad [\text{Ohm}] \tag{3}$$

Where, V is the rated voltage. The reactance is calculated by the connection of the magnetic energy and the inductance relation. The magnetic energy in a winding set shown in Fig. 1 is the sum of the magnetic volumes of the circular truncated cone of LV and HV windings and the main gap g [7].

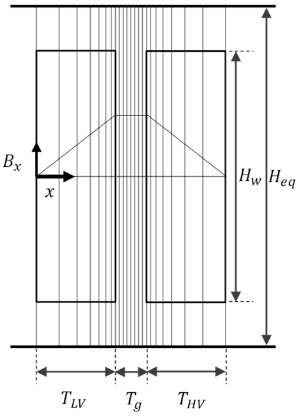

Fig. 1. Leakage field with equivalent height and Magnetomotive force diagram (H: height, T: thickness, and B_x: axial flux density)

The term $S_r u_k$ represents the short circuit reactive power is calculated as,

$$S_r u_k = IV\, 2\pi f \frac{\mu_0 \pi I N^2}{H_{eq} V}\left[\frac{1}{3}(T_{LV}+T_{HV})+T_g\right] D_m 100 \qquad (4)$$

where, D_m is the mean diameter of the winding set, f is the power frequency, N is the no. of turns μ_0 is the relative permeability, and H_{eq} is the equivalent or magnetic height. Analyzing $S_r u_k$ by dividing it into set of parameters,

$$S_r u_k \sim \left\{200\pi^2\mu_0, f, (IN)^2, \left[\frac{\left(\frac{1}{3}(T_{LV}+T_{HV})+T_g\right)D_m}{H_{eq}}\right]\right\} \qquad (5)$$

or,

$$S_r u_k \sim \left\{\begin{matrix} Constant, Frequency, Magnetic\ Energy, \\ Winding\ Geometry \end{matrix}\right\} \qquad (6)$$

As a result, inserting the $S_r u_k$ term instead of only S_r will add a big advantage for load noise calculation, as it has the information of the frequency, magnetic energy, leakage flux and winding geometry. In addition, the term $S_r u_k$ considers both network and autotransformers.

C. Winding geometry

The winding geometry (WG) parameter in the reactive power $S_r u_k$ indicates the magnetic effect only. To include the mechanical effect of the winding geometry, a standalone parameter is required. The mechanical winding geometry parameter involves diameters and axial heights of the winding arrangement. By benchmarking the vibro-acoustic model and the measured noise values an index value is found. The WG index of each individual winding within the winding set is determined. The actual design WG is normalized to the WG index. Finally, the WG can indicate which of the vibration components (axial or radial) dominates the generated noise.

Additional to the mechanical effect of the WG on the generated noise, the parameter has information of the current density J in the winding conductors and the magnetic energy content ratio in each winding to the total magnetic energy in the winding set (windings and main gap).

D. Winding type

The winding type (WT) parameter is investigated for different types of windings such as disk, helical or layer. It is found that the noise performance of the disk type with radial spacers is comparable to the helical winding, whereas the noise performance of the disk type without radial spacers is comparable to a layer type. Thus, the WT parameter represents insulations, spacers and cooling duct orientation influence.

E. Winding material

The winding material (WM) parameter has the information of the equivalent mechanical properties of the winding conductors. This includes the effect of different types of insulations (fluid, paper, spacer, …etc.) on the mechanical properties of the conductor material.

F. Winding surface

The winding surface (WS) parameter describes the winding area exposed to the insulation fluid normal to the vibration components. Therefore, the WS parameter represents insulations, spacers and cooling duct number.

G. Shield design

Material and geometry of shields are covered by the shield design parameter (SD). Different types of shields such as nonmagnetic, active and passive magnetic shields are investigated. Finally, discrete and/or continuous functions are derived for each shield type.

H. Tank design

The effect of the tank design (TD) on the generated noise is investigated. It is found that the tank design can have a significant effect on the noise as it influences the behavior of the tank during the load operation whether it amplifies or de-amplifies the generated noise of the windings [1].

I. Clamping force

The effect of the clamping force (CF) applied on the winding set on the generated noise is investigated. It is found that depending on the winding type, the clamping force can improve or worsen. Therefore, an optimum clamping force value is required for a low noise design [6].

All the above-mentioned parameters are investigated with the vibro-acoustic model and their influence on load noise is weighted by introducing index and exponents factors matrices.

The detailed form of the load noise formula in terms of sound power level that accounts for all the investigated parameters is,

$$L_{wa} \sim (S_r, u_k, WG, WT, WM, WS, SD, TD, CF, [A], [\alpha]) \qquad (7)$$

L_{wa} Sound power level [dB(A)],
$[A]$ Index factor matrix of all parameters,
$[\alpha]$ Exponent factor matrix of all parameters.

Although the d-LNF accounts for the design parameters relevant to generated noise, which has been proven its high accuracy in calculating the load noise as it will be shown in the validation section, is easier in implementation than the vibro-acoustic model. Nevertheless, it is still reliable for internal use, as most of the design parameters are manufacturer internal know-how and not for share.

IV. LOAD NOISE FORMULA

The d-LNF is further developed by weighting only the most relevant parameters to drive a simplified LNF. The LNF is written in a form to be able to calculate both sound power L_{wa} and sound pressure level L_{pa}. To determine the sound power level, a conversion factor to account for the measurement contour path around the tank is required.

The Load Noise Formula is,

$$L_{wa} = L_{pa} + TF \qquad (8)$$

L_{pa} Sound pressure level [dB(A)],
TF Tank factor (used to convert L_p to L_w by estimating the measurement contour path around the tank) [dB].

By defining the components as follow,

$$L_{pa} = a\,log_{10}(S_r\,u_k) + L_f + L_o \tag{9}$$

$S_r\ in[MVA]$ & $u_k\ in$ [%]

a Scale factor,

L_f A-weighted frequency filter conversion factor. The reference frequency is 50 Hz (0 for 50 Hz and ~2.4 for 60 Hz) [dB],

L_o Other parameters influencing the noise (e.g. number of phases, number of main/return core limbs, temperature, shield, fluid type …etc.) [dB].

Physically, the scale factor a must be less or maximum equal to 20. The scale factor of a decibel logarithmic equation ($10\,log_{10}$) like (9), represents the exponent factor of the term $S_r\,u_k$. An exponent value of 2, which gives a scale factor of 20, means the rated current I^2 or the magnetic energy $(IN)^2$ parameters, which correspond to the electromagnetic force, have an exponent of 2. This is the maximum theoretical limit for a transformer load noise without any consideration to the internal design parameters, where $dB{\sim}F^2$. Therefore, a range of 17-19 is more suitable for the scale factor a. For the current investigated transformer range, a value of $a = 17.5$ is found to achieve the best trend and mean matching with the measured points.

The L_{pa} formula (9) is part of (8) which can be used separately to calculate the sound pressure level in dB(A).

The tank factor TF is expressed in a logarithmic equation as,

$$TF = b\,log_{10}(S_b) + c \tag{10}$$

The building power S_b is used to indicate the tank factor. It has information of the loss performance of power transformer which defines the cooling system dimensions, and hence the tank design. The scale factor b =2.7 and offset factor c = 15 are found to cover all possible ranges of the noise measurement contour path around the tank to convert L_p to L_w with building power range of S_b =10-125 MVA, Fig 2.

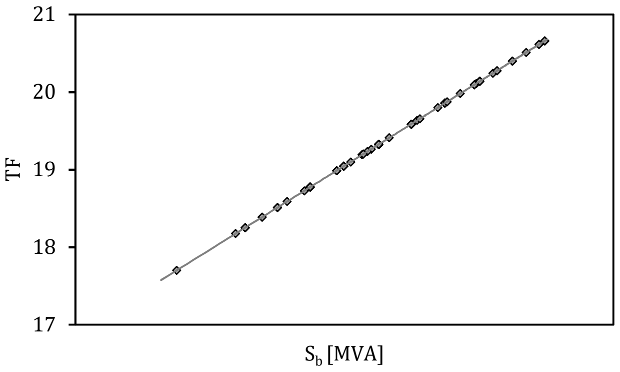

Fig. 2. Tank factor range used to convert L_p to L_w of the investigated units.

The final form of the Load Noise Formula can be written as,

$$L_{wa} = \left[a\,log_{10}(S_r\,u_k) + L_f + L_o\right] + b\,log_{10}(S_b) + c \tag{11}$$

V. VALIDATION

In order to evaluate the accuracy of the newly developed formulas (d-LNF and LNF) in comparison to Reiplinger, all are compared against measured noise data set of units with different designs, power ratings and short circuit impedance. Fig. 3 shows the evaluation of the measured noise data against Reiplinger formula which calculates the load noise as a function of rated power S_r only. It is clear that the deviation is high and the trend is different. The units with same power rating and different designs are inaccurately calculated by Reiplinger and they show a span of about 15 dB(A). Adding 10 dB to Reiplinger formula has proven the advantage of enveloping all the measured data.

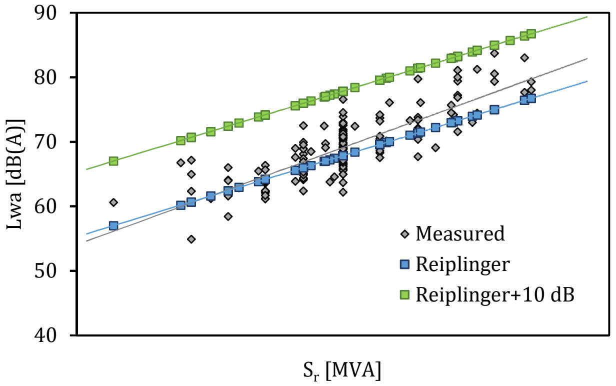

Fig. 3. Evaluation of the calculated sound levels with Reiplinger's formula against the measured data.

Fig. 4 shows the evaluation of the calculated sound levels with d-LNF, which accounts for the most relevant parameters, against the measured data. The mean and the trend of the d-LNF data show an obvious improvement against measured data in comparison to Reiplinger. Thus, the units with same power rating and different designs are more accurately calculated by the d-LNF.

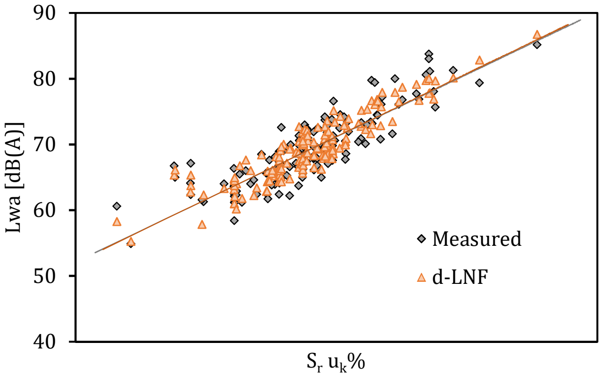

Fig. 4. Evaluation of the calculated sound levels with d-LNF against the measured data.

Fig. 5 shows the evaluation of the calculated sound levels with LNF, which accounts for the most relevant parameters, against the measured data. The mean and the trend of the LNF data show an obvious improvement against measured data in comparison to Reiplinger. Thus, the units with same power rating and different designs are more accurately calculated by the LNF than Reiplinger but less accurate than the d-LNF.

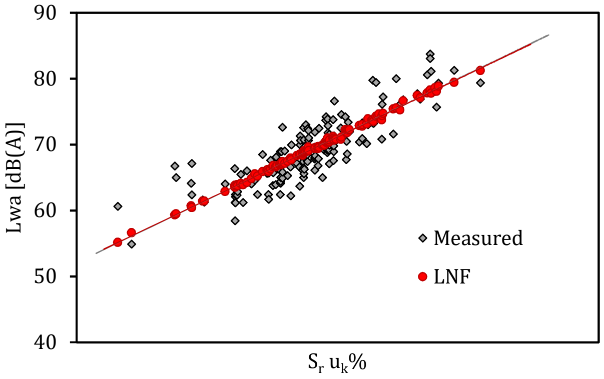

Fig. 5. Evaluation of the calculated sound levels with LNF against the measured data.

The statistical analysis of Reiplinger's formula, d-LNF and LNF is done by presenting the frequency of the data occurrence within 20 bins of 1 dB and a range of ±10 dB as shown in Fig. 6.

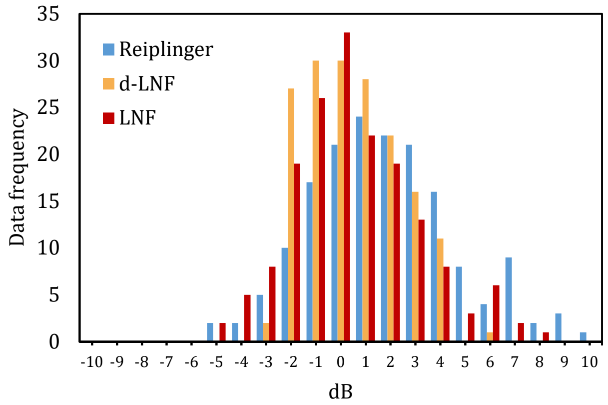

Fig. 6. Frequency of the data occurrence within 20 bins of 1 dB

The probability and the cumulative density functions for the normal distributions of the deviations from the measured data are shown in Fig. 7 and Fig. 8, respectively.

The Reiplinger' formula probability and cumulative curves are shown to be flatter than both d-LNF and LNF, with a positive right-side tendency. Both the d-LNF and the LNF data have higher probability and faster growth cumulative curves than Reiplinger which indicates high probability in calculating within ±σ. The standard deviation σ is lowest by d-LNF and higher by LNF and highest by Reiplinger.

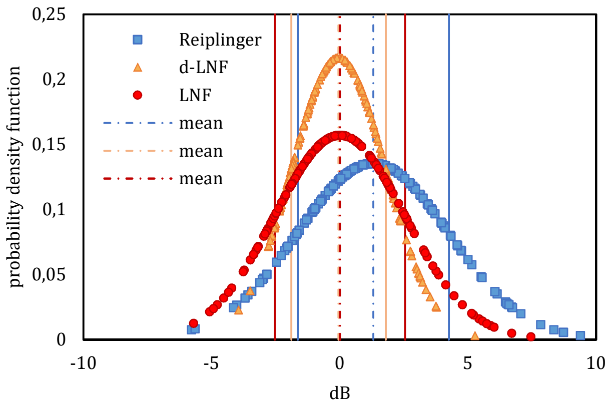

Fig. 7. Probability density functions of the data deviations (measured-calculated)

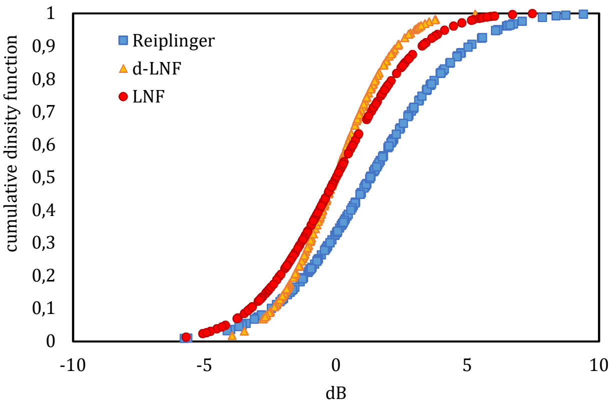

Fig. 8. Cumulative density functions of the data deviations (measured-calculated)

The statistical parameters of all formulas are listed in Table. 1. The negative kurtosis with the low standard deviation σ value of the d-LNF indicate a high number of data points within a small range of $\pm\sigma$, whereas the positive kurtosis with a higher standard deviation value of the LNF indicates a low number of data points within a small range of ±σ. However, it also indicates more data of minimum deviation within a narrow band of ±1 dB. Furthermore, the smaller values of the range, maximum and minimum of d-LNF and LNF prove the improvement in calculating the load noise compared to Reiplinger's formula.

TABLE I

STATISTICAL PARAMETERS OF THE THREE FORMULAS

	Reiplinger	d-LNF	LNF
mean	1.31	-0.05	0.01
standard error	0.23	0.14	0.20
Median	1.11	-0.22	-0.25
standard deviation	2.95	1.84	2.54
Sample variance	8.67	3.39	6.46
kurtosis	0.02	-0.65	0.12
skewness	0.36	0.33	0.48
Range	15.18	9.23	13.16
minimum	-5.77	-3.95	-5.70
maximum	9.40	5.28	7.46
summation	218.52	-7.83	1.33

The advantage of the LNF is that it calculates the load noise sound pressure and power levels in one formula with a high accuracy as compared to the current standard Reiplinger's formula. Furthermore, it accounts for the following:

- All types of transformers such as network and Autotransformers,
- Winding design,
- All tap positions,
- Any power frequency,
- Magnetic energy,
- Leakage flux.

VI. CONCLUSIONS

The design parameters influencing noise generated by power transformers are investigated and used to develop a detailed load noise formulas d-LNF. The d-LNF has proven its reliability in calculating the load noise, and therefore, it has been used in the daily designs to optimize for low noise transformers. The d-LNF is further developed by weighting only the most relevant parameters to develop a simplified LNF. The advantage of the LNF is that it can be easily exchanged between transformer manufacturers and utilities as it involves the main electrical design data without details about the designs of winding, shields, tank and insulations. Furthermore, the LNF calculates the load noise sound pressure and power levels in one formula with a high accuracy as compared to the current standard Reiplinger's formula.

VII. ACKNOWLEDGMENT

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IX. BIOGRAPHY

Ali Al-Abadi graduated from the University of Baghdad, Iraq in 1997 for B.Sc. and in 2000 for M.Sc. He received his Dr.-Ing. degree from Friedrich-Alexander-University, Erlangen, Germany. From 2010 to 2015 he worked as research assistant and research associate at the same University. He was responsible for industrial projects. Ali joined SGB Power Transformers (SGB-SMIT Group) located in Regensburg, Germany in 2015. Since then, he has been working as a Senior Expert and Team Leader of R&D Projects. His main experiences are vibro-acoustics, thermo-fluids, losses and magnetic-field calculations of power transformers. Ali is an active member of IEEE, DAGA and ASME, and a participant member in the CIGRE working groups. He has been publishing, presenting and reviewing many scientific and technical papers in the international conferences and peer review journals. Ali is an active contributor in power transformers and wind energy sectors.