Overview

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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 110 or 220 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.

A 2024 document from the DOE discusses issues with the supply chains of large power transformers.

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.

Location	Percentage
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.

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.

Magnetostriction forces are proportional to the square of the voltage.

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 world), which means there will be stronger harmonics.

Causes of Transformer Noise

Taken from "What Causes Transformer Noise?":

Type	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 delamination	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

Where Do We Expect to Hear Things?

This project is focused on **substation transformers** that handle voltages of generally 230-500 kV and a power rating of 5-20 MVA. These transformers are very powerful, very dangerous, and very well guarded — access isn't exactly readily available. Therefore, we are proving ourselves on the **pad-mounted distribution transformers** that are easily accessible and found on every other street corner in DC. While the distribution transformers are smaller in size and likely built differently, the underlying physical phenomena are the same, which affords us an easy opportunity to prove our technology on something adjacent to our ultimate goal.

In the DC metro area, load peaks between 5-6pm, and is at its nadir between 3-4am. We therefore will be taking transformer and ambient recordings at both times of the day for 100 distribution transformers in DC.

Read the Initial Distribution Transformer Analysis

Market Analysis

PESTEL (Political, Economic, Social, Technological, Environmental, Legal)

Political	Infrastructure bill in EU/US to improve grid infrastructure
Economic	Replacing transformers is slow and expensive (~$5-30k/MWh of lost load value)
Social	
Technological	Continuous monitoring/Remote internet access/Ubiquitous smartphones
Environmental	
Legal	Utilities have a regulated rate of return; looking to raise CapEx and lower Opex

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