

BELLWETHER, LLC

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Details of Transformer Acoustics

1 Intro

Bellwether is using acoustic analysis to identify early warning signs of transformer failure.

2 Generation of Magnetic Flux (50/60 Hz)

The most important part of magnetic flux generation is that it involves a non-functional process (i.e., not a mathematical function) whereby the primary current is turned into magnetic flux. The non-functionality of this process is important, as it creates space for new harmonics to exist in the acoustics that don't exist in the magnetic flux (e.g., a 3rd harmonic).

The generation of magnetic flux comes from the hysteresis loop, which is not a mathematical function because it follows a different curve depending on the direction of current (whether it's increasing or decreasing) and where in the path it changes direction.

3 Magnetic Flux to Acoustics

Another crucial piece of this process is the **magnetostriction**, which functions as a rectifier. The rectification process doubles the frequencies of the underlying current, and it introduces new harmonics (e.g., a strong 2nd harmonic).

The rectification process is where the bulk of the harmonics are introduced. Underlying current harmonics, amplified through the hysteresis loop, become chaotically multiplied.

3.1 Magnetostriction (100/120 Hz)

After the current interacts with the hysteresis loop and creates magnetic flux, the energy is then made acoustic. The primary acoustic manifestation of the electromagnetic field is magnetostriction in the core. Most distribution transformers use a shell-type core, which involves the core encircling the windings, contrary to the core-type core, where the windings are wrapped around the limbs of the core-type core (which looks like a windowpane).

Magnetostriction is when the individual ferromagnetic grains of the core expand and contract with the magnitude of the magnetic field. When the field is maximum positive, the grains are fully aligned in one direction and expand to their maximum size. When the field is maximum negative, the grains are fully aligned in the opposite direction and are still at their maximum size. Thus, for a time-varying magnetic field of 60 Hz, the grains will reach their maximum expansion twice per cycle, resulting in a 120 Hz tone. In this way, magnetostriction functions as a rectifier.

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3.2 Rectification

While the acoustic rectification is done by the previously discussed magnetostriction, it is impossible to overstate its importance. This rectification introduces numerous harmonics that are non-linearly compounded, making the reverse-engineering of them a difficult task.

Reference:

1. Jin, Yang & Dong, Kun & Zhao, Jianfeng. (2024). Analysis of harmonic characteristics of the three-phase rectifier and the impacts on the power quality. Journal of Physics: Conference Series. 2803. 012010. 10.1088/1742-6596/2803/1/012010.

4 Transformer Failures

According to a 2012 survey from the Cigré transformer reliability working group, 45% of transformer failures are due to their windings, and 1 out of every 200 transformers will fail each year. These failures always have warning signs, and Bellwether's goal is to identify those signs for transformer winding failure.

Table 1: Transformer Failure Locations

Location	Frequency
Windings	45%
Tap Changer	26%
Bushings	17%
Lead Exit	7%

These failures need to be analyzed mathematically to determine what the electromagnetic effect of a failure is and how that would manifest acoustically.

Winding failures are generally when the vibrations of the transformer cause the tightly-wound coils to come loose, which reduces the magnetic field that the transformer can support, which makes it more likely to become overloaded.

5 What Do We Expect to Hear?

The specific event that we are trying to hear is that of overloading: when a transformer is overloaded, its magnetic field reaches and maintains its peak for a longer period of time. This turns an otherwise sinusoidal wave into a square wave, which produces many strong harmonics, which are then audible through magnetostriction.

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5.1 Windings

As winding insulation breaks down, a discharge branch is able to develop, where an exposed path of less insulation becomes the preferred path for electricity. This can impact the mechanical structure of the transformer, causing mechanical sidebands. Jia (2026) found that this created sidebands around the audible harmonics, which preceded the development of acetylene in dissolved gas analysis tests.

Yuhang (2016) found that winding deformation created half harmonics. The presence of half-harmonics in the post-rectified acoustics is interesting, as it implies the addition of even harmonics to the current. These even harmonics would be canceled out in three-phase wye or delta connections, but would be present in the magnetic flux.

In addition, Mechefske (1995) found that winding loosness produced 60 Hz harmonics. The 60 Hz harmonics as an indicator of winding deformation are confounded by the signature produced by DC bias and phase imbalance, but correlates with the production of even harmonics prior to rectification (i.e., even harmonics in the current produce half harmonics when rectified).

References:

1. Jia, Yunfei & Yuan, Yao & Huang, Kejie & Wang, Song & Zhang, Wei & Peng, Zaixing. (2026). The Vibration Sideband Phenomenon of Transformer. IEEE Transactions on Power Delivery. PP. 1-4. 10.1109/TPWRD.2026.3684771.

2. Yuhang, Shi & Ji, Shengchang & Zhan, Cao & Zhang, Fan & Ren, Fuqiang & Zhu, Lingyu & Pan, Zhiyuan. (2018). Diagnosis on Winding Failure Through Impulsive Sound of Power Transformer. 105-110. 10.1109/IPMHVC.2018.8936691.

3. Mechefske, C.K. (1995). Correlation power transformer tank vibration characteristics to winding looseness. *Insight*, 37, 599-604.

5.2 Core Delamination

As the core delaminates, foreign material (e.g., air or oil) is introduced between the laminated sheets. This causes the hysteresis loop to become wider and the material to become more “hard” and less “soft”. This “hardening” is due to the tendency of the foreign materials (which are not the optimal material for magnetic field conduction) to resist the direction change of magnetization and demagnatization.

5.3 Phase Imbalance

Phase imbalance results in a failure to cancel out the current along the neutral conductor, which results in DC bias in the transformer. This DC bias shifts the magnetic field up along the hysteresis loop, resulting in one half of the cycle being closer to saturation than the other. This uneven effect

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creates half-harmonics when rectified. Thus, we look for the presence of 50/60 Hz harmonics in the acoustics, which are otherwise unexpected.

In addition, phase imbalance will increase the amplitude of zero-sequence harmonics (multiples of three). The presence of zero-sequence harmonics is a metric that can separate the half harmonics due to phase imbalance from those due to winding issues.

References:

1. Han, Shaohua & Wan, Xinqiang & Lai, Yong & Ge, Lei & Pang, Jinian. (2022). DC Bias Diagnosis of Power Transformer with Soundprint Features. 213-217. 10.1145/3558819.3565080.
2. Zhou, Y., & Wang, B. (2022). Acoustic Multi-Parameter Early Warning Method for Transformer DC Bias State. *Sensors, 22(8)*, 2906. https://doi.org/10.3390/s22082906

5.4 Partial Discharge/Bushing Failure

Transformer bushings are designed to insulate a conductor from its surroundings. As a bushing breaks down over repeated use and electromagentic stress, electrons are more and more likely to leak out. These electrons ionize nearby fluids (air and insulating oil), which produces a broadband ultrasonic signature.

Much of the research suggests that sample rates in the megahertz range are required, which may make this infeasible from a phone.

References:

1. Sikorski, Wojciech & Walczak, Krzysztof. (2013). Power Transformer Diagnostics Based on Acoustic Emission Method. 10.5772/55211.
2. Ramírez-Niño, José & Pascacio, Alberth. (2009). Acoustic measuring of partial discharge in power transformers. Measurement Science and Technology. 20. 115108. 10.1088/0957-0233/20/11/115108.
3. Wen H, Abu Talip MS, Othman M, Azam SMK, Mohamad M, Ibrahim MF, Arof H, Ababneh A. Advanced Signal Processing Methods for Partial Discharge Analysis: A Review. Sensors (Basel). 2025 Dec 1;25(23):7318. doi: 10.3390/s25237318. PMID: 41374693; PMCID: PMC12694323.

5.5 Tap Changer

Tap changers cause 26% of transformer failures according to a 2012 Cigré survey. Improper tap changer movement is detected via an uncharacteristic increase in overall amplitude of the acoustics.

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1. Dabaghi-Zarandi, F., Behjat, V., Gauvin, M., Picher, P., Ezzaidi, H., & Fofana, I. (2024). Using Deep Learning to Detect Anomalies in On-Load Tap Changer Based on Vibro-Acoustic Signal Features. *Energies, 17(7)*, 1665. https://doi.org/10.3390/en17071665

6 Causes of Transformer Noise

The following table is an incomplete listing of causes that contribute to transformer noise.

Table 2: Causes of Transformer Noise

Source	Description
Magnetostriction	This is the fundamental 120 Hz tonal that is from standard operation of the transformer on 60 Hz AC electricity
Tank resonance	The encasement of the transformer can often vibrate in approximate resonance with the line frequency (often 2-4 Hz lower)
Non-linear loads	Non-linear loads draw power in short bursts. These bursts distort the otherwise sinusoidal waveform, and this distortion produces harmonics in the waveform. Since the magnetic field is proportional to the square of the voltage, these harmonics are then communicated via the magnetic field and are audible through magnetostriction
Core delamniation	When the core (constructed of thin layers of laminated sheets of steel) begins to peel apart, the core is no longer as able to inhibit the production of eddy currents. Thesee eddy currents then produce a harmonic signature in the current which becomes audible
Cooling fans	Standard noise from the operation of the cooling fans. These will be at a variable speed and so while the tonals might be nominally fixed, they will vary
Load conditions	The magnetic field is proportional to the square of the voltage, so as more reactive loading comes on, the voltage drops, and the magnetic field reduces. As more real loading comes on, the frequency drops, and the magnetic field increases.
Loading	When a transformer loading increases, the relationship among the harmonics changes

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