Overview of Transformer Acoustics

1 Intro

Bellwether is using acoustic analysis to identify early warning signs of machine failure. Our initial application is electrical substation transformers.

2 What is a Transformer?

A transformer is a piece of electrical hardware that takes alternating-current electricity at one voltage and transforms it into another. This is needed because while our home appliances are designed to run at 120 or 240 V, this voltage is really inefficient for transporting. Therefore, electricity is transported at extremely high voltages (e.g. 230,000 V) and is stepped up to that from the generation source and stepped down to the loads which use it.

A transformer is fundamentally two windings, the primary and the secondary, each wrapped around a magnetic core. The windings are simply copper wire that is wrapped in a coil, which allows for the storage of a larger magnetic field than uncoiled wire, wrapped around a steel core, which can support an even larger magnetic field. The windings and the core define the size of the magnetic field that the transformer can support without becoming saturated, which is when an increase in current does not produce an increase in magnetic field.

The primary windings are connected to the power source, and the secondary windings carry the induced voltage to the load.

If the primary windings are overloaded (providing all the power that the magnetic field can support), the magnetic field will become saturated, and the induced voltage on the secondary windings will have a more-square waveform, which causes distortion.

3 Magnetic Flux to Acoustics

An important point to remember is that the power analysis we do is acoustic, which involves a non-linear process whereby the magnetic flux is turned into acoustics. The non-linearity 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 strong 2nd harmonic).

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.

Document ID: DOC-260220-83 1733 20th St NW, #205, Washington, DC 20009-1149
+1 (603) 729-7097 • info@bellwether.llc • https://bellwether.llc

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.

Magnetostriction (120 Hz)

The primary acoustic manifestation of the electromagnetic field is magnetostriction in the core. The core of the transformer is an steel core that enhances the capacity of the magnetic field and provides a path for the energy to move from the primary magnetic field to the secondary magnetic field. 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 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 and expand to their maximum size. When the field is maximum negative, the grains are fully aligned in the opposite way 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.

Distortion Harmonics (N * 120 Hz)

Distortion is a result of how square a sine wave is and is manifested in the harmonics of the underlying frequency: if the core is saturated, the underlying 120 Hz magnetostriction tonal will become square at points (experiencing what's known as "soft clipping" in the audio engineering

Document ID: DOC-260220-83 1733 20th St NW, #205, Washington, DC 20009-1149
+1 (603) 729-7097 • info@bellwether.llc • https://bellwether.llc

world), which means there will be stronger harmonics.

However, true core saturation does not happen on the electric grid, and the distortion that transformer acoustically exhibit has an unknown relationship to the current distortion; it is again important to remember that the distortion harmonics present in the acoustics are related to the underlying magnetic field but are not a linear representation of the current harmonics.

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
Acoustic resonance	The encasement of the transformer can potentially vibrate in resonance with the magnetostriction
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 delaminated sheets can produce a noise
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.
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

7 Alternative Applications

Many parts of the electric grid make noise: transformers, power lines, capacitors, etc. We are interested in monitoring and exploring any of the noise productions from transformers and substations and are happy and willing to pivot towards something else that other experts know to be an indicator of failure.

Document ID: DOC-260220-83 1733 20th St NW, #205, Washington, DC 20009-1149
+1 (603) 729-7097 • info@bellwether.llc • https://bellwether.llc