Abstract

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**Power transformers typical audible noise spectra and new approaches for noise optimization**

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Abstract—This paper presents power transformer audible noise spectra according to manufacturer experience. After having introduced origin of noise spectra and influent parameters, it is observed that the knowledge of typical transformers’ spectra associated to grain-oriented steel (GOS) performances related to flux density levels can help to significantly reduce overall no-load noise levels. Keywords—Power transformer; Audible noise; Spectrum; Grain-oriented steel; Optimization I. INTRODUCTION Power transformers are noisy apparatuses installed ever more frequently in densely populated areas. Environmental laws of many countries as well as utilities legal obligations lead to a continual increase for low-noise solutions demands. The most typical requirement concerning transformers’ sound performance is the overall sound power level, measured in decibels A-weighted (dB(A)). This physical amount characterizes the noise...
source and is the principal input allowing the assessment of environmental noise impact caused by substations’ loudest equipment. However, transformer audible noise spectrum gives enhanced information enabling a more accurate estimation of sound levels in substations’ vicinity, as sound propagation laws are frequency-dependent. Furthermore, the tonal character of power transformer noise is a recognized source of annoyance for people exposed to substation noise emissions, conducting some countries to specify tonality criteria. It is intended to present typical noise spectra of power transformers by focusing on no-load contribution. Authors have identified through the study of about 100 different transformers noise spectra measured during factory acceptance tests (FAT) to define trends concerning no-load noise dominant frequencies components. The knowledge of these trends associated as well as grain-oriented steel (GOS) noise characteristics regarding transformers’ flux density level allows the power transformers manufacturer to optimize overall noise levels by selecting relevant GOS grades and suppliers, to design transformers with optimized flux density. Furthermore, it is observed that optimization of overall noise levels leads to harmonize levels of each harmonic, hence reducing tonal emergence and improving by this way substations’ neighbors’ comfort. II. TYPICAL POWER TRANSFORMERS NOISE SPECTRA Power transformers audible noise is a well-known example of annoying noise source, for overall levels radiated in the environment as for spectral composition. Indeed, its typical spectrum considering no-load and load components is dominated by low frequencies, which are considered harder to attenuate than high frequencies with conventional screening methods. Moreover, it presents distinct tonalities at twice the network frequency and related harmonics, which is perceived as a disturbing noise source independently of overall levels as studied in [1]. In operation, power transformers emit audible noise produced by three major sources: characteristic no-load and load contributions as well as cooling devices sound emissions mainly caused by aeracical phenomena and generally considered as broadband source. No-load and load components have a particular spectrum, influenced by several parameters related to transformers’ electrical and mechanical designs. Fans and pumps sound levels and spectra aren’t covered in this article as they belong to specialized manufacturers expertise. A. No-load noise spectra Power transformers radiate no-load noise as soon as they are energized, i.e. when their cores are magnetized even if electrical power flowing inside tends to be nil. This is the dominant contribution for power transformers intermittently loaded such as interconnection transformers. Transformers no-load spectra consist of a pure-tone comb where the fundamental frequency is twice as the network frequency, namely 100 Hz for 50 Hz networks and 120 Hz for 60 Hz networks. Almost all multiples of fundamental frequency admit significant sound levels, up to high harmonics for some cases. Figure 1 presents an example of no-load noise spectrum measured around a 600 MVA step-up transformer according to IEC 60076-10 standard procedure during audible noise FAT, using a narrowband filter: Fig. 1. Example of no-load noise spectrum It can be observed that low order harmonics are dominant and that harmonics amplitudes are decreasing with increasing frequencies, which is very typical for power transformers no-load noise. Frequencies above 3000 Hz don’t participate to overall levels at all, and more generally frequencies over 1000 Hz are generally not of interest for characterizing transformer no-load noise. A review of parameters influencing spectra composition will be presented in the next section, while typical relative dominance of low order harmonics will be introduced by authors in the last section. B. Load noise spectra Load noise is generated by transformer windings and varies with the current flowing in transformer. It is historically considered as second order contribution compared to no-load noise. However, large power transformers such as step-up units are dominated in some cases by load component. Load noise spectra almost exclusively consist of a pure tone at double network frequency. Figure 2 shows an example of load noise spectrum measured around a 600 MVA step-up transformer (same unit as Figure 1) according to IEC 60076-10 standard procedure during audible noise FAT, using 1/3 octave band filter: Fig. 2. Example of load noise spectrum III. TRANSFORMERS NOISE LEVELS AND SPECTRA INFLUENT PARAMETERS A. No-Load noise spectra No-load noise is composed by the combination of magnetostriction phenomenon created inside power transformers core laminations and Maxwell forces existing in gaps between laminations, particularly at cores’ corners level. GOS laminations magnetostriction characteristics can be determined with Epstein frames or single sheet testers in conjunction with vibrations acquisition systems. Measurement results enable the comparison of the performances of different GOS grades and suppliers; but they don’t allow the prediction with good accuracy of transformers overall noise levels and spectra due to the influence of core geometry as well as stacking and corner architectures, as observed in [2]. Level and frequency composition of magnetostriction vary with flux density levels with a non-linear behavior. This is widely studied in the literature for instance in [3] and depends mainly on GOS manufacturing processes. The clamping forces applied on laminations as well as their distribution along cores are also a significant parameter influencing no-load noise emissions. [4] shows that clamping level affects noise emitted by cores in a complex way: evolution of harmonics levels regarding compressive stress measured on a model core isn’t following trends established during magnetostriction measurements. Furthermore, core types, dimensions and geometries have an impact on main vibration modes, which could in case of coincidence with transformer no-load noise harmonics create severe amplification of vibrations and no-load noise levels. B. Load noise spectra influential parameters Load noise consists of two main sources: windings and magnetic shunts or shields fixed on tank walls. Windings’ load noise is caused by the interaction between stray field originated from one winding with other windings carrying current. This phenomenon creates reaction forces on winding conductors, which in response vibrate mainly at twice the magnetizing frequency. These Lorentz forces are influenced by active part and windings designs as well as current density in main windings. Transformer load noise characteristics also depend on windings’ clamping pressure and distribution, as well as internal constitution, in particular the presence of solid insulating material and overall dimensions which influence the modal behavior. Magnetic shunts or shields implemented on tank walls contribute significantly to load noise amplitudes as these vibration sources are directly connected to the radiating structure. C. Other influencing parameters Several other parameters have an influence on power transformers noise levels and spectra. First, the conversion between vibration sources and noise radiated in the environment depends on the ratio of energy transmitted through structure and fluid (insulating oil) paths.
Then the tank design plays a fundamental role in the global noise radiation process, as their shape and damping properties will selectively amplify or attenuate certain harmonics. Furthermore, elements like radiators or control cabinets located around the tank can also influence the acoustic field around power transformers. The excitation waveshapes (voltage and/or current) can significantly affect the transformer noise for both the overall levels and the frequency composition; especially in presence of DC or when the current contains a high level of harmonics, such as in HVDC applications. Finally, noise measurement procedure and environment can themselves influence transformer spectra, such as the near-field effect increasing artificially low frequency components, as discussed in [5].

IV. NO-LOAD NOISE OPTIMIZATION BY GRAIN ORIENTED STEEL GRADE AND FLUX DENSITY SELECTION

Taking into account all previously reported parameters of influence, it should be judged that magnetostriction measurements can’t be directly used to estimate power transformers no-load overall noise levels and spectra. According to the manufacturer’s experience, dominant factors affecting no-load noise emissions are GOS grades, GOS manufacturing processes associated to each GOS supplier and the core flux density, as long as other parameters linked to core design are already optimized.

The impact of these parameters on transformer no-load noise performances can be determined thanks to the knowledge of overall and each dominant harmonic level regarding flux density variation on the one hand, and thanks to the knowledge of typical noise spectra of power transformers on the other hand. Indeed, a proven solution to reduce transformer no-load noise overall levels consists in decreasing its flux density. However, this measure won’t lead to the same noise reduction when applied to small or large power transformers or when GOS grades/suppliers A, B or C are used.

A. Variation of noise spectra regarding flux density variation

Transformer manufacturers can characterize variation of noise levels and spectra regarding flux density levels during FAT. Fig. 3. Evolution of no-load noise spectra with variation of flux density (B). This figure shows an example of sound intensity spectra measurement results from a 40 MVA transformer excited at various flux density levels. In this example, a relative linearity is observed between each harmonic noise levels increase and flux density increase. This is particularly visible for 100, 200 and 315 Hz components. On the contrary, 630 Hz 1/3 octave band level increases a lot between 1.1T and 1.2T, then remains relatively stable between 1.2T and 1.7T before raising significantly beyond to become the dominant component. This example taken from a medium power transformer noise characterization illustrates the complex behavior of the transformer harmonic noise levels with respect to flux density variations. For some GOS grades and suppliers, certain flux density ranges will admit stable noise levels, while for some other ranges overall levels will increase significantly, particularly when approaching core saturation.

B. Determination of typical no-load noise spectra

The authors propose defining typical transformers no-load noise spectra by analyzing the noise measurement database collected during noise FAT. As described in [6], for 50 Hz systems, power transformer fundamental tone and dominant harmonics coincide well with useful width of 1/3 octave bands up to 500 Hz band. Furthermore, transformer manufacturers experience shows that almost all sound energy is comprised between 100 and 630 Hz 1/3 octave band components for all types of power transformers. Consequently, this allows to extract relevant information concerning no-load noise spectra from 1/3 octave band spectra measurements.

A database comprising no-load noise measurements from 100 transformers with different electrical and mechanical designs has been collected, representing a broad production range, from 25 to 600 MVA. All transformers are equipped with high permeability steel grades coming from various suppliers. Their flux density levels cover a range between 1.28 T and 1.75 T and are evenly distributed with an average value of 1.55 T. The consideration of a database of transformers built in the same factory, with the same design principles, same manufacturing processes and tested in the same test laboratory ensures to get limited variation between some of the influencing parameters and then helps to define reliable trends for noise spectra. However, the results presented in this section don’t intend to be representative of power transformers spectra in general, as technologies and manufacturing aspects vary considerably between transformer manufacturers. From the measurements database, the variation of each dominant harmonic from 100 Hz to 630 Hz regarding overall levels compared to transformer building power is determined by using linear approximations. In Figure 4, the X-axis represents power transformers size through the building power in MVA, while the Y-axis represents the difference between transformers’ overall no-load level and each considered 1/3 octave band level. This means that the lower the curve the more dominant the harmonic is: Fig. 4. Relative dominance of main harmonics regarding transformers power. The graph shows that the average spectrum of power transformer no-load noise varies between small and large power transformers. Dominant harmonics are 200, 300, 500 and 600 Hz components for small transformers. Large transformers admit important levels for 300 and 400 Hz components. The defined trends are linear regressions and can be optimized by using more adapted approximation methods. However, the authors observed that these tendencies are still valid when parameters like flux density levels, core types and even GOS grades and suppliers in a lesser extent are isolated statistically. Defined trends admit important level of uncertainty, and these curves don’t pretend to allow valid predictions of power transformers spectra. But when similar curves optimized for each pair of GOS grade and supplier are combined with no-load noise levels regarding flux density level data, this allows the manufacturer to determine the more optimized GOS product for optimizing overall no-load noise for a given transformer power designed at a given flux density.

C. Example of no-load noise level optimization

This section illustrates through a practical example in which proportion it is possible to reduce overall no-load noise levels by selecting the optimized product. Fig. 5. Comparison of overall sound intensity levels for similar transformers manufactured with same grade coming from different GOS suppliers. This figure presents a comparison of the overall no-load sound intensity levels with respect to the flux density level variation for two identical 40 MVA transformers having the same design and the same GOS grade. The only difference is the GOS supplier, called “Supplier A” and “Supplier B”: A significant deviation is observed between overall no-load noise performance measured for flux densities between 1.2 T and 1.8 T. In this example, the highest noise reduction is measured at 1.4 T with a difference of 7 dB(A). More generally, the authors estimate that the overall noise reduction achieved by the selection of optimized GOS product at given flux density levels is in the range of 2 to 3 dB(A) compared to non-optimized process. The difference between GOS grades and suppliers noise
performance tends to disappear as the average flux density approaches saturation. Therefore, the proposed optimization method remains particularly efficient for moderate flux density levels between 1.3 T and 1.6 T and is then preferred for low-noise markets. To complete the analysis, Figure 6 shows the comparison of noise spectra for previous transformers at 1.4 T: Fig. 6. Comparison of no-load noise spectra for similar transformers manufactured with same grade coming from different GOS suppliers measured at 1.4 T excitation. In the chosen example, the overall noise reduction is significant, and each harmonic level measured for the transformer equipped with “Supplier A” product is improved compared with transformer equipped with “Supplier B” material. With this knowledge, each GOS product could be dedicated to a specific type of transformer. A given GOS product could be the optimized one for a 40 MVA transformer designed at 1.4 T and could be at the same time an inappropriate choice for designing a low-noise 600 MVA one designed at 1.6 T. Figure 6 shows that the transformer admitting the lowest overall no-load noise level (“Supplier A”) presents the flattest spectra at 1.4 T, i.e. main dominant harmonics (200, 300 and 400 Hz components) have relatively equal sound intensity levels. This point is verified through to many no-load noise spectra measured in this study. Consequently, it can be concluded that no-load noise optimization process is driven by the selection of flux density and GOS product combination providing flattest spectra. V. CONCLUSION Typical noise spectra of power transformers were introduced according to manufacturer practical experience. A set of parameters influencing no-load noise were presented. The most significant are the flux density levels related to GOS grades and suppliers. The knowledge of combined flux density variation regarding GOS products and power transformers’ typical noise spectra permits to optimize both no-load noise levels and spectra. The estimated overall no-load noise reduction is in the range of 2-3 dB(A). This performance is achieved by selecting appropriate GOS products and flux density levels to harmonize the levels of dominant harmonics. Thanks to this optimization process, annoyance linked with power transformer audible noise emission is reduced. [1] G. Di, X. Zhou and X. Chen, “Annoyance response to low frequency noise with tonal components: A case study on transformer noise”, in Applied Acoustics 91, 2015, pp. 40-46. [2] Pholphongviwat “Investigation of the influence of magnetostriction and magnetic forces on transformer core noise and vibration”, PhD Thesis, Cardiff University, August 2013. [3] M. Ishida, S. Okabe, T Imamura and C. Komatsubara, “Model transformer evaluation of high-permeability grain-oriented electrical steels,” in Journal of Materials Science & Technology, Vol. 16, 2000. [4] M. Mizokami and Y. Kurosaki, “Noise variation by compressive stress on the model core of power transformers,” in Journal of Magnetism and Magnetic Materials, N381, May 2015. [5] M. Ertl, H. Landes, “Sound power measurements in the near field of transformers” Proceedings of the Internoise 2012/ASME NCAD meeting, August 19-22, 2012, New York City, NY, USA. [6] “IEC 60076-10-1 Power transformers – Part 10-1: Determination of sound levels -Application guide”, Edition 2.0, March 2016.

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