Audio Transformer Bandwidth Design Guide

Practical First-Pass Design Method

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An audio transformer cannot be judged by the phrase "flat from 20 Hz to 20 kHz" by itself. The useful question is: flat into what load, driven from what source impedance, at what signal level, and with what allowable error? Without those values, the bandwidth claim is incomplete.

This article presents a practical first-pass way to think about audio transformer bandwidth. It is intentionally simple. The goal is not to pretend that the transformer is solved by four equations. The goal is to separate the low-frequency problem from the high-frequency problem so the first design direction is reasonable before the real construction details are handled.

A simple audio transformer bandwidth design has two main enemies:

- At the low-frequency end, the primary magnetizing inductance must be high enough that it does not draw too much current.
- At the high-frequency end, leakage inductance and winding capacitance must be low enough that they do not remove or distort the top end.

Those two requirements fight each other. More turns can improve low-frequency response by increasing primary inductance, but more turns can also increase leakage inductance and capacitance. This is why audio transformer design is not simply "add turns until the bass is good."

This method is intended as a first-pass engineering approach, not a final production design. A finished audio transformer must still be checked for core material, flux density, signal level, distortion, DC bias, winding capacitance, leakage inductance, shielding, insulation, winding resistance, temperature rise, and actual measured response.

1. The First-Order Model

For the first pass, treat the transformer as ideal except for two nonideal elements:

- primary magnetizing inductance, which controls the low-frequency behavior;

- leakage inductance, which helps limit the high-frequency behavior.

At low frequency, use this simplified primary-side model:

Source resistance feeding a transformer input of: $Z_{in} \approx R'_L \parallel jX_m$

Where:

- R'_L is the secondary load resistance reflected to the primary side.
- X_m is the primary magnetizing reactance at the low-frequency limit.
- The secondary load is assumed real.
- The primary magnetizing branch is assumed imaginary.

This is not the whole transformer. It is just the cleanest model for understanding why primary inductance matters at the low end.

2. Reflect the Load Before Judging the Primary

The secondary load must be moved to the primary side before comparing it to the primary magnetizing branch. For a transformer with primary turns N_P and secondary turns N_S:

$$R'_L = \left(\frac{N_P}{N_S}\right)^2 R_L$$

This reflected load is the real load branch that appears in parallel with the primary magnetizing inductance. Once the load is reflected, both branches are on the same side of the transformer, see the same primary voltage, and can be compared honestly.

This is the main point that is easy to miss. The magnetizing current is a primary-side current. Therefore the clean comparison is not usually magnetizing current versus actual secondary current. The clean comparison is:

Primary magnetizing current compared with primary-side reflected load current.

That comparison is more meaningful because both currents are caused by the same primary voltage in the simplified equivalent circuit.

If the actual secondary current is used instead, the target changes when the turns ratio changes. That can make the design look stricter or looser for the wrong reason. Referring the load to the primary keeps the comparison on one side of the transformer.

3. The 10 Percent Magnetizing Current Rule

A practical "good" starting point is:

$$I_m \approx 0.10 I_L'$$

Where:

- I_m is the primary magnetizing current.
- I_L' is the primary-side reflected load current.

Since the magnetizing branch and reflected load branch are in parallel, they see the same primary voltage. Therefore, for the magnetizing current to be 10 percent of the reflected load current:

$$X_m \approx 10 R_L'$$

Then the required primary magnetizing inductance is:

$$L_m = \frac{X_m}{2\pi f_L}$$

Where f_L is the required low-frequency limit.

This is why low-frequency audio transformers can need large primary inductance. If the transformer must work cleanly at 20 Hz, the inductive reactance must already be large at 20 Hz. If the low end only needs to reach 200 Hz, the same inductance gives ten times the reactance and one-tenth the magnetizing current.

A useful way to say it is:

> The lower the required bass extension, the more the transformer must depend on inductance.
> The higher the low-frequency cutoff, the more frequency itself helps the design.

4. Impedance Matching and Turns Ratio

If the purpose is impedance matching, choose the turns ratio so the load reflects to the source impedance.

For example, if the source is 50 Ω and the load is 200 Ω, the required primary-to-secondary turns ratio is:

$$N_P : N_S = 1 : 2$$

That reflects the 200 Ω load to:

$$R'_L = \left(\frac{1}{2}\right)^2 200 = 50\ \Omega$$

Now the transformer has been converted into a primary-side problem. At the low end, the first-pass input model is:

$$Z_{in} \approx 50\ \Omega \parallel jX_m$$

For the 10 percent magnetizing current target:

$$X_m = 10(50) = 500\ \Omega$$

At 20 Hz:

$$L_m = \frac{500}{2\pi(20)} \approx 3.98\ \text{H}$$

So a first-pass matched 50 Ω to 200 Ω, 20 Hz audio transformer would want about 4 H of primary magnetizing inductance for this rule.

If someone instead compares magnetizing current to the actual secondary current, they would get a different answer. For this 1:2 transformer, that stricter comparison gives about 8 H. That is not electrically impossible or useless. It is simply not the same criterion. For primary inductance sizing, the cleaner criterion is the primary-side reflected load current.

5. The High-Frequency Side: Leakage Inductance

At high frequency, leakage inductance behaves like unwanted series inductance. A simple first-pass rule is to keep leakage reactance small compared with the primary-side reflected load impedance.

A reasonable starting target is:

$$X_{LL} \leq 0.10 R'_L$$

For a stricter design, use 5 percent instead of 10 percent.

The leakage inductance limit referred to the primary is:

$$L_{LL,P} \leq \frac{X_{LL}}{2\pi f_H}$$

Where f_H is the high-frequency limit.

Using the previous 50 Ω reflected-load example and allowing leakage reactance to be 10 percent at 20 kHz:

$$X_{LL} = 0.10(50) = 5\ \Omega$$

$$L_{LL,P} \leq \frac{5}{2\pi(20000)} \approx 39.8\ \mu\text{H}$$

That value is primary-referred. To refer leakage inductance to the other side of the transformer, scale it by the square of the turns ratio. In the 1:2 example, the secondary-referred value is four times the primary-referred value.

This side-reference issue matters. A leakage value is not just a number; it must say which side it is referred to. A value that seems wrong may be correct if it is referred to the other winding.

6. A Harder Example

Consider a transformer intended to match a 75 Ω source to a 1200 Ω load from 30 Hz to 30 kHz.

For impedance matching:

$$N_P : N_S = 1 : 4$$

The reflected load is:

$$R_L' = \left(\frac{1}{4}\right)^2 1200 = 75\ \Omega$$

For 10 percent magnetizing current relative to primary-side reflected load current:

$$X_m = 10(75) = 750\ \Omega$$

At 30 Hz:

$$L_m = \frac{750}{2\pi(30)} \approx 3.98\ \text{H}$$

If the leakage reactance limit is 5 percent of the reflected load at 30 kHz:

$$X_{LL} = 0.05(75) = 3.75\ \Omega$$

$$L_{LL,P} \leq \frac{3.75}{2\pi(30000)} \approx 19.9\ \mu\text{H}$$

Because the transformer is 1:4, the same leakage inductance referred to the secondary side is 16 times larger:

$$L_{LL,S} \approx 318\ \mu\text{H}$$

This example shows the basic design tension. The low end wants several henries of magnetizing inductance, while the high end may tolerate only tens of microhenries of primary-referred leakage inductance. The transformer must therefore be designed with both turns count and winding geometry in mind.

7. What This Method Does Not Pretend To Solve

This first-pass method is useful because it gives direction. It does not replace a real transformer design.

It does not fully solve:

- core loss and distortion at low frequency;
- flux density at the maximum signal level;
- DC bias or unbalanced drive;
- winding capacitance and self-resonance;
- interleaving, shielding, safety spacing, or insulation system;
- copper loss and winding resistance;
- measured insertion loss and phase response.

The value of the method is that it keeps the first decision honest. The low-frequency target is set by magnetizing current compared with the reflected load current. The high-frequency target is set by leakage reactance compared with the reflected load impedance. Both comparisons are made on the same side of the transformer.

That is the clean way to start.

Leakage inductance is only one first-pass limit. Winding capacitance and leakage-capacitance resonance must still be checked by measurement.