

Unwinding Distribution Transformers

- High Voltage Audio Distribution
- Transformers at the Power Amp End
 - Turns Ratio
 - Saturation
 - Insertion Loss
- Transformers at the Loudspeaker End
 - Impedance Matching
 - Isolation

Paul Mathews
Rane Corporation

RaneNote 159
© 2005 Rane Corporation

Introduction

What could be more mundane than the transformers and autoformers that are the backbone of audio distribution systems? This article will show you that there is a lot more going on with these chunks of iron and copper than you ever suspected. Learn why **transformers are often the power bottleneck in distribution systems**, learn how to interpret datasheets, believe or disbelieve manufacturers' claims, how to specify HV components, and how to setup HV systems to deliver the best possible power, fidelity, and bandwidth.

High Voltage Audio Distribution Systems

Although the term *Constant Voltage* is still in common use, this article adopts the less confusing *High Voltage* (HV) terminology. HV systems are in widespread use for these principal reasons:

- HV systems minimize power losses in low-cost wiring.
- HV systems facilitate connection of multiple loudspeakers without careful consideration of impedance matching.
- Once an individual power adjustment on a loudspeaker has been made, the loudspeaker continually receives the same amount of power even when other loudspeakers are added or removed from the system, resulting in more constant and uniform coverage.
- Volume control by transformer tap at the loudspeaker end is more efficient than resistive pads.

Transformers at the Power Amp End Boosting the Output Voltage

Solid state power amplifiers usually need a voltage boost to get to the 70.7 volt and 100 volt levels of most HV systems, and a transformer or autoformer will do the job. The differences between transformers and autoformers will be covered later (see the *To Isolate or Not to Isolate?* section). In the meantime, the term *transformer* will be used to refer to both types. The transformer boosts the amplifier output by a fixed ratio, called its *turns ratio*. The correct transformer will provide the right amount of boost, which is simply the desired HV system voltage, e.g., 70.7 volts, divided by the amplifier full power output voltage.

Here is the basic procedure for selecting an output transformer for an HV system where the amplifier power required P has been determined using suitable methods:

1. Determine TURNS RATIO to get proper HV level.

- Measure the unclipped rms output voltage available from the power amplifier or calculate if from Ohm's Law:

$$V_{OUT} = \sqrt{P \times R}$$

For example, for an amplifier rated 100 watts at 8Ω:

$$V_{OUT} = 28.3 \text{ Vrms}$$

- Calculate desired voltage boost ratio, aka *turns ratio*,

$$N = V_{HV} / V_{OUT}, \text{ e.g., } N = 70.7 / 28.3 = 2.5$$

Select candidate transformers with turns ratio within 20% of calculated N and with datasheet power ratings similar to amplifier output wattage.

2. Determine TRANSFORMER SIZE to prevent saturation.

- VERY IMPORTANT: Decide on the lowest system frequency f_{LC} for good fidelity and full power delivery.
- Find datasheet ratings or conduct tests to determine voltage tolerance of candidate transformers at f_{LC} .
- To qualify, a transformer must not saturate when driven with V_{OUT} at f_{LC} . You may or may not be able to determine this characteristic from datasheets. Read on.

The low frequency voltage capabilities of the transformer will be the primary limiting factor in system power delivery.

TURNS RATIO: Finding It on the Datasheet

Turns ratio does not show up on many datasheets, but you can usually calculate it from other specifications. From the information on a transformer datasheet, find any combination of specifications that relates primary voltage, or primary power and impedance, to secondary voltage. Use these equations, based on Ohm's Law and Joule's Law, to calculate the missing specification.

$$V_{PA} = \sqrt{P \times R} \quad V_{HV} = N \times V_{PA} \quad N = \frac{V_{HV}}{V_{PA}}$$

For example, from transformer datasheet specs showing "300 watts at 4Ω" (amplifier/primary side) and "70.7V output" (secondary), use the first equation to calculate power amp output voltage $V_{PA} = 34.6V$. Then, use the third equation to calculate $N = 2.04$.

Some transformers have what their datasheets call *voltage taps*. For example, a transformer might have 25 volt, 35 volt, and 45 volt primary taps, along with 70.7 volt and 100 volt secondary taps. For any combination of primary and secondary taps, the effective turns ratio is simply the ratio of the secondary tap value to the primary tap value, as given in the third equation above.

Now that we have the Turns Ratio (Step 1 above), let's look at the other most important performance determining characteristic, which is voltage capability, usually determined by transformer size and weight.

SATURATION: What's All the Flux About?

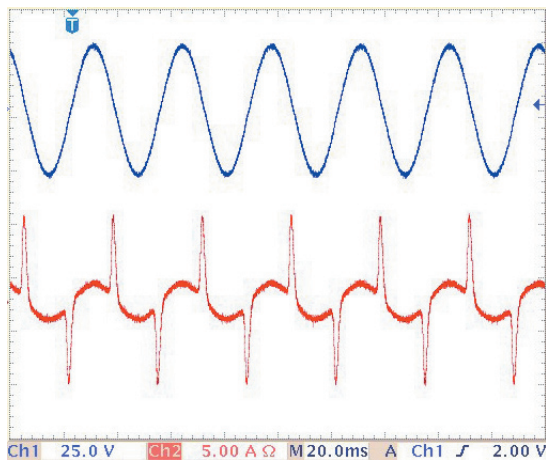
Transformers have *saturation* problems that limit their capabilities at low frequencies. In fact, a transformer that is doing a great job at 100 Hz can be an amplifier killer just an octave lower. What happens when a distribution transformer saturates? What does saturation sound like? Does this mean you have to high pass all your HV systems? These and other questions are answered here.

What Happens When a Transformer Saturates?

Transformers transfer power from winding to winding by coupling through mutual magnetic fields. This transfer of power is amazingly efficient, and it happens with or without a core. However, the iron core plays two essential roles:

1. The core *contains* the magnetic fields. Without a core, significant portions of the magnetic fields balloon out around the windings, reducing mutual coupling and potentially causing interference problems.
2. The magnetic field in the core itself *opposes uncoupled current flow in the primary*. This is why the transformer primary, even though it is made of heavy copper wire, does not normally act like a short.

Without a core, the primary **does** act like a short, and a **saturated** core is not much better than no core.



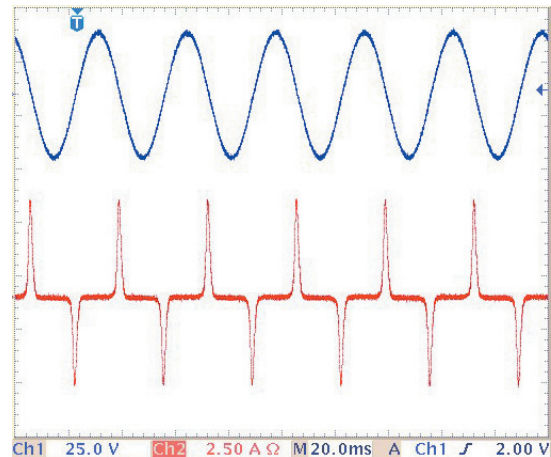
Here are the primary voltage (top) and current (bottom) oscilloscope traces for a distribution transformer entering saturation toward the end of each half cycle of input. Both waveforms should be sinusoidal, but the spikes on the current waveform are due to saturation. Notice that the power amplifier, in this case, is still doing a good job of delivering a sine wave, in spite of the current spikes. A less-robust power amplifier would show noticeable distortion coinciding with each spike. The coupling between primary and secondary is not much affected by core saturation. However, during saturation, the dc resistance of the primary suddenly appears in parallel. The power amplifier tries to maintain its output voltage, but the load impedance has taken a sudden dive.

Core saturation happens when the magnetic field in the core reaches its maximum possible density, which

is what happens when the applied voltage polarity remains the same for too long.

Saturation has nothing to do with power delivery: the onset of saturation depends only on the voltage waveform applied to the primary.

To reinforce this point, the next graphic shows amplifier voltage and current with an unloaded (open circuit) secondary. The current waveform stays near zero until the volt-seconds limit of the primary is reached.



For audio signals, core saturation is more likely as you lower the frequency and raise the applied voltage. In the preceding photo, the input was 20 Vrms at 25 Hz. The onset of saturation depends on voltage and time, so expect to see a similar problem for 40 Vrms and 50 Hz.

The saturation **voltage** of a transformer rises linearly with frequency. This means that **power** handling capability declines with the inverse square of the frequency.

It should be no surprise that DC voltages are a serious problem for transformers, since DC is like zero frequency. Indeed, dc offsets of a few tens or hundreds of millivolts can asymmetrically saturate a transformer, meaning that saturation current spikes will occur primarily on one signal polarity. For this reason, some power amplifiers are a poor match to distribution transformers. This is also one reason why some manufacturers recommend installing resistors and capacitors in series with distribution transformers, further impacting low frequency response. Well-designed power amplifiers have low offsets, and well-designed transformers tolerate a reasonable level of offset.

The Sound of Saturation

When power amplifiers suddenly finds itself having to deliver massive amounts of current, most will protect themselves by throttling back their output voltage. On the better amplifiers, Safe Operating Area (SOA) circuitry kicks in. On less well-designed units, the internal power supply voltages collapse, and the amplifier circuitry is simply unable to continue to deliver a faithful signal. Some amplifiers may blow fuses or simply fail. The sound that you hear depends very much on how a particular amplifier responds to this type of overload. Most likely, you will hear badly distorted bass and/or signal drop-outs.

Size Matters

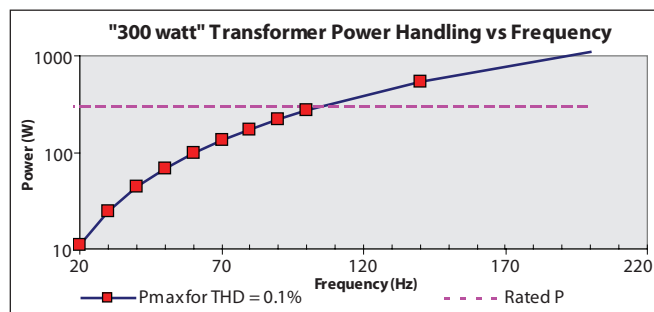
As with most things audio, you need larger components to handle lower frequencies, and the same is true for transformers. If other design elements are held constant, the larger cores can tolerate higher primary voltage levels, because magnetic fields produce lower flux densities over their larger cross-sectional areas. Another way to improve the voltage capability of a transformer is to increase the number of turns in each winding. However, unless the wire size is made smaller (resulting in higher resistive losses), the core may still have to be made larger to accommodate the additional turns of wire.

Many of the distribution transformers we tested would have much improved performance if their designers had simply added a few turns of wire to their design.

Where Does It Say *Saturation* on the Datasheet?

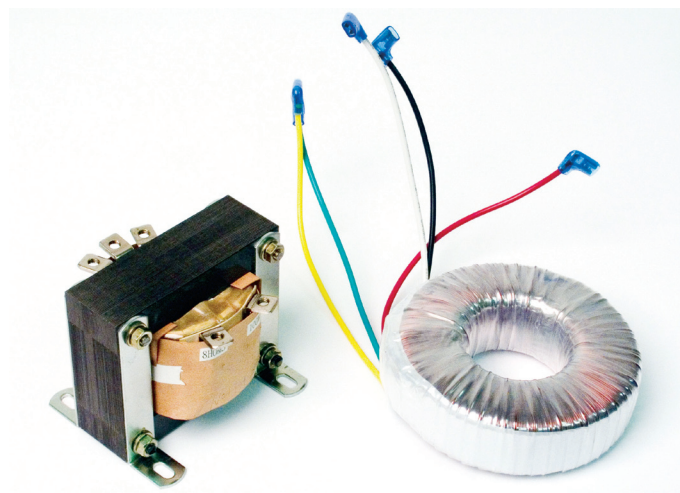
Unfortunately, most transformer datasheets are not much help in providing specifications for low frequency performance. Some provide a vague 'Frequency Response' range. Our tests indicate that this is usually hopelessly optimistic if not dishonest: the power bandwidth at the low end is generally much lower than the specification. Fortunately, since no secondary load is required to observe saturation, bench measurements are easy. Connect a sinewave source to the primary with a small-value resistor in series. Measure the rms voltage across the primary with a voltmeter or an oscilloscope. Similarly measure the voltage across the resistor. Start at 1 kHz and sweep downwards. Across the resistor, you should measure a small voltage (proportional to primary current) that increases slowly as you decrease frequency. At some frequency, you will

observe an abrupt increase in resistor voltage, indicative of the onset of saturation. Change the drive voltage and repeat the sweep. You should be able to derive a graph like the one shown here. This particular '300 watt' transformer has a datasheet indicating "Frequency Response: 20 Hz to 20 kHz." How would you rate it?



What About High Frequencies?

From the discussion about low frequencies and saturation, you have probably guessed that saturation is not a problem at high frequencies. However, other non-ideal characteristics come into play. Stray magnetic fields, uncoupled between primary and secondary, show up as *leakage inductance* in series with the windings. Leakage inductance reduces the voltage available to the load at higher frequencies. Core losses are another phenomenon affecting high frequencies. The better cores use more expensive steels and thinner laminations. Datasheet specifications are reasonably reliable indicators of high frequency performance.



Toroidal (at right in photo) types of transformers tend to have lower leakage inductance and better high frequency performance than most E-core models (at left in photo). However, excellent performance is available from either type of core: it all depends on the details of the design.

What About Insertion Loss?

Insertion loss seems to be a mandatory specification for distribution transformers, although we find it difficult to understand why. Losses in loudspeakers themselves totally dominate most audio systems, and audio power is easy to find and cheap to buy. It is almost impossible to overheat even very lossy distribution transformers with audio program material: there is just too much iron, copper, and surface area in a transformer that is large enough to couple at low frequencies, and average audio power is so much lower than the peaks that the transformer must accommodate. Finally, the winding resistance that causes insertion loss can be a desirable feature, since it improves the transformer's tolerance for DC offsets.

Insertion loss is not useful as distribution transformer specification. Instead, focus on the a transformer's ability to deliver power at the highest and lowest required frequencies.

Transformers at the Loudspeaker End

On the secondary side of the power amplifier distribution transformer, we connect HV loudspeakers in parallel (each with its own step-down transformer), and adjust *power taps* as required to achieve required loudness in each area. System designers usually specify HV loudspeakers with integral transformers, so you might suppose that the drivers and transformers are well-matched, so why worry? It turns out that ten little 10 watt transformers in parallel can be just as troublesome as one big 100 watt transformer.

The transformer characteristics discussed above apply equally at the loudspeaker end.

Loudspeaker Step-down Transformers and Saturation

The transformers at the loudspeaker end are prone to saturation, just like their big cousins at the amplifier end. Imagine the effect of 10 or more transformers all reaching voltage saturation in parallel and at the same time. Moreover, since saturation depends only on voltage, each loudspeaker transformer should be able to withstand full HV voltage levels at the lowest system frequency, regardless of the amount of power

allocated to it. This is why most HV loudspeaker modules include a series capacitor to reduce the likelihood of transformer saturation. Note, however, that these capacitors are perfectly suited to carrying saturation current spikes once those spikes begin to flow.

Is Impedance Matching Important?

For best results, adjust loudspeaker taps so that they sum to either the power amplifier output rating or to the power amplifier distribution transformer rating, whichever is smaller. This will present the proper rated load impedance to the power amplifier, allowing it to develop rated power, while minimizing saturation effects in the transformer at low frequencies.

If additional loudspeakers are added or power tap settings are increased beyond the amplifier or transformer rating, load impedance for the power amplifier will go down proportionately. However, a smaller but still linear load impedance is usually the preferred alternative to a highly nonlinear saturating transformer.

To Isolate or Not to Isolate?

Distribution transformers are available in both autotransformer (non-isolating) and transformer (isolating configurations), so you have the option of isolating the loudspeaker wiring from the amplifier wiring. Here's a couple of reasons why you might want to.

Safety Isolation

Distribution transformers can provide an additional barrier between lethal mains power potentials and accessible loudspeaker terminals. HV lines from isolating transformers have no potential relationship with respect to earth ground, so that shocks are unlikely except in the event of contact with both lines at once. Some electrical inspectors require that HV lines be isolated from power amplifier outputs.

Isolation to Break Ground Loops

For the many types of audio equipment that have shielding potentials connected to safety ground, non-isolated HV loudspeaker lines occasionally provide a return path for ground loops with enormous extents. In this era of plastic loudspeaker enclosures, this is becoming more rare.

Summary

1. Selecting a Distribution Transformer at the Power Amp End:
 - a) Select **proper turns ratio** to boost to HV system level *and* to present an acceptable impedance to the power amplifier. You may have to derive turns ratio from other specs.
 - b) Select for adequate low frequency **voltage** capability to prevent saturation for **good low frequency power transfer**. You may have to make your own measurements.
 - c) Verify sufficiently low leakage inductance and low core losses for **good high frequency power transfer**. It's usually OK to use datasheet information.
2. Transformers at the Loudspeaker End:
 - a) Suffer from the same problems and can equally become the weak link in a system.
 - b) Are often 'matched' to and included with loudspeaker modules, so be aware of inherent characteristics.
3. Toroids versus E-cores: details are more important than shape.
4. Transformer isolation: can improve safety and eliminate ground loops.