The sound of silence

Designing and producing silent transformers

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Silence is a source of great strength. Although these words were first coined by the ancient Chinese philosopher Lao Tzu, they could equally well apply to modern power transformers. As important as these devices are in assuring our power supply, it is important not to ignore the negative sides of their operation. One of the major issues here is that they produce annoying noise.

Probably the strictest noise ordinance in the world is enforced in New York City. To be able to supply transformers for installation here, ABB had to meet extremely demanding requirements. Through the company's deep and detailed understanding of transformer vibrations and noise, it was able to fulfill these demands and is now well poised to supply low and ultra low noise transformers to other major cities, around the world.

Simple and friendly

Today, the world is showing increasing concern over environmental matters, and the minimization of noise in the vicinity of residential areas is one aspect that is growing in importance. Transformers exhibit vibrations while operating, and generate a characteristic hum classified as “noise” 1. This noise is characterized by mainly four pure tones, the frequencies of which are in the range of human speech 2. The noise, being of a marked tonal character, causes irritation and discomfort. It is hence important to assure that residential areas are not disturbed. This work is of especial importance in urban areas where houses are built very close to power-transmission and distribution-size transformers.

1 Noise level contours around a small substation with two 40 MVA transformers. Where such noise exceeds certain levels, it can be of great discomfort to humans.

In many countries, local and national governments have stipulated maximum permissible noise levels. These permissible levels vary in value from normal levels in rural areas, to lower values near large metropolitan cities, and to ultra-low values in some parts of New York City.

In order to fulfill these noise restrictions, it is necessary to understand the total process of sound generation, transmission and radiation. Such knowledge has enabled ABB to successfully design and build quiet transformers for customers in different parts of the world. Most recently, ABB delivered a number of ultra-low-noise transformers, referred to in this article as the “silent transformers,” to the ConEd company in Manhattan, NY, where the noise ordinance is the toughest in the world. This is discussed in more detail later in this article.

Noise level and frequency spectrum

Sound produces minute oscillatory changes in air pressure and is audible to the human ear when its level is above a certain threshold and the frequency of the pressure oscillations is in the 20 Hz to 20 kHz range. Sound level limitations are typically determined by the human perception of sound, which is both logarithmic and frequency dependent. For example, the human ear is ten times less sensitive to sound at 100 Hz than it is to sound at 1,000 Hz, and each doubling of the absolute sound pressure is felt as a small addition on the sound level. Sound is therefore measured in decibels (dB), where, a decibel is defined as 10 × Log10 (sound pressure). Sound levels are typically presented and specified in A-weighted decibels; dB(A), where the sound levels are attenuated according to their frequencies per an “A-filter,” which depicts the frequency response of the human ear 3.

There are at present industry standards (IEEE and IEC) that specify how transformer noise is to be measured. However, some customers require reporting of the total collective noise level of the transformer in dB(A), whereas others require reporting of individual frequency components. Some customers require measurement of only the core and fan noise, and some require measurement of the total noise level of the transformer, including load noise.

Transformer noise

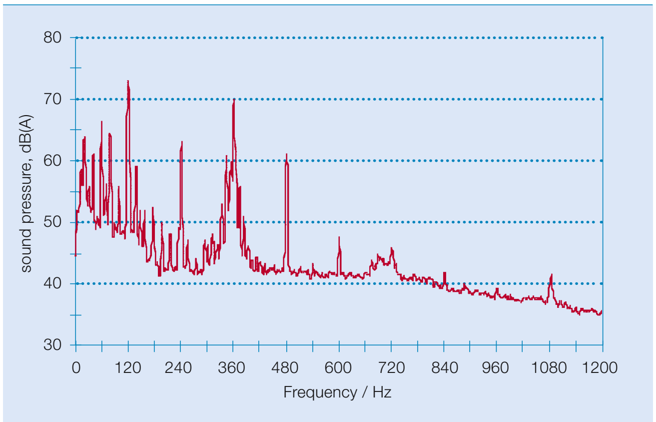
There are three sources of sound/noise in power transformers:

- Core noise, caused by magnetostriction effects
- Load noise, caused by electromagnetic forces in the windings and structural parts due to leakage flux associated with the current
- Noise generated by the operation of the cooling equipment, fans and pumps

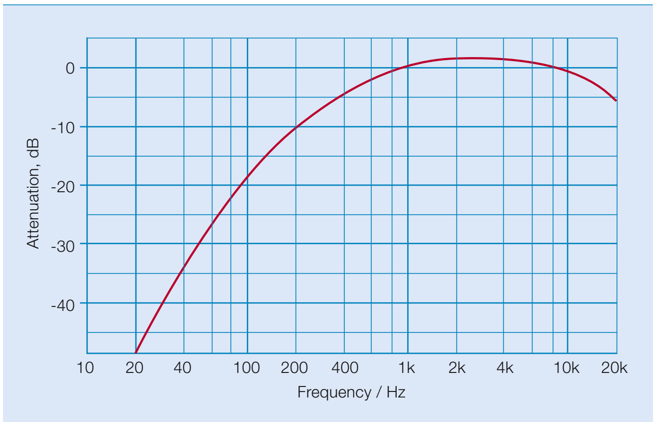
Core noise, caused by magnetostriction

Magnetostriction is a term used for the small mechanical deformations of

2 Typical frequency spectrum of noise produced by a 60 Hz power transformer



3 Frequency response of the A–weighting filter to sounds of different frequencies



core laminations in response to the application of a magnetic field. The change in dimension is independent of the direction of the flux and hence it occurs at double the supply frequency. However, because the magnetostriction curve is non-linear, higher frequency harmonics of even orders are introduced at higher flux densities 4. Therefore, core noise has components at multiples of 100 or 120 Hz (for 50 Hz and 60 Hz transformers, respectively). The relative magnitudes of the noise at these different frequency components is dependant on core material, core geometry, operating flux density, and how close the resonance frequencies of core and tank are to the exciting frequencies.

Load noise caused by electromagnetic forces

Load noise is mainly generated by the interaction of the load current in the windings and the leakage flux produced by this current. The main frequency of this sound is, therefore, twice the supply frequency; 100 Hz for 50 Hz transformers and 120 Hz for 60 Hz transformers. If the load current contains significant harmonics, eg, in rectifier transformers, the forces will contain higher frequency harmonics. These additional harmonics are a significant source of noise that must be considered when the transformer is ordered. The load current noise level is strongly dependent on the transformer load. Reducing the current by 50 percent provides a reduction of the load current noise by 12 dB.

Sound generated by cooling equipment

The frequency character of fan noise is different from the sound from the core and windings. It does not have discrete tones but covers a broad frequency band with a peak at the "blade passage" frequency, which is the frequency at which the fan impeller blades pass some rigid disturbance in the air flow – and sometimes at twice that frequency. Pumps also produce noise of a broad band nature and contribute to the total noise of the transformer.

Design features

Power transformers of ABB's present design generation, designated as TrafoStar, typically have noise levels that are significantly lower than those built 20 or 30 years ago. Some of the more important contributors to achieving these low levels of transformer noise are:

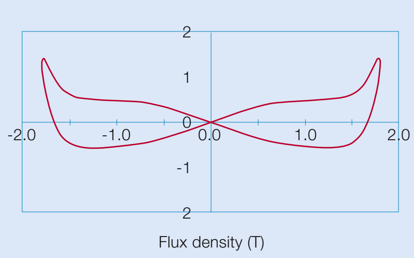
- Designing transformer cores to provide a more uniform distribution of magnetic flux with a lower content of flux harmonics globally in the core and locally in the core joints. Detailed 2-D and 3-D magnetic field modeling have been used to optimize core designs to minimize core noise 5.
- The core is held together by a clamping structure that provides uniform pressure on the core laminations while local deformations are avoided. ABB is using in-house developed tools to calculate the vibrations of the core considering different modes of vibrations and mechanical resonance as well as the complex forces exciting a three-phase transformer core 6.
- The TrafoStar tank is designed to avoid any unnecessary noise increase through its high radiation efficiency or tank resonance. Acoustic simulations, verified by scale models and full-size experiments, have provided the tools needed to avoid tank resonances and reduce sound radiation 7.

Lower-noise transformers

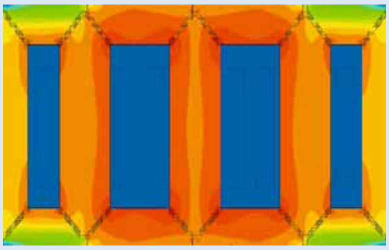
Lower core noise

In addition to seeking low magnetostriction, using steel with higher grades of magnetic orientation for the

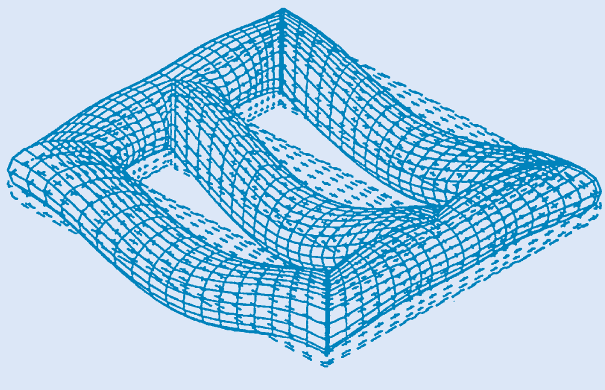
4 Example magnetostriction curve; relative change of core steel lamination length during a complete cycle of alternating flux



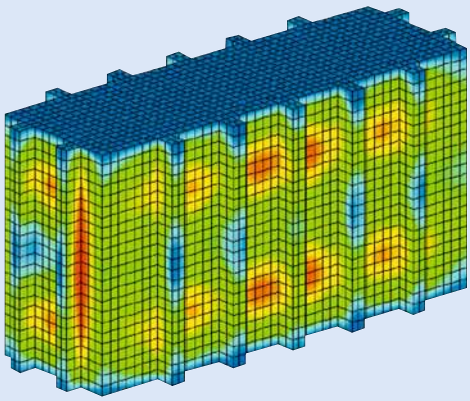
5 Magnetic flux distribution in a three-phase core



6 3-D modeling of mechanical vibrations of a three-phase core



7 3-D modeling of sound radiation from the tank of a three-phase transformer



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core and reducing the flux density in the core, noise from the core can be reduced by a number of other measures that have been developed over the years. These include:

- De-coupling of core vibrations from the transformer tank. In order to get good results from this, it is necessary to consider carefully the dynamic properties of the transformer core and of the transformer tank. The vibration isolation elements need to be properly designed.
- Avoiding both tank and core resonances. This necessitates accurately pre-determining values of the different core and tank resonance frequencies 8.
- Damping treatment of the tank.
- Using sound panels or enclosures covering parts of or the entire tank (for transformers that must fulfill especially low levels of noise).
- A number of new techniques that attempt to reduce the transmissibility of the core vibrations and hence the resulting sound radiation.

Lower load noise

Winding type, winding arrangement, current density, tank shielding / shunts, and tank design parameters have a significant effect on the magnitude of load noise. Extensive development work has resulted in the following measures for load-noise reduction:

- Using winding designs that generically provide for lower magnitudes of leakage flux density
- Avoiding winding resonance
- Improved tank shielding against leakage flux
- Damping treatment of the tank
- Improved tank design having lower sound radiation properties
- Sound enclosures covering the entire tank

Lower cooling–system noise

Noise from cooling fans can be reduced by selecting low-speed fans or fans with sound-absorbing elements at the inlet and outlet. Other means include special fan or blade designs with improved noise performance. In many cases, in which very strict noise requirements apply, fan noise is eliminated by designing the transformer with more radiators instead of fans. When cooling pumps are required, pumps with low noise emission are adopted.

ConEd transformer requirements

In order to satisfy the harsh limits that the NYC Noise Ordinance has imposed on all sources of noise in the city, ConEd's electric equipment department has revised its noise specifications for new power transformers. These specifications ensure ultra-low-noise transformers in the ConEd power system. These specifications have the following very stringent requirements:

1) 15 to 20 dB lower than typical for these sizes of transformers
2) Guarantee noise levels are not exceeded at:
   a) 100 percent voltage combined with 100 percent load
   b) Maximum over-excitation combined with 40 percent load
3) Limits govern not only total noise levels but also each individual frequency component

The maximum allowable limits of the frequency spectrum of the total noise of the transformer (sum of no-load and load noise) for the three most important frequency components of the transformer noise are shown below Factbox.

These levels correspond to a total noise level of about 59 dB(A) at maximum overexcitation and full current. The corresponding value for the total dB(A) at 100 percent voltage and full current is in the 54 dB(A) range. In comparison, transformers of this size would typically have noise levels in the 70 dB(A) range for no-load noise alone. Low-noise transformers will have 10 dB less (again, no-load value alone). This demonstrates the extent of the ConEd noise requirements relative to typical or even low-noise transformers.

But these were not the only challenges. The ConEd requirements impose other design restrictions. These are:

- Tight limits on weight, width, and height to permit transportation in Manhattan
- Tight limits on transformer impedance variation across the range of the tap changer
- Significant overload requirements (up to 200 percent)
- Limits on temperatures of hot-spots in the windings at different loads

The designs requested by ConEd were for their standardized 65 MVA and 93 MVA network transformers.

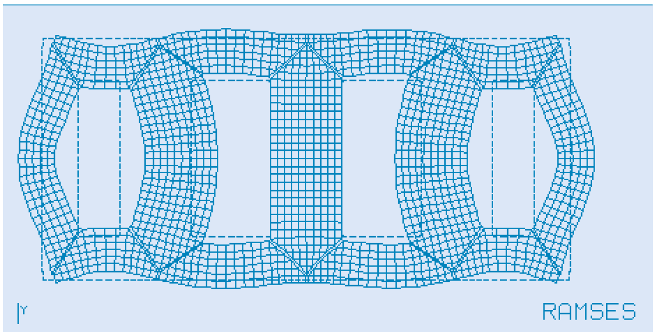
Solutions for the ConEd transformer

Designing a transformer for such ultra-

Factbox Maximum allowable limits for the three most important frequencies

Octave band center frequency (Hz)	125	250	500
Permissible level (dB)	71	64	57

8 Modeling of mechanical resonance of a five-limb, three-phase core



9 Ultra-low noise ConEd transformer with Sound Enclosure

10 Ultra-low noise ConEd transformer with Sound Panels

11 Ultra-low noise ConEd transformer with no Sound Enclosure or Panels

low noise levels while at the same time satisfying all the other limitations is only possible if the transformer manufacturer is capable of the following:

- Accurate calculation of the noise level of the core versus its flux density
- Accurate calculation of load noise
- Accurate calculation of resonance frequencies for the core, windings, tank plates and tank stiffeners
- Accurate calculation of frequency spectrum of core noise versus flux density
- Effective means of reducing both core and load noise for the different frequencies
- Proper transformer mounting techniques
- Accurate indoor measuring techniques of low noise levels in the factory

The more accurately calculations can be performed, the lower the margin of the resulting design and the more feasible it becomes to satisfy tough specifications.

A success story

As of the spring of 2003, ABB had the technology to design low-noise transformers but not to the levels or the details required by the revised specifications for the ConEd ultra-low-noise transformers. Recognizing this fact, ABB identified the research and development work that needed to be done to advance the technology existing at the time to the level of rigor necessary to successfully design and build the transformers required by ConEd.

For the next few years, the ABB technology development team worked very hard on all of the seven noise-related technology areas discussed in this article. As a result of the progress achieved, ConEd awarded ABB the contract to produce the first ultra-low-noise 93 MVA transformers. These transformers were designed using the technology available at that point in time and it was successfully tested and delivered in 2005. The first of these was equipped with a sound enclosure 9. The second and third transformers had only sound panels attached to the tank walls 10.

> The more accurately calculations can be performed, the lower the margin of the resulting design and the more feasible it becomes to satisfy tough specifications.

After the delivery of these transformers, ConEd awarded ABB an order for ultra-low-noise 65 MVA transformers. These transformers were designed using the latest noise technology that was available at the time (2005). The transformers were produced with no external sound enclosure or panels 11. In fact, the second unit was designed with significantly less winding weight while testing 4 dB lower load noise than the first unit. Frequency components of the total of core and load noise of this transformer were between 2 and 5 dB lower than the ultra-low levels specified by ConEd.

As a result of this success, ConEd awarded more of these 93 and 65 MVA transformers for delivery in 2008 and early 2009. These transformers were again designed using the latest technology developed at ABB. It was therefore possible to upgrade the design of these transformers with significantly less weight of core and windings while still satisfying the ConEd requirements.

The ultra-low-noise transformer technology resulting from this development is now being used in producing optimum designs for low-noise transformers for other customers in metropolitan areas around the world.

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