Chapter 1: An Introduction to Transformers in Audio Devices

A White Paper from Lundahl Transformers
www.lundashl.se

Presented by ProSoundWeb
By Ken DeLoria

LUNDAHL
– TRANSFORMERS –

Introduction

In the dawning days of audio, transformers played a vital role in the functionality of first-generation all-tube based electronic circuitry. It was circa 1920 and radio broadcasts for the general populace had just begun, generating a rapid rise in the demand for broadcast audio systems, all of which needed transformers to function.

Later, as equipment for live sound reinforcement began to emerge, transformers again proved indispensible as the only means of matching microphone impedances to vacuum tube preamplifiers. Transformers were also used as inter-stage devices in amplifiers, for line output drivers, and for matching a power amplifier's output stage to the impedance of a loudspeaker voice coil – just as they are still used today in audiophile tube-based amplifiers and musical instrument amps.

Eventually, widespread use of transistor-based preamps and power amplifiers lessened the need for transformers, but as any electric guitarist will tell you, tubes "just sound better."

Insurance Policy

However, transformers do much more than just impedance matching. They can differentially balance a microphone or line-level signal at the source, and then de-balance the same signal at the destination (or more properly stated, the "load"). In the process, electromagnetic interference (EMI), the cause of all-too-familiar hum and buzz, is cancelled out as a function of the transformer's common-mode rejection ratio (CMRR or CMR).

The term "common mode" refers to any stray field that is common to both the plus and minus poles of a balanced line. Add the word "rejection" and it describes exactly what the transformer is doing: it phase-cancels the EMI because the poles are 180 degrees opposed to each other, thus rejecting any unwanted field induced in the cable.

This is pretty important stuff. When a line is not balanced, it becomes vulnerable to picking up all kinds of stray energy. Usually this takes the form of 60 Hz (or 50 Hz in Europe), along with related harmonics. The interference is induced in the cable from nearby alternating current (AC) power cables or from AC rectifiers in electrical devices.

Problems can also be caused by radio transmitters and other high-power devices that generate unwanted energy fields, such as diathermy machines and wood welders (yes, there really is such a thing as a wood welder). In the case of higher frequencies, the invasive energy may not be audible, but it can wreak havoc in a sensitive broadband mic preamp if the energy is not cancelled out by a precision-grade transformer (or by other means).

High-grade audio transformers, such as those manufactured by Lundahl in Sweden and Jensen in the U.S., exhibit high CMRR values across a broad spectrum of frequencies; low-grade transformers may help reduce hum and buzz a bit, but their CMRR is rarely sufficient to solve any significant problem. When it comes to hum and noise rejection, precision high-grade transformers are an invaluable insurance policy.

Ground Control

Audio transformers not only provide differential balancing of signals, they eliminate ground loops as well.

In fact, very well.

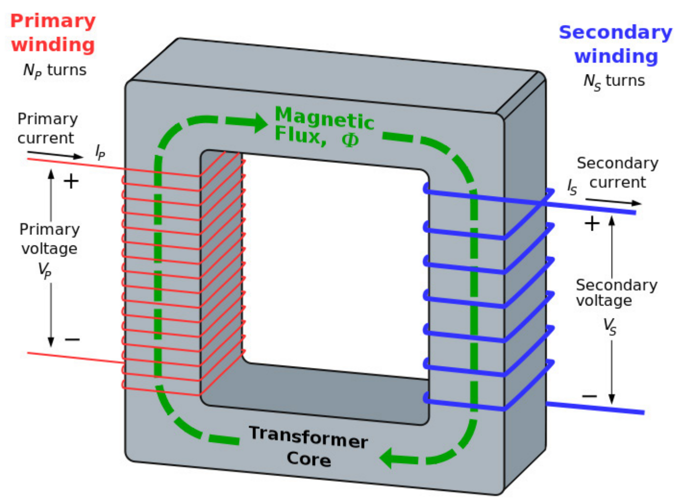
Ground loops occur when two points should be at the same ground potential, but aren't. They're caused by improperly installed equipment (or sometimes improperly designed equipment), with the result being noise and interference in a system. Merely plugging AC power cords into outlets that do not share the same ground path can create a ground loop when one piece of equipment is connected to another.

When many devices are interconnected, or when devices are far apart, the likelihood of a ground loop increases significantly. Ground loops are what keep audio professionals working through the dinner break. They can be difficult to sort out because different manufacturers of consoles and signal processing gear use different grounding techniques.

Enter the transformer. It stops ground loops cold, without resorting to the dangerous practice of lifting the AC ground pin on (one or more) power cords. Those who know this carry a handful of "barrel" style line-level transformer isolators to gigs.

Matter Of Magnetics

A unique feature of transformers is the ability to transfer a signal from the primary winding to the secondary winding without any galvanic connection, thus the input and outputs are said to be galvanically isolated from one another.



Power (VI) applied to the primary coil is magnetically transferred to the secondary coil, hence the galvanic isolation.

Galvanic isolation refers to isolating one branch, or section, of an electrical system from another, preventing current flow. No conductivity is permitted between the sections, yet energy and information are still exchanged. This perfectly describes the function of an audio transformer. Instead of a galvanic connection, the input signal induces a magnetic field in the transformer's primary, which in simple terms is a coil of wire wrapped around an iron core. The transformer's secondary consists of another coil of wire wrapped around the same core, but insulated from the primary coil.

The two coils may have the same number of turns, or one coil may have greater or fewer turns than the other. This is known as the "turns ratio" and determines whether the transformer steps-up the applied voltage, steps-down the applied voltage, or does not re-scale it at all, but serves only to isolate.

When an AC signal is applied to the primary coil, it generates a field that is magnetically induced in the secondary windings, thus reflecting the properties of the applied signal, but not making direct electrical contact. This is the means by which ground loops are broken and unwanted current is prevented from flowing between two or more units that share ground conductors.

For this same reason, no transformer will ever pass direct current DC, because DC does not generate an alternating magnetic field. Note: DC blocking does not apply to auto-transformers that are sometimes used in 70-volt/100-volt distributed loudspeaker systems, because the primary and secondary windings of auto-transformers are connected galvanically.

Sonic Characteristics

It's important to understand that even though transformers are passive devices, they are actually quite complex with internally distributed resistance, capacitance and inductance. Thus they still exhibit varying electrical and performance characteristics, just as active circuits do. They are, in fact, not dissimilar to loudspeakers – except there are no moving parts.

Earlier, we referred to CMRR (common-mode rejection ratio), which is one of the most important performance characteristics that audio product designers and system integrators look for when specifying transformer-coupled interconnects. But an impressive value of CMRR does not fully define a transformer's overall performance. It must also get high marks in each of the following characteristics if the end result is to be clean and transparent sound quality.

Distortion. Like an active circuit, a transformer will inevitably introduce a measure of distortion. In a high-grade design, distortion will be quite low, but present nonetheless. Transformer distortion is a function of level and frequency; the lower the frequency and the higher the signal level, the more distortion. In particular when operating limits of the transformer are exceeded (high level at low frequencies), and core saturation is eminent, distortion will increase rapidly. Core saturation occurs when a transformer's iron core cannot absorb any additional magnetism, thereby "clipping" the signal.

Linearity. Rarely published as a specification, linearity describes how the other parameters (frequency response, distortion, phase response and transient response) will stay stable (or not) under a range of input levels.

Level. This specifies the maximum input and/or output levels at a specified frequency (normally 20 Hz or 50 Hz) before saturating and becoming non-linear.

Frequency Response. Like any other audio device, there is an upper and lower response limit. Within those limits the response may be perfectly flat – or it may deviate a little – or a lot.

Phase Response. This parameter describes any deviation from a flat phase response within the specified frequency range. Even among the leading transformer manufacturers, phase response data is not always available. When it is, it's usually presented as a graphical plot, often with the frequency response depicted on the same graph, as they are proportionally related. In low-grade products, usually very little data is supplied.

Transient Response. Specifies how fast the transformer can respond to a short signal burst (or the leading edge of a continuous signal), and how quickly it stops emitting energy after the applied signal has stopped. Like phase response, this data is not always available, but can be extrapolated by examining frequency response and self-resonance data (pulse transformers for digital audio may delve into this specification more deeply).

Transformers that generally exhibit good frequency response and effective CMRR can still color the sound, sometimes dramatically, due to a slow initial response and significant overshoot at the tail end. Sometimes this can be pleasing to the ear, providing a sense of "warmth," but most times it is not. In any case, it's an inaccurate representation of the signal.

It's better to use a plug-in, or a signal processor intended for such an effect, rather than to infect the system with a sub-optimal transformer. As with everything else in audio, when evaluating a transformer, it pays to spend time listening.

Key Applications

Many microphone types utilize transformers, either for step-up (typically ribbon transformers) or step-down (typically tube microphones), or 1:1 for dynamic microphones. Some manufacturers, such as Cascade, offer upgraded transformer options for many of their ribbon mics. The company even specifies the transformer brand and model, which indicates how important the transformer's contribution is in achieving optimal sonic quality.

Another common stage source is the direct box, or DI. For many years, all DIs were transformer based, and with good reason. An instrument plugged into a DI has one ground reference through the instrument amplifier, while the sound system has a different ground reference. As a rule, a transformer-based DI will solve a ground-loop problem faster and easier than an active DI.

Transformer-based mic splitters incorporate specialized transformers, with one primary and one, two, three, or more secondaries. We mentioned transformers as a form of insurance policy earlier. Nothing equates to more "audio insurance equity" than a well designed and built transformer-based mic splitter.

Mic preamps are another key application. While many brands offer only electronically balanced inputs, a good number of premium products are either transformer-based from inception, or offer transformer versions as an option.

Moving along the signal path, some high-end consoles employ transformers, and/or offer transformer options on lineoutputs. Considering that the console is where all signals come together, this is a good place to consider specifying transformer options, when available.

The console, in turn, feeds signal processing of all types: loudspeaker management systems, outboard equalizers and limiters, and/or banks of self-powered loudspeakers. All are candidates for transformer usage, especially in situations that vary from day to day, when there's little time available to solve induced EMI or ground loop problems.

Conclusion

Present day audio transformers are appreciated and revered for their unique problem solving capabilities; they are perhaps more valuable now than ever before. Today's audio systems have become incredibly complicated, with many interconnected devices comprising even a small system, and a staggering number of devices in large-scale systems.

In the past, transformers were the only way to get things done; now, in many cases, they may be the only right way.

About The Author

Ken DeLoria is senior technical editor for ProSoundWeb and Live Sound International magazine, and has had a diverse career in pro audio over more than 30 years, including being the founder and owner of Apogee Sound.

Chapter 2: Transformers–Insurance Against Show-Stopping Problems

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Introduction

Modern sound systems are subject to ever-increasing signal routing demands. For decades it was just front of house and monitor world that shared the signals from the stage. But today's sophisticated productions often call for a lot more. Potentially, there's a broadcast mix and a recording rig to worry about, and sometimes as many monitor consoles as there are musicians. Add to that some on-stage signal sharing that feeds several iterations of an artist's personal recording gear, feeds to press rooms, CCTV in the facility, Internet streaming, and so on.

The task seems straightforward enough: signals need to be shared, sometimes a large number of them, yet remain as clean and clear as the original source with no risk of harmful interaction among the various circuit branches. While it's easy to describe what's needed, it's not always so easy to accomplish it. Let's look at the obstacles, the various reasons why it's not best practice to simply hardwire paralleled connections from one source to feed multiple devices (which from this point on we'll refer to as "loads").

Ground loops are at the top of the list, as they're the most obvious offenders. Ground loops cause hum and buzz, and are time consuming to troubleshoot in a complex system without starting from scratch and adding only one load at a time. But even if you go through the system methodically, load #4 might be causing hum when loads #2 and #7 are connected, but not loads #1, #3 and #5. It can be very difficult to know which device is reacting with which, and the sheer number of isolation tests needed in a large system can be daunting, even if time is not of the essence. Now add in a time factor – and there always is one – and the potential for trouble is quite high.

Another common offender is sub-optimal loading from too many paralleled loads. The problems can range from merely a decrease in signal level that affects the S/N ratio, to a lot more. Not every input stage of every commercial device is a perfect study in "worst-case" design practices. When you switch "IN" an input pad on your console, the input impedance may drop to a problematically low value. This is not necessarily an issue if the console is used by itself, but potentially a big problem if two or three consoles are paralleled together. When the load impedance becomes too low, the result is a loss of low frequency response if the input stages are capacitively coupled (which they should be to prevent DC offset), as well as a potential for an increase in distortion as the source tries to drive a combined load impedance that is below its design capability.

Whenever loads are combined in parallel, the net impedance will always be lower than that of each individual load. An easily remembered formula is "the product over the sum" notated like this: $(Z1 \times Z2) / (Z1 + Z2) = Zt$. In this simple equation, Z1 is the impedance of load #1, Z2 is the impedance of load #2, and Zt is the value of the impedance when the two loads are paralleled together. For example, two 600-ohm loads in parallel will present a 300-ohm load to the source, which is well below the lowest impedance that most sources are designed to drive. This formula is useful in calculating any number of paralleled loads by breaking down the loads into pairs.

Going further, what happens when an input is fed by a paralleled signal and that device is not powered up? Instead of "seeing" a reasonable load impedance, the signal instead is feeding a network of resistors and capacitors followed by an op-amp or transistor input stage. The problem is that when powered down, op-amps and transistors behave like diodes, clipping the signal. The use of diodes in the signal path is how the early guitar fuzz-tones were made.

Isolate, Isolate, Isolate

Like the old real estate catch-phrase "location, location, location," the best insurance against the problem of feeding multiple loads from a single source is to "isolate, "isolate, isolate" – each of the circuit branches, that is. This can be accomplished actively by means of buffer amps, or it can be done passively by the use of transformers – or – it can be done by combining both approaches.

Passive transformer isolation is well-known as the workhorse of professional audio. Transformer equipped "splitter boxes" have been around for a long time and are still the go-to choice for the majority of needs. When a splitter box is built using precision transformer components, it provides the all-important galvanic isolation that interrupts and eliminates ground loops. As noted in Chapter 1 of this series, transformers have no galvanic connection between their primary and secondary windings; instead they are electro-magnetically coupled, thus isolating the ground connections and avoiding problems that occur due to differing ground potentials among the circuit branches.

The alternative to transformers is active splitting, usually based on op-amp circuitry. Active isolation without transformers has significant value in its own right, but typically serves to isolate only the signal, not the ground reference. On the plus side, an active splitter will avoid the too-low impedance problem discussed above, while also isolating interaction among the branch circuits. However, paths to ground still exist with the potential for ground loops, whereas transformers isolate the signal *and* the ground path. So transformers are the clear winner. Or are they?

A passive transformer solution for splitting signals cannot provide make-up gain, or a way to visually monitor signal levels without designing active circuitry into the passive splitter. This makes a pretty good case for combining the two technologies: a transformer based splitter with an active gain stage. There are certain advantages to this. An active input stage can be scaled to accept a wide range of levels from low-output ribbon microphones to high level line sources. LED monitoring, and/or remote control of gain can also be designed into an active splitter, both of which may be important in certain situations, and gain can readily be added as needed.

Disadvantages are significant though. A power interruption, or other failure mode within the active splitter, could cause a total loss of the signals passing through it. This is known as the "all of your eggs in one basket" syndrome. Additionally, the inclusion of isolation transformers at the input and the output of each channel of an active splitter will carry a significant cost premium. Precision transformers are expensive; putting two of them in every channel, along with active circuitry, would be a pricey proposition.

Thus, an ideal application for an active transformer splitter is when a common signal must be distributed to many loads without loss of gain, such as in a press pool – a device intended to provide many audio feeds for use by members of the press who cover award shows, political rallies, sports and other newsworthy events. A typical press pool has only one input transformer, but many output transformers.

Splitter Transformers with Multiple Secondaries

A long proven solution for trouble free signal distribution, one that's used in a great number of applications, is the multiple-secondary transformer splitter. Transformer designers are well aware of the needs of professional users and have responded by developing transformers with more than one set of secondary windings for splitting the signal to more than one load. The source signal is connected to the primary of the transformer, and then multiple secondary windings feed the various loads, one winding for each load (Figure 1).

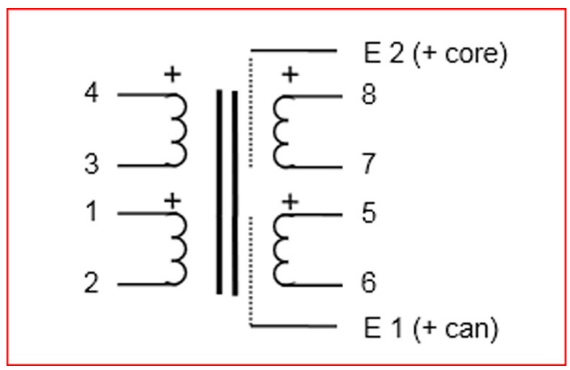

Figure 1: The schematic shows a pair of primaries (normally connected together in parallel) and two secondaries for driving two separate loads. Note the individual Faraday shields on each of the secondary windings (E 1 and E 2).

Such an arrangement isolates each of the branch circuits, thereby avoiding ground loops. This is very important, especially when one console might be in an OB truck with a very different ground reference than the consoles located inside the venue. Another advantage is that bandwidth is preserved, which can be an issue when long lines come into play. A passive splitter requires no batteries or power supply, and phantom power (+48 VDC) from one console cannot cause damage to another console, as transformers do not pass DC.

True professional grade splitter transformers are precision devices, available from only a small number of suppliers such as Lundahl Transformers, which offers a variety of models for splitters as well as transformers for many other purposes. The company's passive splitter transformers have internal Faraday shields individually surrounding each of the secondary windings, thus avoiding interference from electrostatic noise sources (Figures 1 and 2).

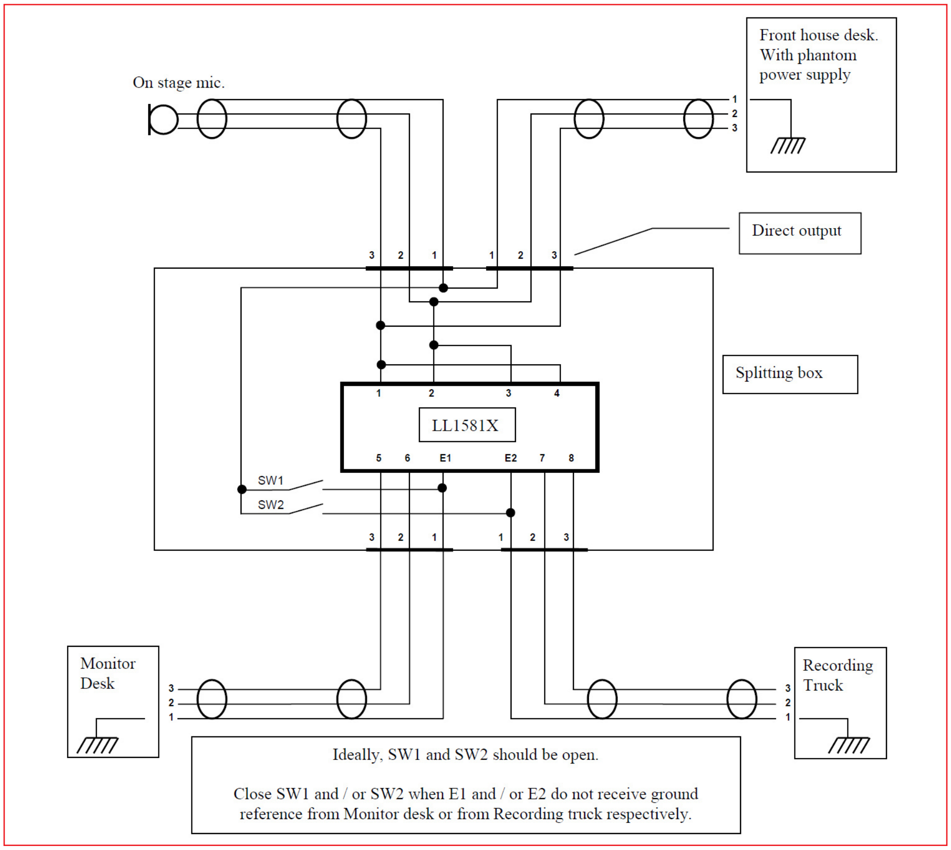

Figure 2: A circuit showing dual secondaries of a Lundahl LL1581XL splitting transformer.

Efficient Faraday shields and high immunity to noise are particularly valuable when signal levels are low, such as from most microphones. Lundahl also manufacturers transformers for active splitting with up to four secondary windings, but as signal levels are normally at line level in an active splitter, those models do not require internal Faraday shields.

Mid-Side Mic Technique with Splitting Transformers

An interesting and useful approach to stereo recording and broadcast is mid-side (MS) miking. The technique involves the use of two microphones, one with a figure-8 pattern and the other with a cardioid pattern, though an omni can replace the cardioid for a more spacious effect (Figure 3).

Figure 3: Two popular microphones placed in a mid-side (MS) configuration.

With MS miking, the width of the stereo field can be varied by changing the gain of the mics in relation to one another. Additionally, the two mics will always sum perfectly to mono, making the technique especially useful when the content may need to be distributed both stereophonically and monaurally.

MS miking requires a matrix network to provide the sum and the difference of the two microphones. The use of two 1 x 2 splitter transformers makes it an easy task to construct such a network (Figure 4).

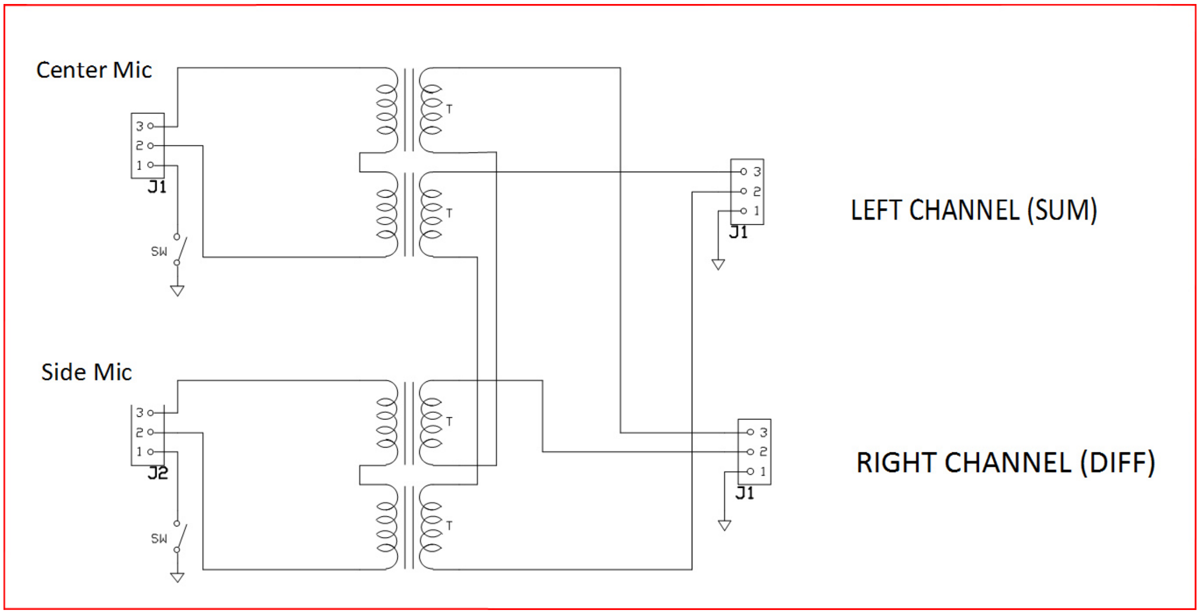

Figure 4: This schematic shows how the dual secondaries are wired to provide the sum and the difference of the two M-S microphones.

Conclusion

In sound reinforcement, live recording and live broadcast, there's never a chance to go back and re-do a show. The judicious use of transformer-based splitters – both active and passive – has proven to be the best possible insurance against unfavorable outcomes.

About The Author
Ken DeLoria is senior technical editor for ProSoundWeb and Live Sound International magazine, and has had a diverse career in pro audio over more than 30 years, including being the founder and owner of Apogee Sound.

Chapter 3: Anatomy of a Transformer

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Introduction

As discussed in the previous segments of this series, transformers play a vital role in professional audio, in large part because of the galvanic isolation achieved by magnetically coupling two (or more) coils of wire around a metallic core. The basic concept is simple: electromotive force generated by AC signals passes through the transformer, but ground references do not.

But like many "basic concepts," the design and manufacture of an ideal transformer is a complex undertaking. A tour of Lundahl's modern facility in the town of Norrtälje, about 70 km north of Stockholm, Sweden, provides highly interesting, not to mention highly useful, insight on the process.

Governing Factors

There's more than one way to manufacture a transformer; in fact, the topologies and underlying methods are numerous. The differences from one transformer type to another can be significant, with governing factors that include material selection as well as mechanical and electrical choices made during the design phase, encompassing wire gauge, core size and more. Most important is the topology of the design; i.e., how the coils and core material are constructed and assembled together. Combined, these factors determine the performance characteristics of the final product.

For most manufacturers, design topology is limited to the type of machinery that can be purchased to produce the final product, including the crucial aspect of coil winding. Yet transformer companies typically limit their production operation to common bobbin-style winding machines, spools of wire, and off-the-shelf transformer "cans."

On the other hand, Lundahl determined early-on that a dual, open-ended coil topology provides many benefits over standard bobbin winding. These include better electromagnetic coupling, lower unwanted capacitive coupling, freedom from industry-standard form-factors, and more. The problem was that the machinery needed to manufacture transformers using Lundahl's preferred topology simply did not exist.

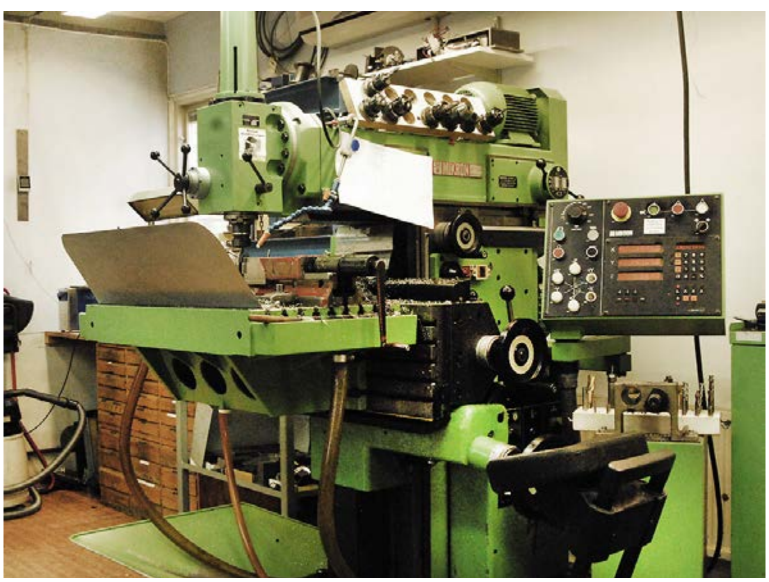


Figure 1: CNC milling machine in Lundahl's machine tool fabrication shop where production equipment is designed and manufactured.

As a result, the company not only designs and manufactures its own transformers; it also designs and builds the actual machinery that, in turn, is used to manufacture the transformers. This is done not because Lundahl has a penchant for building machinery, but rather, because the specialized machines it needs are not available for sale. Lundahl operates a full-time tool shop and fabrication facility in the basement of its factory solely to build and maintain production machinery. The shop is equipped with top flight CNC milling and drilling machines, metal lathes, metal saws, and other essential tools (Figures 1, 2, and 3). Almost nothing in the process is farmed out, not even the software that controls the servo motors, sensors, and pneumatic valves on the various production machines. The resultant production lines are elegant, efficient, and reliable.

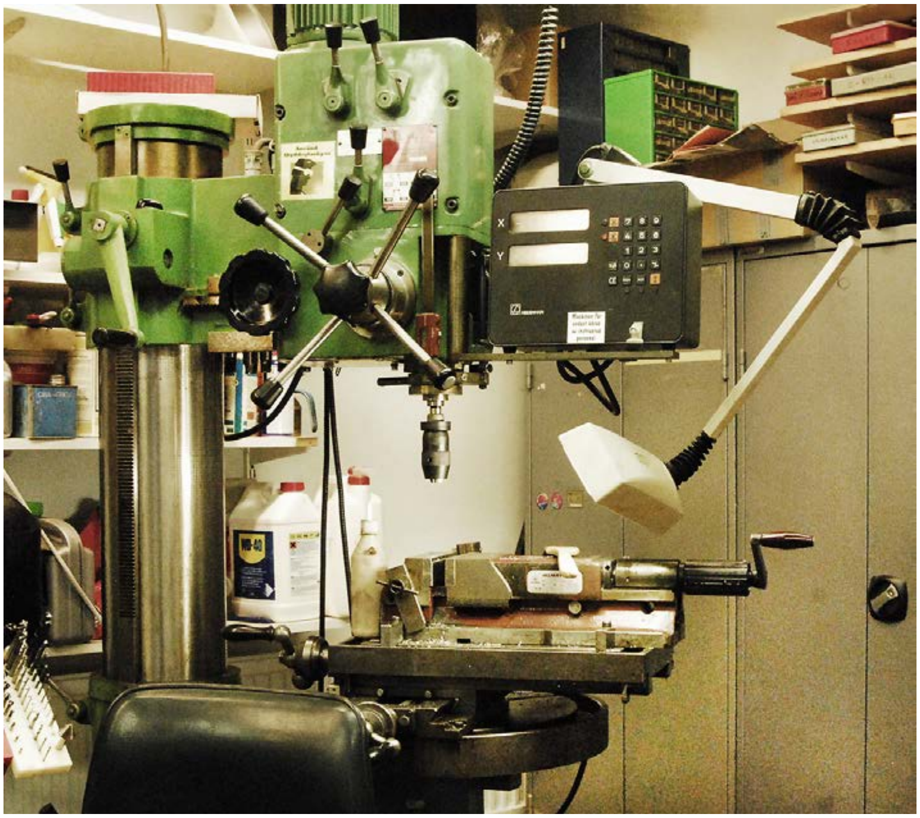


Figure 2: A CNC drilling machine.

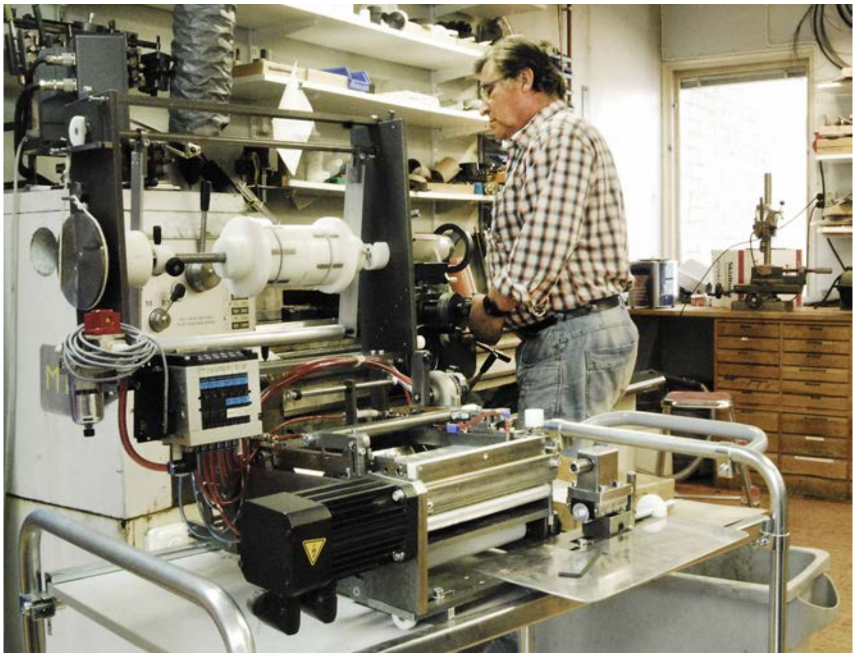


Figure 3: A senior machinist operating a metal lathe with prototype coil-winding machine shown in foreground.

Coils & Foils

This leads us to the construction details that make a Lundahl transformer unique. Recall that the foundation of any transformer consists of at least two coils -- the primary and secondary windings wrapped around a core material. The typical method is to wind the coils using bobbins, something like the bobbin on a sewing machine, and then place the core material inside the bobbins.

By contrast, Lundahl uses a method called stick winding. To produce a stick-wound coil, a mandrel that resembles a stick is temporarily placed on a custom built Lundahl winding machine (Figures 4, 5, and 6). During the winding process, copper wire is wound onto the insulation surrounding the mandrel. Lundahl's specialized machinery automatically inserts insulation material between each individual layer of copper wire in order to reduce internal capacitance and increase high voltage tolerance.

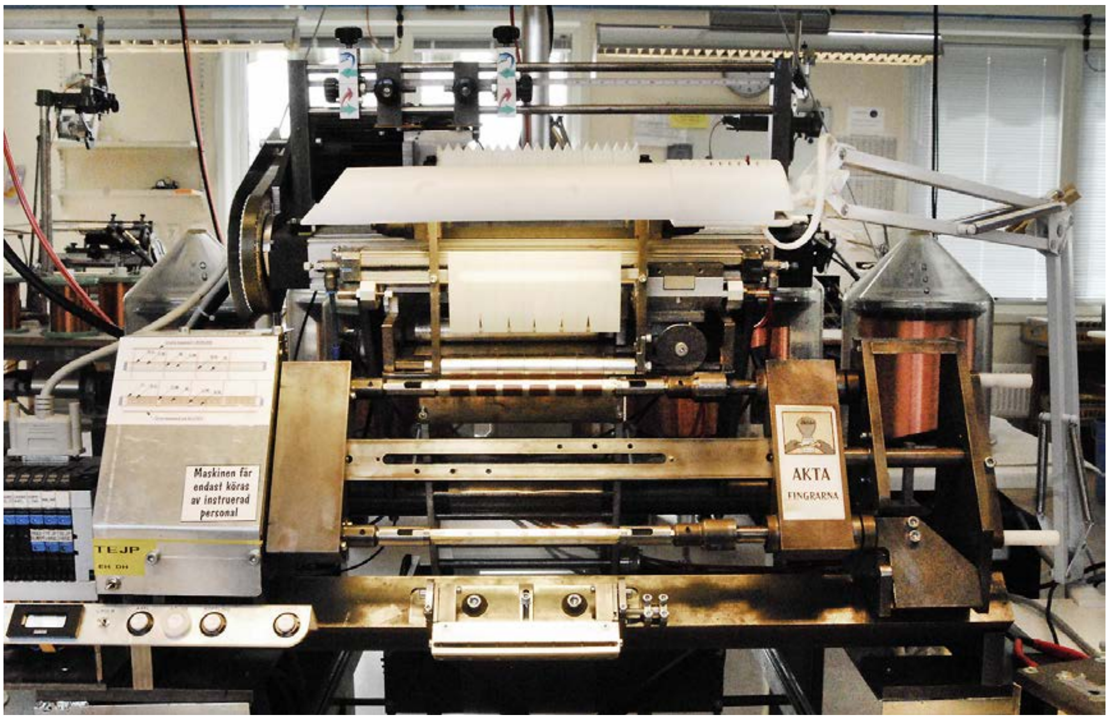


Figure 4: Front view of a Lundahl coil-winding machine.

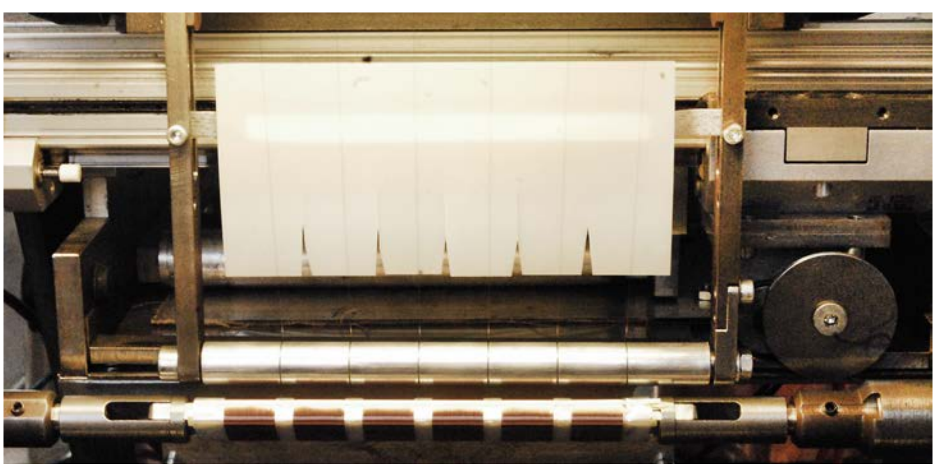


Figure 5: Close-up showing reusable mandrel and "stick" winding method.

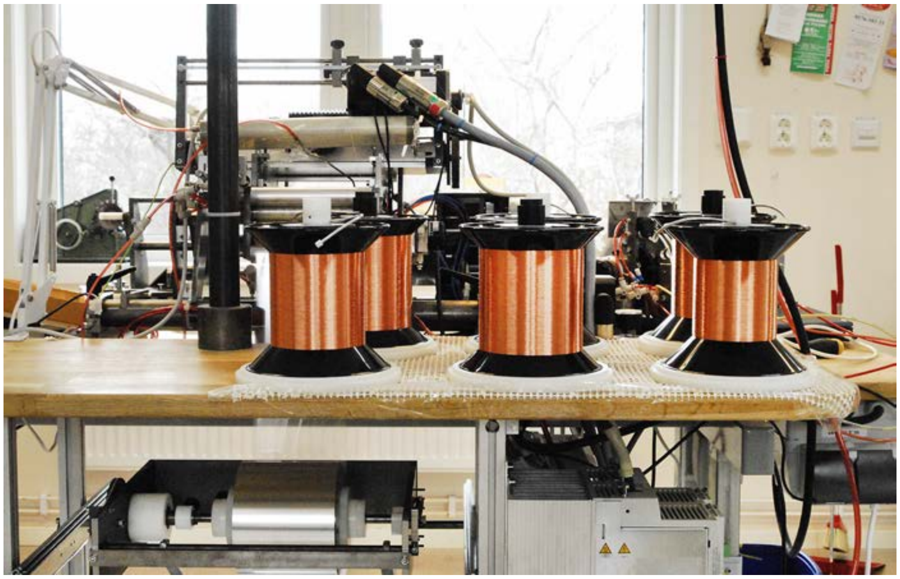


Figure 6: Rear view of a Lundahl coil-winding machine showing wire spools.

A computer control system driven by custom software written by Lundahl, controls the number of wire turns based on the design specifications of the specific transformer model that the winding machine is running at that time. When the prescribed number of wire turns have been completed, the mandrel is removed, and the resultant "stick" with the completed coils of wire moves on to the next fabrication process.

The turns ratio, that is the number of turns in the primary coil relative to the secondary coil, determine if the transformer is a 1:1 isolation type, or is intended to step-up, or step-down, the primary voltage. Lundahl provides many different models with varying turns ratios to meet the diverse needs of microphone manufacturers, pre-amp manufacturers, splitter manufacturers, console manufacturers, press pool manufacturers, and others who require transformers as a critical component in their products.

Numerous models have dual primary coils and/or dual secondary coils, and some even have quad coils for the primary, the secondary, or both. This allows the coils to be connected in parallel or in series by the equipment manufacturer, thereby altering the turns ratio as needed for different applications.

Most models are also equipped with internal Faraday shields, carefully factored into the design topology. Figure 7 shows a machine built by Lundahl that installs the Faraday shielding, which provides significantly increased common mode rejection.

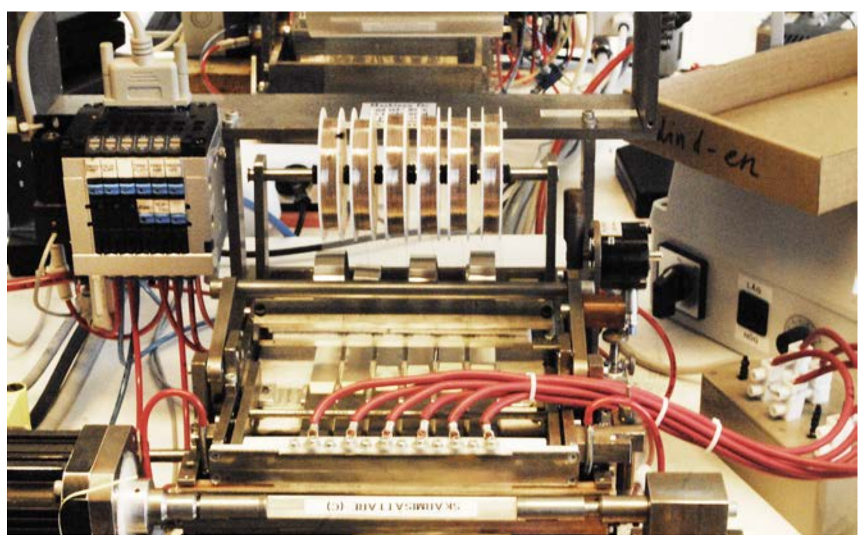


Figure 7: Awesome complexity! Front view of a Lundahl machine that inserts Faraday shields in the transformers for significantly improved CMR (Common Mode Rejection).

In addition, transformers are manufactured in different sizes, ranging from very small for use in microphones to much larger form factors for use as interstage and output transformers in tube amplifiers. Consequently, Lundahl has also developed varying sizes of winding machines to accommodate the wide range of products that the company offers (Figures 8 and 9).

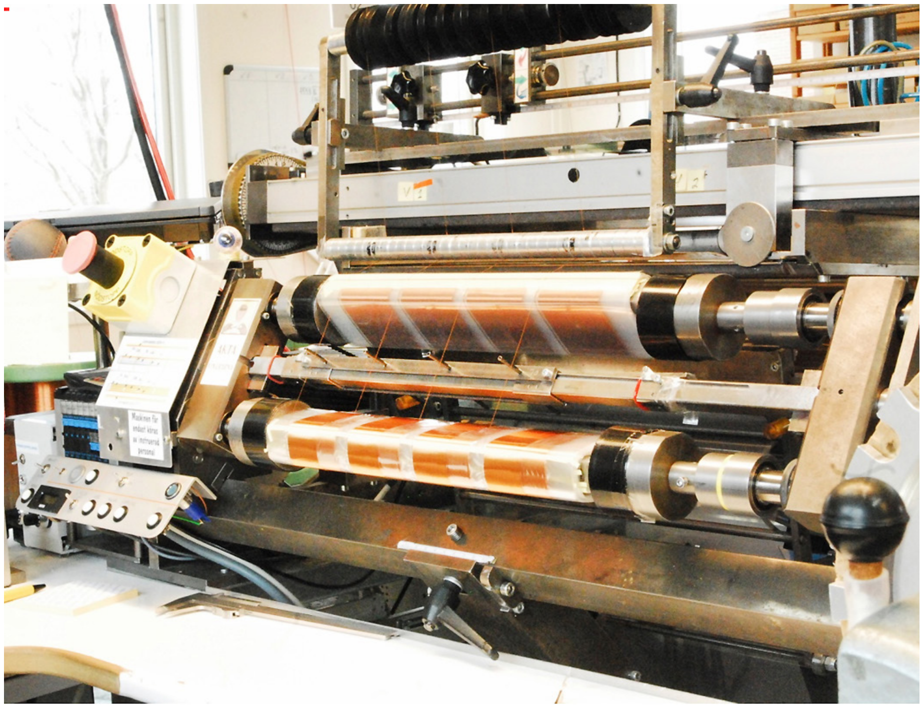


Figure 8: Front view of a Lundahl coil-winding machine for larger format transformers.

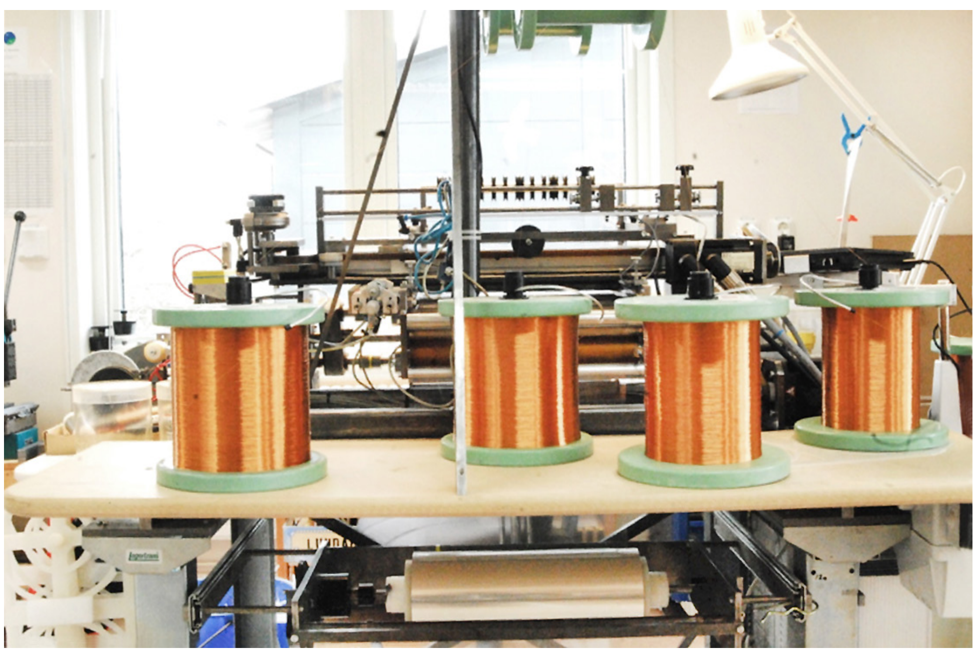


Figure 9: Rear view of large-format Lundahl coil-winding machine showing wire spools.

And, not all transformers are wound with copper wire. Lundahl's high-end moving coil step-up transformers are available with high purity silver wire windings. Despite the small difference in electrical conductivity between copper and silver (approximately 6 percent), the sonic differences can be substantial.

Core Of The Issue

In addition to the primary and secondary windings, another critical component is the core. Audio transformers use stacked cores (made from E- or U-shaped laminations) or C-cores, which are constructed of steel bands that are typically wound into an oval shape. When the oval is cut into two halves, the halves look like the letter "C," hence the name.

This is another aspect where Lundahl is not content to simply purchase pre-made cores or to farm out the fabrication work, but rather, wind the cores from a variety of sizes and types of material to meet exacting specifications. As with the coil winding machines, the machines that wind the steel bands into cores are manufactured by Lundahl exclusively for their own use in production.

Different core materials possess different properties, presenting the design engineer with a range of choices when optimizing a transformer for a particular purpose. For example, amorphous steel has low internal losses and is widely used in high voltage power transformers, but is also used in the specialized transformers that Lundahl manufactures for audiophile tube amplifiers, an application in which amorphous steel is considered very desirable.

Conventional crystalline alloy steel is more commonly used for pro audio applications. When power efficiency is not the governing design goal, cores of varying Ferro-magnetic alloys have certain advantages in respect to wide frequency response and low distortion characteristics. One Lundahl customer ran a double-blind listening test to characterize and grade the performance of differing core materials; as it turns out he was rather surprised by the results.

The bottom line is that different core materials are known to result in different sonic signatures, but it's not so simple to say that one material is categorically better or worse than another.

The world of transformers is not a simple one. In addition to core materials, there are many other factors that effect transformer sound quality, including the selection of other materials, the precision fit of the coils and core, the uniformity of the windings, the use of layered insulation; the quality of the assembly work, and more.

While the majority of Lundahl's product line is designed and manufactured to be as sonically transparent as possible, there are some exceptions. For example, the LL1940 tube microphone transformer uses a silicon-iron C-core, unusual in its intended application. The result is a transformer with more "sound character" compared to a classic mu-metal lamination transformer.

Owning the Process

Experiencing first-hand the complex series of steps required to manufacture audio transformers to the standards noted in this paper is like entering another world. Spools of wire finer than a human hair run through robotic-looking winding machines, while the line operators confidently and efficiently perform their tasks (Figures 10 and 11).

Figure 10: Lundahl coil-winding machine in use.

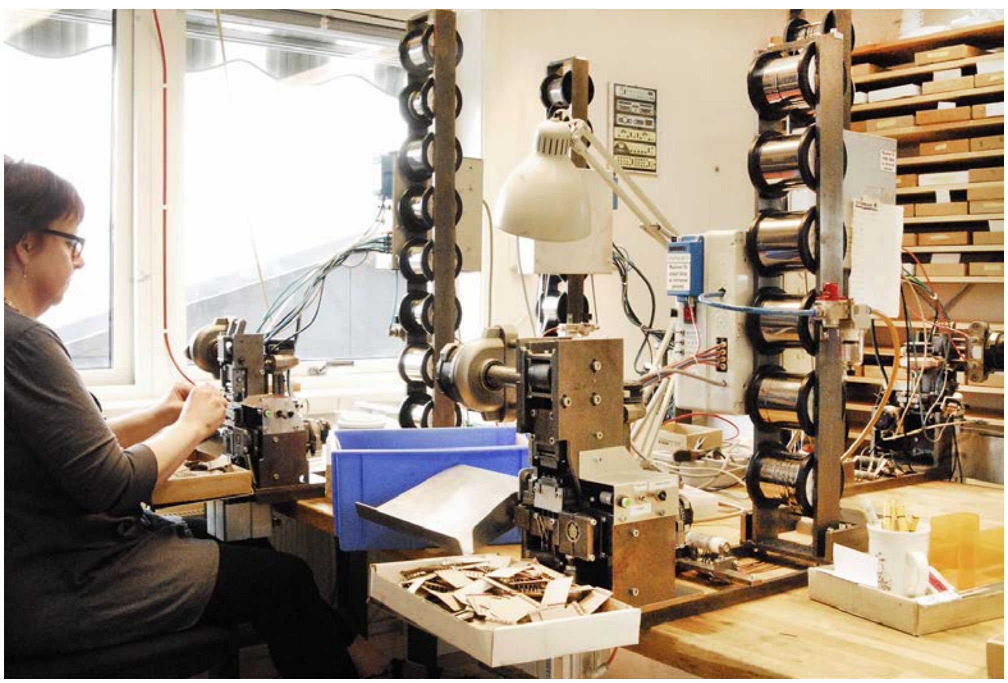


Figure 11: Production worker operating a custom-built fabrication machine.

Machines form and shape the packaging cans, spot welding the ends together in a quick, semi-automated sequence, while others manufacture the cores, and still others the hollow pins that become the transformer's I/O connection points. Industrial ovens, running a three-day heating-and-cooling cycle, cure the epoxy resin that bonds the internal components together and eliminates oxidation, ensuring that each transformer will enjoy decades of longevity. Other, higher temperature ovens are used to anneal the C-cores and the nickel housings, removing molecular stress in the materials in order to improve the magnetic properties.

After the coils are wound, the core has been shaped, slit, and is ready for assembly, the pieces are put in place and the basic transformer now begins to take shape. The extremely fine copper wire leads are inserted into the Lundahl-manufactured hollow connecting pins, to be soldered later in a submersion process. Quality control is comprehensive with every single production unit receiving a series of tests to insure that it meets the factory's rigid performance specifications (Figure 12).

Figure 12: Test station with trays of production units ready for QA (quality assurance) testing.

Note that the manufacturing cycle of a given Lundahl transformer can be a full week, from start to finish. It's an exhaustive process, and one that requires a high level of investment. Yet by controlling the entire process, from raw materials to finished goods, Lundahl has positioned itself as a premium provider of a key component in the world of audio and systems.

About The Author

Ken DeLoria is senior technical editor for ProSoundWeb and Live Sound International magazine, and has had a diverse career in pro audio over more than 30 years, including being the founder and owner of Apogee Sound.

Chapter 4: An Interview with Managing Director Per Lundahl, and the History of the Company

A White Paper from Lundahl Transformers
www.lundashl.se

Presented by ProSoundWeb
By Ken DeLoria

LUNDAHL
— TRANSFORMERS —

Lundahl Transformers is an extraordinary and unusual manufacturing company that originated in the basement of a house near the city of Stockholm in 1958. Founded by Lars Lundahl and his wife Gunnel some 55 years ago, the company has become a leader in the field of high-quality audio transformers. Lundahl products are used the world over in pro-audio and audiophile sound equipment, consistently garnering acclaim in applications that range from ribbon microphones, to preamps, to exotic audiophile vacuum tube amplifiers.

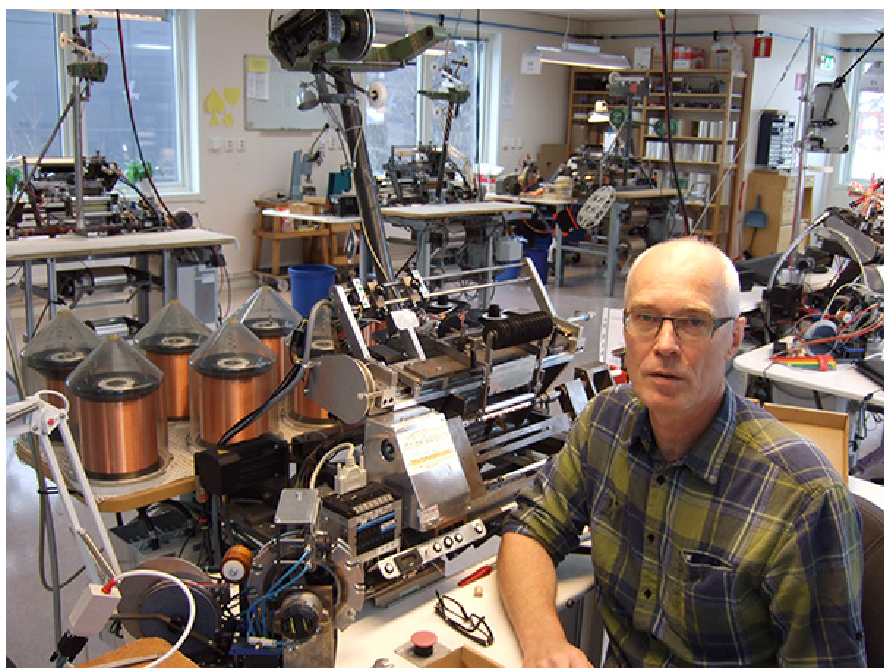
In 1940 at the age of 12, Lars Lundahl had already developed a keen interest in electronics. He was in the process of building his first radio receiver, but with World War II underway, electronic parts were difficult or impossible to find. Undaunted, young Lars developed workarounds that demanded unconventional ways of solving problems, and just two years later, he was working (part time, of course) as a repair person in a radio shop, receiving payment in the form of electrical components. This formative period, when inventiveness made up for parts availability, had great impact on the man who would spark an irreversible change in the transformer industry.

Fast forward to 1958. Lars now has an engineering degree under his belt, along with several years of professional experience. His theoretical and practical knowledge has made him acutely aware that most commercially available transformers, of that time, were of sub-optimal quality. Not one to mince words, "rubbish" was a term he freely used when describing market offerings of that era.

In response, he and Gunnel began their company in the basement of their home, literally building their lives around their passionate endeavor. As the company grew, the family eventually moved to Norrtälje, a small coastal town about 70 km north of Stockholm, in pursuit of quality of life away from the bustle of the big city.

Lars and Gunnel built a factory dedicated to manufacturing transformers, and a few years later, they added an apartment big enough for themselves and their four children. One of those children, Per Lundhal, is now the Managing Director of the present day company. The unusual approach of using a residential environment for a factory (or vice versa depending how you look at it) would prove to echo other unusual methods that the company would come to employ, in its mission to manufacture products that perform to the highest possible level.

As the business grew, extensions to the building were added as needed, including a third floor for additional manufacturing capacity. In the present day, a large commercial elevator provides access from the top floor to the bottom, while spiral staircases remain in place for practical usage, and as a nostalgic reminder of the company's earlier years.


Per Lundahl in his company's manufacturing facility.

I met with Per Lundahl at company headquarters in Norrtälje, and was given an extensive tour of the facililty, which was absolutely fascinating (see Chapter 3 to learn more). Nearly every machine used in the manufacturing process has been designed and built by the Lundahl staff. For example, the winding equipment that's pivotal to manufacturing Lundahl transformers simply cannot be purchased, so it must be designed and built by the company from the ground up. This unique manufacturing methodology is both the basis, and the key, to the superior sonic quality of the products.

During my visit, Per and I cloistered ourselves in a meeting room where he spoke thoughtfully and at length about how the company came into being, and what it represents to its worldwide customer base in today's marketplace. I found his knowledge of the electrical, mechanical, and magnetic properties of precision audio transformers to be profound.

Ken DeLoria: Would you elaborate further on your parents and the origins of the company?

Per Lundahl: My father was the "great inventor" (spoken wryly). Before starting the company, he worked for AGA in the development laboratory. AGA was a large Swedish gas company that sought to become an electronics manufacturer. During his time there, he concluded that the world really needed high-grade transformers. Nothing of good quality was available at that time in Sweden. And unlike vacuum tubes, for example, a transformer factory could be started on a small scale. So that's what he did.

Together with my mother, who handled administration, they created Lundahl Transformers. My mother and father probably didn't understand what each other did every day, but they managed to work things out very well, capitalizing on their individual strengths.

I understand how vacuum tubes would take significant resources but specifically, why did he choose transformers instead of, say, potentiometers?

My father was fascinated with transformers, which at that time – and today still are – rather complicated components that require careful scrutiny if they're to be maximally optimized. He was not looking for an easy ride.

Who were the original customers?

AGA, where he remained working during the early days of the transformer company, began to manufacture televisions and radios. It was the birth of the stereo era, and a thought at that time was to use the television receiver as one channel of the stereo signal, and a radio for the other. The television needed a transformer to isolate the high voltages for safety, so AGA became his first customer.

I was about five or six years old, but I remember it clearly. The basement of our house, including a built-in garage, was filled with transformer winding machines, a lathe, and a milling machine for production development, plus vacuum-pressure systems for impregnating and curing. In addition to AGA, Swedish Defense and Swedish Radio were also important early customers.

What were the various phases of expansion that led to your present-day facility?

It was originally constructed in 1963, with five later expansions. The third level was the largest increase in area. The roof started leaking so instead of just fixing the roof, we added an entirely new level. Personally though, I like the idea of "the North Wing," which further increased our size and capacity. We were manufacturing a lot of product as the North Wing was completed. Unfortunately, soon afterwards, the market began to decrease as a recession set in.

When – and why - did you switch from conventional bobbin-style designs to your present proprietary methods?

Early on, my father had the idea that he should combine manufacturing with a good tool shop, to not be channeled into purchasing the standard machinery that other transformer manufacturers were limited to. He started by modifying conventional designs and that concept went much further to creating the machinery that makes our products unique in all the world.

We wind our coils using a “stick method” instead of the conventional bobbins that other manufacturers use. The advantages are better electrical characteristics and more useful sizes and shapes for fitting our transformers into products, especially diminutive ones such as microphones.

I’ve seen the many different machines that you’ve designed and built. They appear to be uniquely irreplaceable.

Yes, of course. And that’s why we don’t purchase them from outside vendors. We build them in-house so that we can build more as needed, repair any that break down, and refine our proprietary designs and manufacturing processes on an ongoing basis.

Let’s talk about how you design new transformer models.

New designs are based largely on requests from customers. We first ask them to try models that we already have in place that match as closely as possible to what they require. But there are times when we need to change the turns-ratio, alter level capability, change physical size, or work with other parameters to meet a customer’s specific needs. Sometimes it’s a simple adjustment; sometimes it requires all new tooling, which we can readily do.

How many models of transformers do you currently produce?

In our standard pro audio range, there are about 70 models that we keep in stock. In our audiophile range, about the same number.

Do you anticipate any significant changes in materials or techniques in the future? Or are materials and processes mostly stable at this time?

Largely they are stable. We use industrial copper for most of our windings and mu-metal nickel cores. Mu-metal is both linear and highly repeatable from one manufactured unit to another. We do get requests for oxygen-free copper wire, silver wire, and amorphous cores, usually in the audiophile side of our business, and we are well equipped to accommodate these specialized needs for our customers.

As for manufacturing processes, we have finely honed our methods and our approach through decades of development, but we seek to always make improvements in every area that we can.

How does an amorphous core differ from a mu-metal core?

Metal is crystalline (when solid) with a highly ordered arrangement of atoms. Amorphous metals are non-crystalline, with a glass-like structure. But while glass is an insulator, amorphous metals are electrically conductive. There are many opinions about how each material affects the sound. We let our customers make their own determinations, and we build for them what they want.

How did you become personally involved with the company, other than the obvious connection through your family? Was this something you always wanted to do from an early age?

No, I never thought I'd replace my father in the business. At one point I was considering becoming a medical doctor, but after my military service as a medical orderly, I decided medicine was not my thing.

After I graduated from the Royal Institute of Technology in Stockholm, I worked as a computer consultant for a start-up company, and later for Ericson. But I wanted to raise my children outside of Stockholm, so I asked my parents if they would like for me to come to work for them, and they agreed. It's now been 20 years.

Have you considered manufacturing other products?

My father designed a magnetic amplifier as an integrated audiophile amplifier unit when my parents were still running the company. In a magnetic amplifier, the amplifying elements are not tubes or transistors, but pre-saturable chokes. It is thus a type of pulse width modulating amplifier.

What became of it?

We sold some units, but when I took over the company I decided to remain focused on transformers rather than trying to become an audiophile company, so we discontinued the project. For one thing, we did not want to compete with our own customer base of audiophile product manufactures. But still, it's nice to run into people from time to time who have one of these amplifiers and to hear how satisfied they are with the sound quality.

To what extent do you test each and every transformer that comes off your production line?

Thoroughly, to say the least. Depending on the model we perform as many as five tests on each production unit, including function, distortion, continuity, and Faraday shielding, if so equipped. We also test the insulation at 4,000 volts to validate the conformity of the insulation. If the unit passes, then we know it will last almost forever.

What's at the heart of the business philosophy of your company?

Lundahl Transformers is like the Hard Rock Cafe: "Love All and Serve All." We don't play favorites with our customer base, and we provide our best know-how and best quality manufacturing for all customers, large and small. We will continue to manufacture the highest quality products possible, while building additional market share – which means staying closely in touch with industry trends, and each customer's specific requirements.

Our manufacturing capacity is capable of supporting substantial growth so that we need not make excuses when it comes to delivery times. Our driving belief is to manufacture the most transparent and neutral transformers in the world, and to this end we will continue to design, develop, and refine our products.

NOTE: To learn more about the Lundahl Factory, be sure to download Chapter 3 of this white paper series on ProSoundWeb.

# # #

About The Author
Ken DeLoria is senior technical editor for ProSoundWeb and Live Sound International magazine, and has had a diverse career in pro audio over more than 35 years, including being the founder and owner of Apogee Sound.

Chapter 5: Understanding Impedance In Audio Transformers

A White Paper from Lundahl Transformers
www.lundashl.se

Presented by ProSoundWeb
By Ken DeLoria with Mirza Zametica

LUNDAHL
– TRANSFORMERS –

Introduction

The term "impedance" is the backbone of all things audio, fundamental to understanding how an AC circuit behaves in respect to its input source and output load. For those new to electrical theory, all audio signals are AC, or alternating current. This includes the power amplifiers that drive loudspeakers, signal level devices coupled to other signal level devices, microphones and direct boxes, and in particular, audio transformers.

Transformers are of special interest because they are capable of transforming impedances, while also providing galvanic isolation, along with many additional benefits.

Impedance & Resistance

In order to understand impedance, it's useful to start by clarifying the difference between impedance and resistance. A measurement of DC (direct current) resistance is a simple function that stays relatively constant, except in the case of the resistance value changing either intentionally – such as rotating a pot shaft – or situationally, such as the heating of a lamp filament or a loudspeaker voice coil. Heat inevitably causes DC resistance to rise in value. As temperature increases, so will the resistance of the wire that the current is passing through.

Impedance, on the other hand, is not as simple. To comprehend impedance we have to understand the relationship between voltage and current in a given circuit. The definition of impedance: "The measure of the opposition that a circuit presents to current when voltage is applied." Therefore, the magnitude of the impedance is the ratio of the voltage amplitude to the current amplitude. Don't feel too bad if you don't get it immediately. It's tricky. But it is also the explanation why long cable runs can ruin good sound.

Transformers Rule (The Laws Of Physics, That Is…)

As mentioned above, all audio input and output circuits, all loudspeakers, all microphones, and all transformers use impedance as a measurement of electrical value. This is because they are AC devices, not simple DC circuits. But among AC circuits, only transformers (and their first cousins autoformers) possess the unique property to transform a given input impedance value to a given output impedance value, and vice-versa, without needing an active power supply and the potentially complicated, costly, and distortion inducing circuitry that would otherwise be required to do so.

This is more important than it may seem at first glance. Improper impedance in interconnected circuits leads to all manner of troubles. Optimal interconnectivity cannot be achieved when impedance problems are not addressed. And that's precisely where the transformer comes into its own.

The inherent value of a precision transformer in an audio device can be priceless when it comes to achieving ultimate sonic quality – characterized by flat response and freedom from noise, distortion, hum, and buzz – all of which may be due to sub-optimal interconnectivity. This applies equally to solid-state equipment as it does to tube (valve) equipment.

Source & Load

In normal practice, when two audio devices are connected together, one is the "source" and the other is the "load" driven by the source. The source has a given output impedance, and the load has a given input impedance. Transmission lines and cables exhibit impedance too, but for simplicity's sake we will not delve into them here. They represent only a relatively small factor, except when very long lines are driven by sub-optimal output stages. In such cases, the capacitive and inductive reactance of the cable should indeed be taken into account, because it can cause current limiting in the output stage of the source, a condition that can be solved by employing a high current line-level amplifier driving a precision output transformer. But that is not a commonly encountered situation.

Lundahl transformers inside an Electronaut mic/instrument preamp.

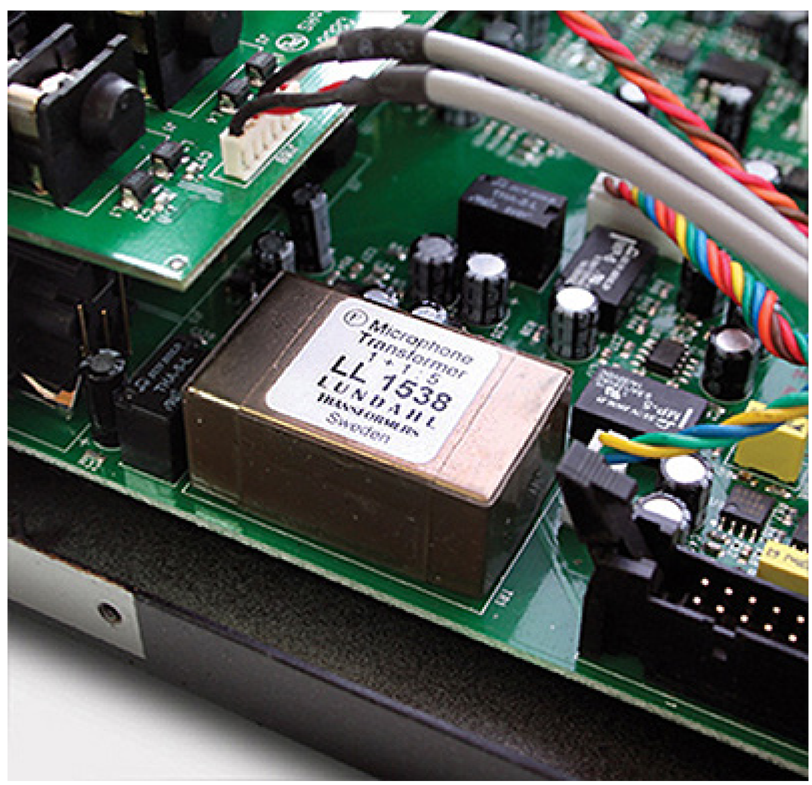
In the early days of audio, product manufacturers attempted to "match" source impedance to load impedance, most often using the value of 600 ohms for signal level devices. This is called "matching impedance" and results in maximum power transfer, an important consideration in long distance communication back in the day when telephony systems were in early development and power was needed to make voice communication audible over long distances.

Now, in these enlightened times, most source impedances of active devices (e.g., mixing console outputs, loudspeaker processors, equalizers, etc.) are kept to a low value, typically around <100 ohms. Most input impedances of signal level devices are much higher, around 10K ohms or more. When the load impedance is 10 times (or greater) than the source impedance, it is referred to as "bridging impedance." Bridging results in maximum voltage transfer from the source to the load.

At the present time, nearly all audio devices are connected via bridging inputs (low impedance outputs feeding high impedance inputs) because we want maximum voltage transferred between one device and another to reduce the noise floor. Bridging inputs are now so common that the term itself, "bridging," is hardly ever used anymore (not to be confused with bridged channels in a power amplifier). That said, if you find yourself having to deal with system components in a decades-old sound system installation, it's useful to be aware of the former standard of 600 ohm to 600 ohm matching impedance. Lundahl makes transformers that will enable the proper connections to be made.

Tubes Are Back

The resurgence of tube-based power amplifiers, microphone pre-amps, direct boxes (DIs), and



A Lundahl transformer at the heart of a Focusrite ISA One mic preamp.

even mixing consoles – especially in recording work, but also in many live sound applications – all depend on transformers to match the high impedances of the tubes to useful interstage and output impedances. Guitarists, bassists, Hammond organists and other musicians know, without having to think about it, that the sound they want to achieve is only possible through the use of tube amps and tube preamps. Digital modeling aside (and we're not knocking it), there is nothing quite like the sound and linear control of vacuum tubes in Keith Emerson's organ, or Jimi Hendrix's guitar, to name only a pair of iconic tone masters who relied on tube circuitry and thus on transformers (even if they didn't know it at the time).

But the debate over solid state circuitry versus tubes is not as clear-cut when it comes to mic preamps, DIs, compressor/limiters and other signal processing devices, in which high levels of controlled distortion are not the same goal as they are in instrument amplifiers. That said, a quick glance through a current pro audio catalog will show that tube-based pre-amps, DIs, microphones, and many other products are not only alive and well, but gaining ground. Without the availability of precision transformers – and "precision" is the key word here – the clean, clear, accurate, and sonically pleasing reproduction of tube microphones, tube pre-amps, and tube power amps would not be possible.

The use of tubes in a circuit requires transformers to match impedances from one audio stage to another. And even op-amps and transistors, collectively known as solid state devices, can benefit greatly by the use of transformers. Whether it's an inter-stage connection in a tube amplifier, or multiple solid state devices connected one to another, sub-optimal impedances will "impede" optimal performance. Transformers were developed to address these engineering issues and they do just that.

Does solid state spell the end of the transformer? A good question. Op amps are used in the majority of all modern audio products and the optimal noise performance is attained when the characteristic "noise resistance" of the amplifier, Rn, is equal to the source resistance, Rs. While transformers are not required, as in tube circuits, a precision input transformer will optimize the op-amp to the source impedance, which is unequal to the op-amp's Rn. And that's why many high performance mic preamps that use solid state integrated circuits, also employ transformers.

Microphones

Mics need to provide sufficient voltage to the pre-amp to overcome noise, as well as suitable source impedance and a high value of CMRR (common mode rejection ratio). However, many mic elements are not natively able to do so. This is an important application for transformers which are present in one form or another in the majority of today's mics. Moreover, the last two decades have seen many new tube microphones enter the market. The pre-amp circuits in the mics require transformers to properly feed the preamp stage, which may also be of the tube variety, closing the loop (as it were).

But to fully close it, all-tube mixing consoles also exist, though the breed is rather rarefied. Hybrid consoles, that is, solid state combined with tubes, are more common (though still quite esoteric) in the quest to "warm-up" the sound of digital. All of these products require the use of transformers.

Transformer Function

Transformers consist of coils of wire wound around a metallic core. A signal applied to the primary windings is electro-magnetically coupled to the secondary windings, rather than electrically coupled. That's why we say transformers provide galvanic isolation. It helps to think of a transformer as a lever. If the fulcrum is in the middle, like in a see-saw, than neither the voltage nor the current will alter from the primary to the secondary.

Figure 1 depicts a 1:1 transformer. The term 1:1 means that an equal number of windings are present in both the primary and the secondary coils. The lever analogy is shown directly below the schematic symbol. This is a common form of transformer, designed mainly for galvanic isolation, though it will also inhibit RF and block DC. (Note: in the figures, U is voltage, I is current, and P is power.)

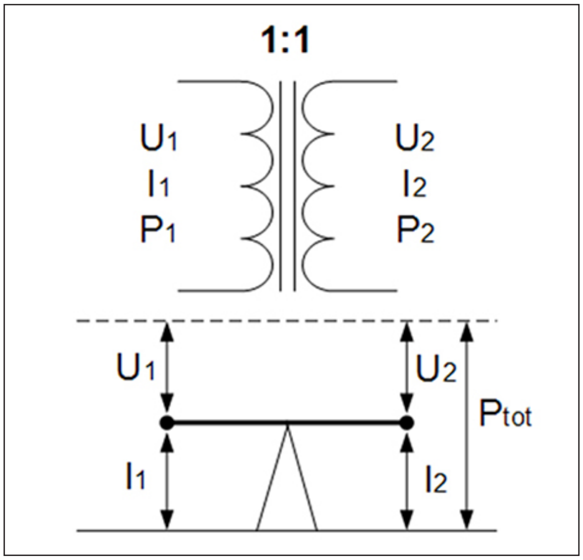


Figure 1

Figure 2 depicts a 1:2 transformer, again showing the lever analogy. In this case, the secondary has twice the number of windings as the primary. Voltage proportionally follows the number of turns and will be two times as high at the output of the secondary windings as it will be at the input to the primary windings (this is a rule of the thumb for an unloaded secondary).

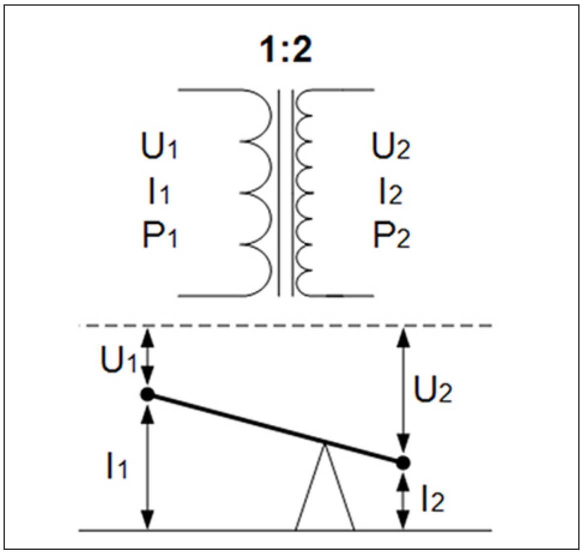


Figure 2

It's important to note that transformers are passive devices and cannot increase power like an amplifier. Instead, they scale voltage and current up or down as needed, to optimize a given circuit.

Winding Methods

In previous papers, we've delved deeply into how Lundahl differs in design and manufacturing, in the quest to make the ultimate transformers for audio applications. But to briefly recap: the majority of transformer manufacturers use bobbins and winding machines that can be purchased for a price.

Lundahl takes an altogether different approach. The company has perfected a unique stick-winding method of constructing audio transformers that sets them apart from virtually all others. This unique winding methodology, combined with top quality materials and exhaustive attention to detail, add up to flat phase and frequency response, exceptional linearity, and extremely low distortion.

These properties give Lundahl transformers an unembellished sonic quality that would be impossible to achieve without the decades of research and development that shaped the company's approach to transformer design and manufacturing.

In the next chapter we'll discuss in greater technical depth how transformers are used to optimize circuits, and will even add in a little math to illustrate the points.

# # #

About The Author
Ken DeLoria is senior technical editor for ProSoundWeb and Live Sound International magazine, and has had a diverse career in pro audio over more than 30 years, including being the founder and owner of Apogee Sound.
The author wishes to thank Lundahl senior engineer Mirza Zametica for his considerable contribution to this paper.

Chapter 6: Exploring The Electrical Characteristics Of Audio Transformers

A White Paper from Lundahl Transformers
www.lundahl.se

Presented by ProSoundWeb
By Ken DeLoria

LUNDAHL
– TRANSFORMERS –

In the previous chapters of this series, we've discussed various transformer-related applications with an emphasis on *why* audio transformers are unique among electrical components in their ability to provide 100 percent galvanic isolation. In this chapter we're going to explore the basic electrical characteristics of audio transformers to better understand the differences among various types, and why one transformer is better for a given application than another.

There are four important properties to consider. These are:

- Primary impedance / Primary inductance $\mathbf{L_P}$
- Copper wire resistance in windings **R**
- Leakage inductance $\mathbf{L_L}$
- Internal capacitance $\mathbf{C_T}$

A transformer is a passive device. Thus, its behavior in any given application is dependent upon the source and load that are connected to it. All transformers have a primary impedance value which is largely a function of the inductance of the windings, determined by the transformer's design. The primary input impedance can be low or high, but in audio applications it should be significantly larger than the impedance of the load (as seen through the transformer) in the required frequency range.

In the schematics below, primary impedance is labeled **Lp**, where the **L** represents inductance and the **p** represents primary. Therefore, **Lp** simply means "primary inductance."

Next, there is always internal resistance from the transformer's copper windings. This is labeled **R**.

Third, all transformers exhibit internal leakage inductance, labeled $\mathbf{L_L}$.

Finally, transformers also exhibit internal capacitance, which is labeled $\mathbf{C_T}$.

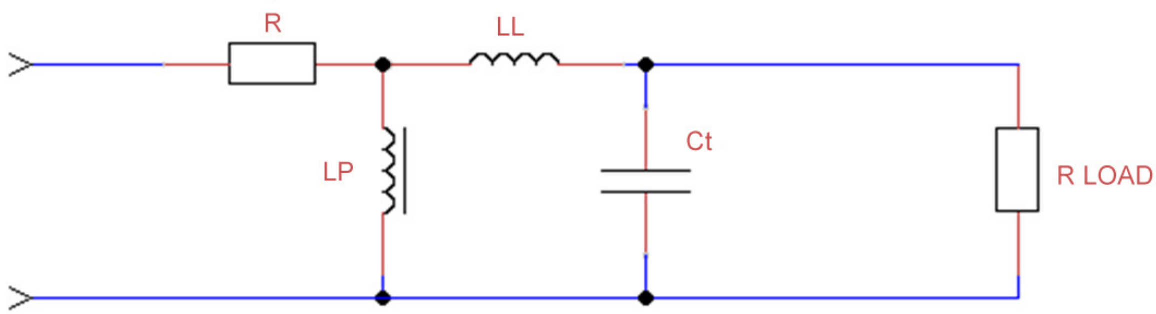


Figure 1

The schematic in **Figure 1** (above) illustrates a simplified electrical equivalency circuit of these properties, each represented by familiar discreet components that together make up the characteristics of a transformer's electrical behavior. For those unfamiliar with equivalency circuits these are not external components that should be *used* with the transformer, but rather, they serve to show what's taking place *inside* the transformer by breaking down the fundamentals into separate "equivalent circuits."

In addition, the properties depicted in the equivalency circuits are actually distributed within the transformer itself, but for discussion purposes they can be represented as discrete components. As you can see, the primary inductance and the internal capacitance are in parallel with the load, whereas the copper resistance and the leakage inductance are in series with the load.

In many applications the above equivalent circuit can be simplified additionally. If the load impedance is high, the leakage inductance can be ignored, as illustrated in **Figure 2** (below).

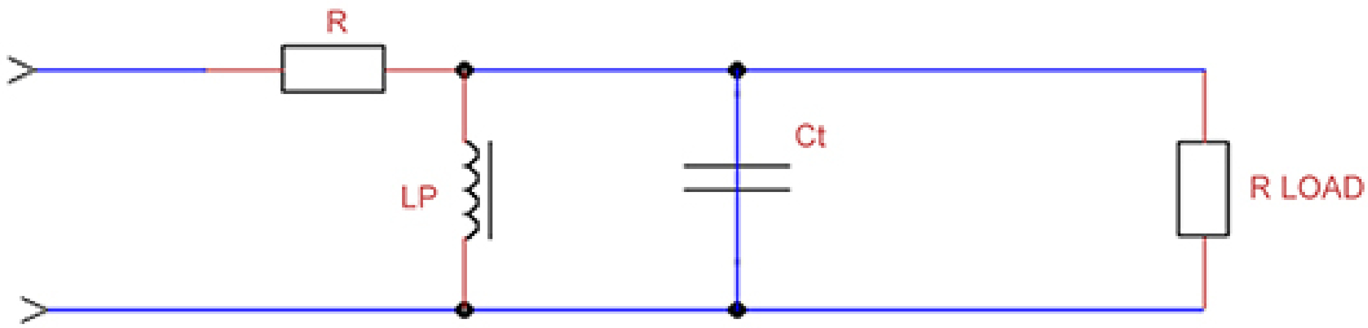


Figure 2

The model in **Figure 3** (below) illustrates the opposite of Figure 2. When $\mathbf{R_L}$, the load impedance is low, the influence of the internal capacitance is minimal, and can thus essentially be ignored.

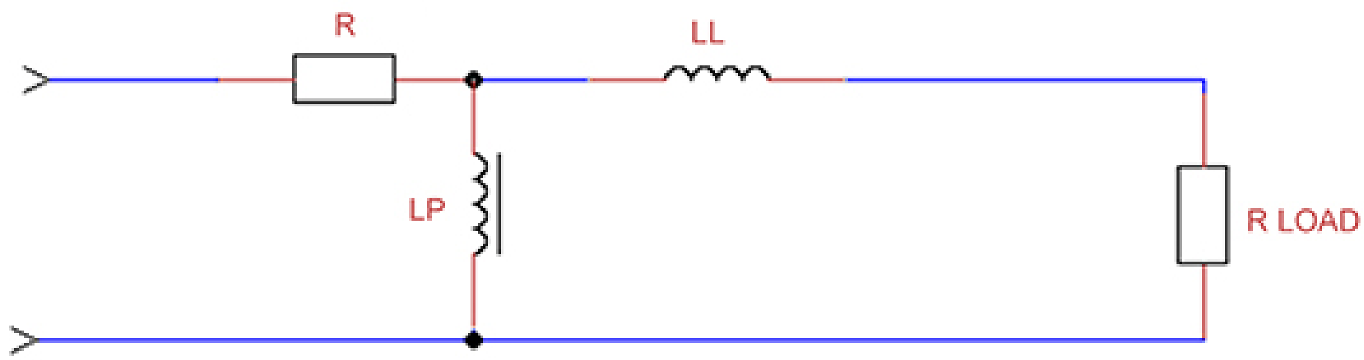


Figure 3

All Transformers Are Not Created Equal

An optimal transformer design must take into account the specific application, as well as any anticipated variations of the 'normal' practices that the transformer design is intended for. While it's certainly useful to test and characterize a given transformer by measuring its frequency and phase response on the test bench with a fixed input and output impedance, the measured results will provide only a piece of the complete picture. Performance will alter as the source and load impedances change; this is a basic fact of physics.

In many applications it may not be possible to always know in advance what the input and output impedances will actually be, a normal condition that rental companies face every day. Moreover, source or load impedances (usually load) might change on- the-fly as additional devices are paralleled together during a system configuration change. Or, the source impedance alters because one output device is substituted for another.

In cases such as these, which are absolutely common in real-world practices, a given transformer's response, in respect to frequency, phase, signal handling capability and distortion, might be quite different than that of its published response curves. It is therefore prudent to choose transformers that will continue to behave linerially – even when source and load impedances alter – so that system changes can be accomodated without compromising audio quality.

Balancing Parameters

We've established that the impact of a transformer's leakage inductance and internal capacitance will vary in respect to source and load impedance. That now begs the question, "What can be done to minimize these effects?" To start with, a transformer's leakage inductance and capacitance are a function of the interleaving of the primary and secondary windings: more interleaving (usually referred to as "sectioning") results in less leakage inductance but more capacitance. Less sectioning, and the opposite occurs: more leakage inductance but less capacitance.

The short answer is that optimal performance ties directly to the design decisions that were made when the transformer was conceived, prototypes were built, and subsequent production units were manufactured. There is no magic bullet. Nonetheless, developing a superior transformer product is not a random event; it is the result of expertly balancing all electrical and mechanical parameters – which include frequency and phase response, bandwidth, signal handling, and distortion – to best meet the specific application that the design was intended for. Optimal transformer design, and superior quality manufacturing processes, are the result of many years of engineering development.

The Perfect Transformer

In an ideal situation you would want **Lp** (primary impedance) to be infinite and **R**, $\mathbf{L_L}$ and $\mathbf{C_T}$ to be zero. If they were, you could ignore the influence of the transformer on your circuit design.

Of course this is not possible. Restrictions such as size and signal level capability – not to mention cost – must be factored into the design. Size is an important and often determining factor; a small transformer cannot handle high signal levels unless high copper resistance is accepted, whereas a large transformer with more iron cannot fit into many products, especially not small devices such as microphones or in-line XLR isolation "barrels."

Moreover, each of the properties discussed above are inextricably linked to one another. An alteration made to one property will change all the others, and normally in an unfavorable direction.

Design Variables

Copper wire resistance in the transformer's windings causes a signal drop because it is a resistance in series with the load. A way to reduce the copper resistance is to use fewer turns of wire. However, this will reduce the transformer's signal level capability while also reducing the primary inductance value.

If the primary inductance (impedance) is not high enough compared to the (transformed) impedance of the load, there will be an LF roll-off. To increase the transformer inductance you can increase the number of turns of wire. But that will also increase the transformer's internal copper-wire resistance.

In high impedance applications (mostly input situations) the $\mathbf{C_T}$ must not be too large, as it is in parallel with the load and will cause an HF roll-off. Given a reduction in $\mathbf{C_T}$ you can reduce the sectioning of the transformer. Sectioning is the extent to which the primary and secondary windings are interleaved, but if you reduce sectioning then $\mathbf{L_L}$, the leakage inductance, will increase.

In low impedance applications (mostly outputs) the leakage inductance must be kept small because it's in series with the load and will cause an HF drop. You can increase the sectioning to reduce leakage inductance, but at the cost of increased $\mathbf{C_T}$. This begins to look like an equation that is impossible to solve.

Making It Possible

When one carefully considers the interplay of tradeoffs that must be addressed in balancing one parameter against another, it becomes clear the task requires engineering knowledge coupled with years of skilled, empirical research experience. The decades of design and development work that have led to Lundahl's success are indeed the *foundation* of that success. There is no substitute for time spent, nor for the passion that has relentlessly driven the R&D efforts of the company.

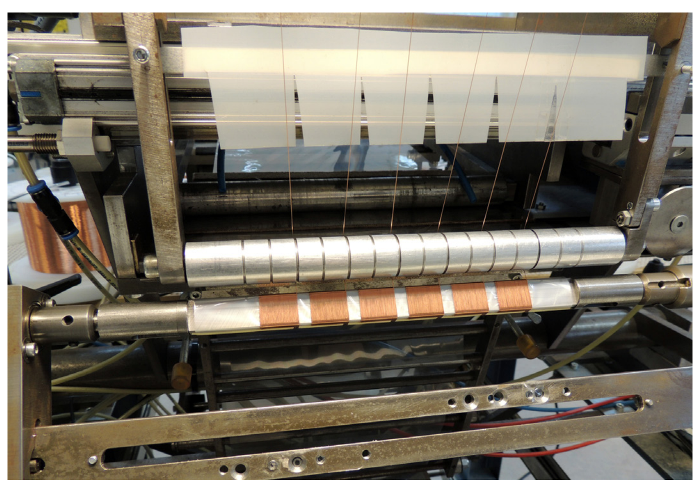
When a customer explains their specific application and requirements, the task is to select a transformer type that balances each of the parameters for optimal performance. In some cases a stock model may be a perfect fit. For other applications the optimal solution may require a custom design of a completely new model. When all design parameters have been expertly balanced in relation to a specific application, it is normally possible to find a solution in which you can almost ignore the transformer properties throughout the audio frequency spectrum, and even throughout an *extension* of the spectrum.

However, finding the best transformer for your particular application, when constraints such as size, shape, budget, etc., are present – and they always are – is extremely difficult to accomplish without an engineering partner that possesses the depth of understanding of how to balance achievable performance against "wish lists," ultimately achieving the desired end-result.

Windings Are Everything

As noted in previous chapters, the nature of any transformer's windings are critical to its performance capability. Sloppy windings equal inferior performance. It's simple magnetics.

Let's briefly recap Lundahl's winding technique. Unlike most – in fact nearly all transformer manufacturers around the world – Lundahl use a technique called stick winding. Other manufacturers use round bobbins that are wound on readily available machinery. Lundahl does not. Instead, the company winds copper wire around "sticks" that range in size from very small (for micro-



A Lundahl winding machine performing stick winding.

phones) to about the size of a pack of gum (and larger) for applications that have less limited size restrictions.

NOTE: All other factors being equal, larger transformers can handle higher signal levels than smaller ones before core saturation occurs. This is due to the greater content of metal in the transformer's core. Saturation results in an immediate rise in distortion and should always be avoided.

One of the many advantages of Lundahl's stick winding technique is that it yields a smaller size for a given performance specification, along with an OEM-friendly form-factor. Form factor is very important in confined spaces. Obviously, most microphones do not have room for large transformers. Other applications are space-sensitive as well. These include direct boxes, 500 Series modules, outboard preamplifiers and limiters (especially tube-based), and in-line isolators. Lundahl manufactures an XLR-XLR isolation transformer in a "barrel" package (pictured below) that accepts full line level signals, exhibits excellent specs, posesses superb sound quality, and is no larger than a typical XLR-XLR ground lift or phase-reverser.

There is no disadvantage to stick winding other than that Lundahl has had to design and build all of its own manufacturing machinery, control electronics, and machine-control software. But ultimately that works out to be an *advantage*, as the company is able to control the entire process from raw materials to finished goods. And with control comes a level of quality and uniformity that's integrated into Lundahl's core philosophy of achieving maximally obtainable sonic transparency.

Many subtleties are present in manufacturing transformers and each plays an important role in how the end product will perform. Not the least is maintaining uniformity in the windings. Lundahl manufacturers its own winding machines in order to optimally control winding tolerances, wire tension, winding speed, and other critical parameters. Below are some examples of how precision transformers can solve various common problems.

Long Lines

Large systems often require very long lines to interconnect one branch of the system to another. Permanent installations in sports venues, large festivals, temporary events with broadcast and recording trucks positioned in the parking lot, and numerous other applications, all require very long audio lines. When driving long lines it's important that $\mathbf{L}_L$, the leakage inductance, is kept low. Otherwise a resonance between the cable capacitance and the transformer leakage inductance may occur. This problem is commonly solved with bifilar wound output transformers, but can also be solved with highly sectioned output transformers, which will provide uncompromised electrical insulation and superior common mode rejection compared to the bifilar technique.

Free Gain

When a signal source exhibits very low impedance, compared to the input impedance of the preamplifier or amplifier that it's driving (e.g., ribbon mic elements and moving coil cartridges fit this description), a step-up transformer can provide the much-needed voltage gain…almost for free. Of course, in the strictest technical sense gain is not actually added (the transformer remains a passive device), but *apparent gain* occurs due to the improved matching of the input impedance to the source and the output impedance to the load.

Impedance Matching & Voltage Step-Up

Impedance is a measure of the relationship between voltage and current. When discussing output impedance, a low value (normally desired) indicates how well a source can maintain a certain voltage under different loads. In particular it indicates how well the voltage can be maintained even if the load impedance drops. A high input impedance (normally desired) indicates how easily, or how little current is required, for a source to reach a certain voltage across the input.

Some signal sources, in particular ribbon microphone motors and moving coil cartridges, have an impedance level that is much lower than optimal. In addition, they also have a very low output voltage and require substantial voltage gain to overcome noise in the line and in the preamp. With the use of a step-up transformer the small voltage signal can be increased noise-free by 20-30 dB (or more) by trading the very low source impedance to a still acceptable medium impedance output.

Other signal sources, such as electron tubes, have plenty of voltage swing but too high of a source impedance to work well in audio systems. In this case, a step-down transformer is used to reduce the source impedance, but at the cost of voltage swing.

As should now be clear, the humble transformer – which seems so simple on a schematic diagram – is anything but. The numerous parameters that must be juggled during the design phase require significant knowledge to comprehend, and a wealth of experience to optimize. The commitment that Lundahl has made to manufacturing what are arguably the most *transparent* and *effective* transformers available anywhere in the world, is the result of Per Lundahl, and his father before him, walking the path of no compromise.

Per Lundahl: "A question often raised is if Lundahl provides an output transformer for matching consumer audio products to pro audio systems. A step-up of 14 dB is normally required. However, as the output impedance of many consumer audio products is in the range of 1K, a 14 dB step-up would increase the impedance to 25K, which is too high to drive a line without the risk of noise pickup. We'd rather miss out on a sizeable market opportunity than make something we know is not optimal."