Beyond the Toroid: Reassessing EI Laminated Transformers in High-Performance Audio Amplifiers

Andrés Sánchez

Olas Audio, Hardware Design Engineer

Abstract— This paper presents a series of experimental measurements comparing the performance of EI laminated and toroidal power transformers in high-performance audio power amplifier applications. Transformer regulation was evaluated indirectly using a linear power supply unit, the PS-4700 from Olas Audio. Ripple voltage measurements were obtained under both unloaded and loaded conditions.

In addition, voltage sag on the positive supply rail was analyzed under dynamic operating conditions using a CSS-4700 audio power amplifier board from Olas Audio while reproducing low-frequency signals at moderate power levels. Frequency-spectrum measurements of the CSS-4700 output signal at medium power are also presented, identifying components related to the mains frequency (60 Hz) and its harmonics.

The primary objective of this study is to assess whether a low-cost EI laminated transformer can represent a technically viable alternative to toroidal transformers, which are commonly regarded as superior in high-fidelity and high-performance audio systems.

Keywords— **EI laminated transformers, toroidal transformers, linear power supplies, audio power amplifiers, transformer regulation, ripple voltage, voltage sag, mains interference.**

I. INTRODUCTION

In high-performance audio power amplifier design, the power supply is widely recognized as a critical subsystem with a direct impact on electrical performance, noise behavior, and perceived sound quality. Among its components, the power transformer plays a fundamental role, as it defines not only the available voltage and current but also influences magnetic coupling, mechanical noise, regulation under load, and susceptibility to mains-related interference.

Over the past decades, toroidal transformers have become the preferred choice in high-fidelity and professional audio applications. Their compact form factor, high efficiency, low external magnetic field, and generally superior regulation have contributed to the widespread perception that toroidal transformers are inherently superior to traditional EI laminated designs. As a result, EI transformers—particularly low-cost, mass-produced units—are often regarded as technically inadequate for high-performance audio systems, and are typically associated with entry-level or non-critical applications.

However, many of the assumptions that favor toroidal transformers are based on generalized characteristics rather than on application-specific measurements under realistic operating conditions. While toroidal cores indeed offer advantages in terms of magnetic leakage and efficiency, they also exhibit well-known drawbacks, such as increased sensitivity to DC offset on the mains, higher inrush currents, and in some cases less favorable behavior under dynamic load conditions. Conversely, EI laminated transformers, despite their larger size and higher stray fields, can offer robust mechanical construction, predictable saturation characteristics, and, under certain conditions, competitive electrical performance when properly specified and implemented.

In the context of linear power supplies for audio power amplifiers, the interaction between transformer regulation, rectification, reservoir capacitance, and dynamic load currents is complex and often insufficiently characterized by no-load or nominal specifications alone. Parameters such as voltage sag under low-frequency excitation, ripple behavior under load, and the coupling of mains-frequency components into the audio signal path are of particular relevance, yet are rarely compared systematically between transformer topologies in practical amplifier systems.

This work aims to reassess the role of EI laminated transformers in high-performance audio amplifier applications by presenting a direct experimental comparison with toroidal transformers under controlled and repeatable conditions. Rather

than focusing on theoretical advantages, the study emphasizes measured behavior in a real linear power supply and amplifier environment, addressing regulation, ripple voltage, dynamic voltage sag, and frequency-domain artifacts observable at the amplifier output. The ultimate goal is to determine whether a properly selected low-cost EI laminated transformer can constitute a technically viable alternative to toroidal transformers in demanding audio applications, thereby challenging prevailing assumptions within the audio engineering community.

II. EXPERIMENTAL METHODOLOGY AND MEASUREMENT SETUP

A. Experimental Workbench and Equipment

All measurements presented in this study were performed on my personal laboratory workbench configured to emulate realistic operating conditions of a linear power supply for audio power amplifier applications. **Figures 1** and **2** show the complete experimental setup, including the transformer under test, rectification and filtering stages, measurement instrumentation, and load elements.

The rectification, filtering, and measurement platform was based on the **PS-4700 linear power supply unit**, developed by **Olas Audio**, which was used exclusively as a stable and repeatable test fixture. The PS-4700 provides a well-characterized diode bridge, reservoir capacitor bank, and access

points for voltage and ripple measurements, allowing the transformer behavior to be evaluated independently from downstream amplifier circuitry.

Unless otherwise stated, all measurements were conducted at a nominal mains frequency of **60 Hz**.

B. Measurement Configuration

To evaluate transformer regulation and load behavior under realistic conditions, the following topology was employed:

Transformer → Bridge Rectifier → Reservoir Capacitor → DC Electronic Load

Key parameters of the setup include:

- Rectification: full-wave diode bridge
- Reservoir capacitance: **15,000 µF**
- Load type: programmable DC electronic load
- Ripple frequency: **120 Hz**

The primary objective of this configuration is to replicate the capacitor-input rectifier commonly used in linear power supplies for audio amplifiers, which imposes highly pulsating current demands on the transformer secondary.
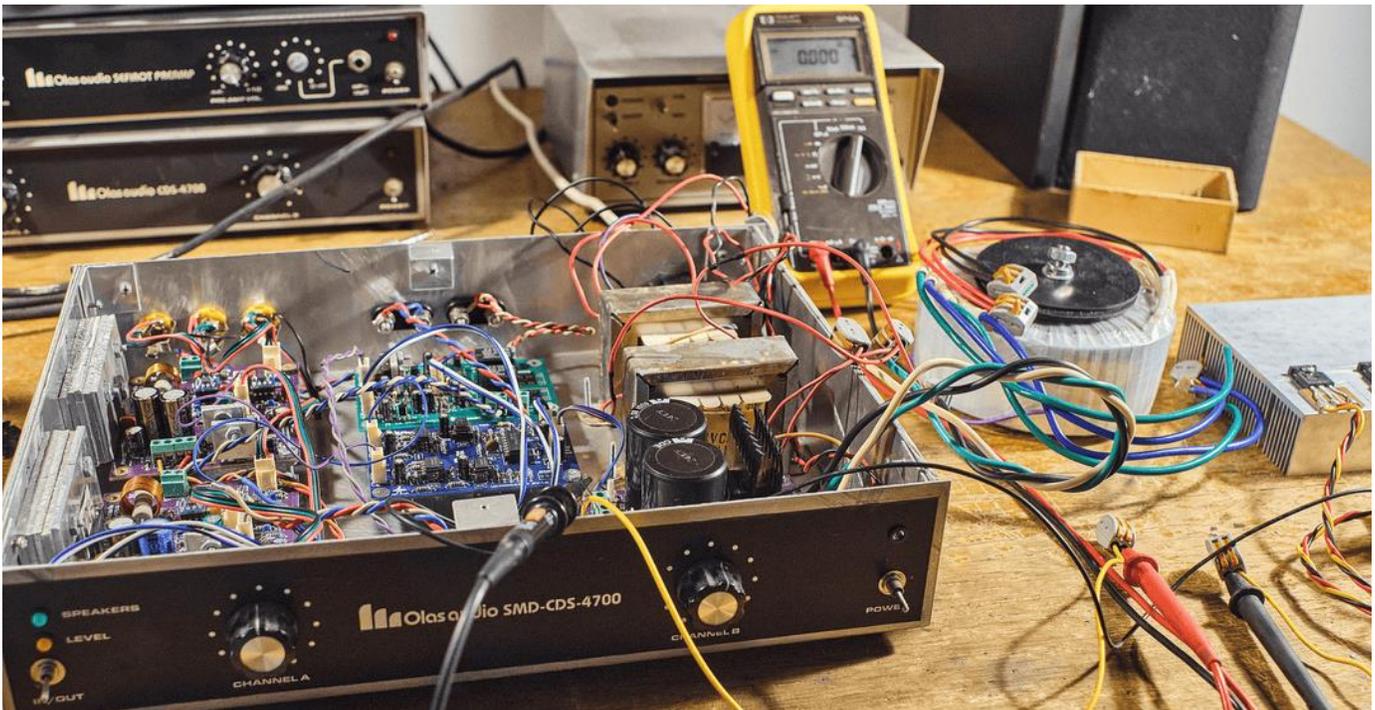

Figure 1. Experimental setup, including the transformer under test, rectification and filtering stages, measurement instrumentation, and load elements.
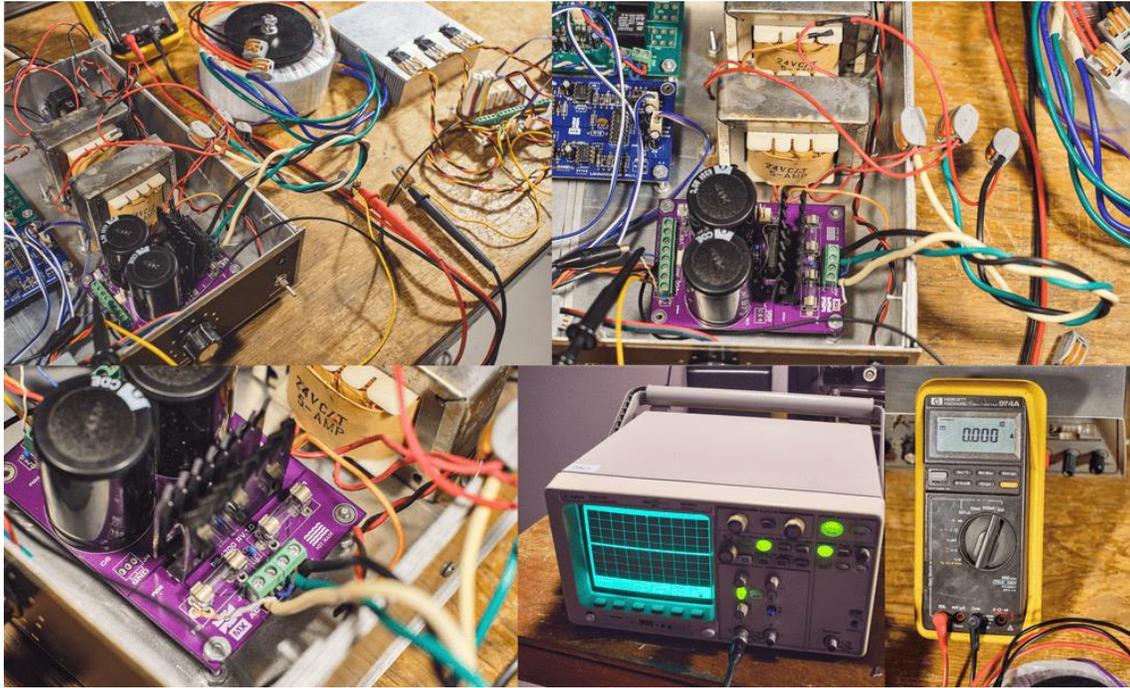
Figure 2. Experimental setup, including the transformer under test, measurement instrumentation, and load elements and the PS-4700 power supply unit.

III. EXPERIMENTAL RESULTS: EI LAMINATED TRANSFORMERS

A. Transformer Description and Test Conditions

The results presented in this section correspond to **EI laminated generic transformers**. These devices consist of two identical, commercially available EI laminated units sourced from a consumer electronics marketplace, with a total cost of approximately **USD 30 for the pair**, representing a typical low-cost solution commonly encountered in entry-level or cost-sensitive audio equipment.

Each transformer is rated at:

- Secondary voltage: **24 Vrms**
- Rated current: **5 Arms**

The transformers were configured as follows:

- Primary windings: connected in parallel
- Secondary windings: connected in series

This configuration results in an effective secondary rating of **48 Vrms at 5 Arms**, prior to rectification.

B. No-Load Measurements

Initial measurements were performed under no-load conditions to establish baseline transformer behavior.

Measured values (see **figures 3 and 4**):

- Secondary RMS voltage: **25.24 Vrms**
- Peak secondary voltage: **36.1 V**
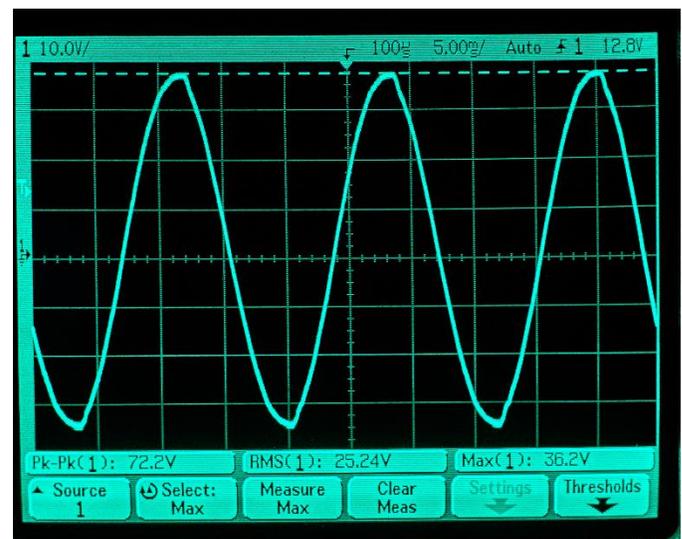- DC output voltage: **35.85 V**
- DC load current: **0 A**

Figure 3. Measured secondary voltage waveform of the EI laminated transformer with the power supply unloaded.
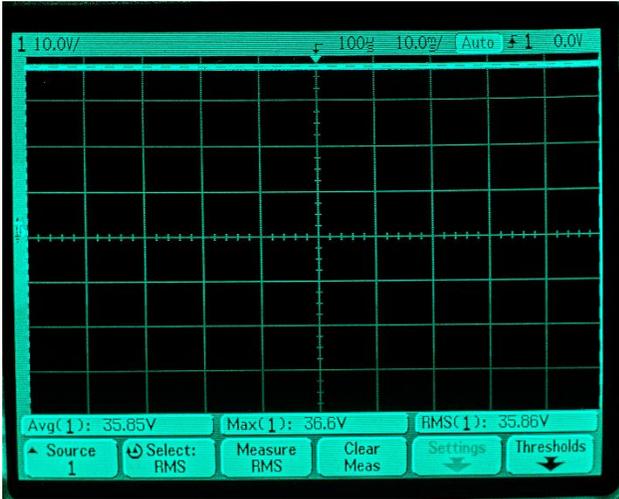
Figure 4. DC output voltage of the PS-4700 power supply under no-load conditions.

The measured RMS voltage exceeds the nominal rating by approximately **5.2%**, which is consistent with the typical regulation characteristics of EI laminated transformers under no-load conditions. The measured peak voltage closely matches the theoretical value:

$$V_{peak} = V_{rms} \cdot \sqrt{2} \approx 35.7 \text{ V}$$

The DC output voltage confirms minimal diode conduction and a fully charged reservoir capacitor, indicating negligible losses under no-load operation.

C. Measurements Under Moderate DC Load (≈1.06 A)

With a DC load current of approximately **1.055 A**, the following values were obtained (see **figures 5, 6 and 7**):

- Peak secondary voltage: **29.69 V**
- DC output voltage: **28.35 V**
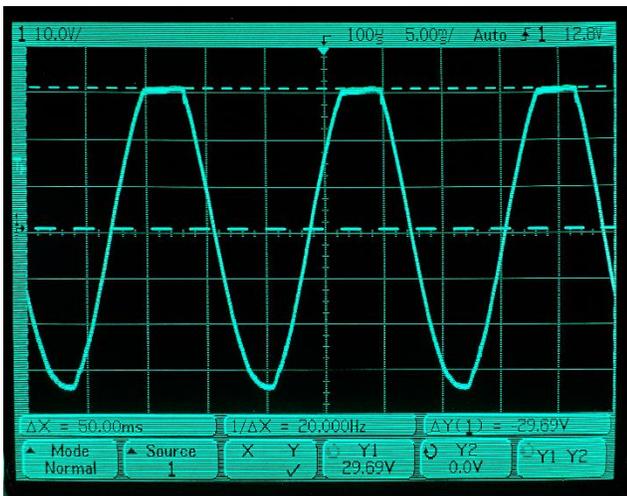- Ripple voltage: **512 mVpp**

Figure 5. Peak voltage at the secondary winding of the EI laminated transformer, showing noticeable waveform flattening at the voltage peaks.
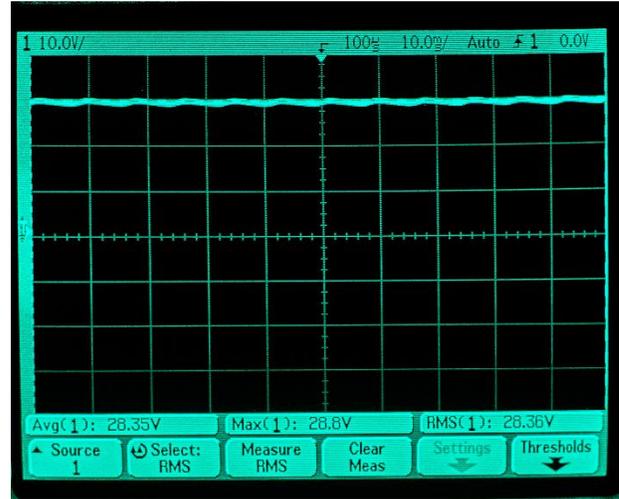

Figure 6. DC output voltage of the PS-4700 power supply under a load current of 1.055 A.
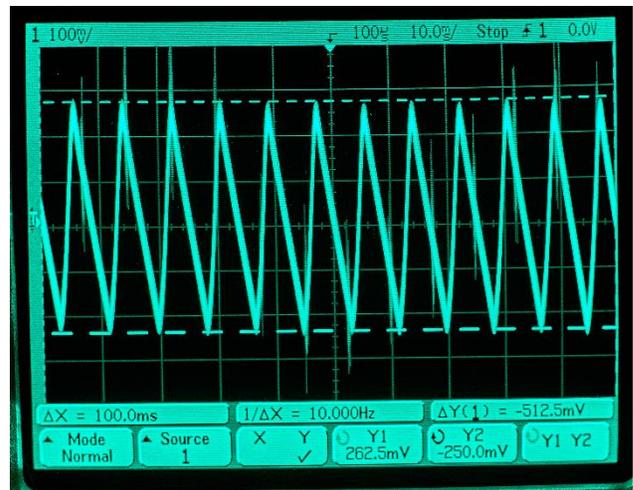

Figure 7. Ripple voltage on the positive rail of the PS-4700 power supply under a load current of 1.055 A.

Compared to the no-load condition, the peak voltage exhibits a reduction of **6.41 V**, corresponding to a **17.8% drop**, despite the relatively modest DC load current.

This behavior indicates a high effective series impedance, resulting from a combination of copper losses, leakage inductance, and partial core saturation under pulsating load currents.

The measured ripple voltage closely matches the theoretical expectation:

$$V_{ripple(pp)} \approx \frac{I_{DC}}{f \cdot C} \approx \frac{1.055}{120 \cdot 15000 \mu F} \approx 586 \text{ mVpp}$$

The excellent agreement between theory and measurement confirms that the reservoir capacitor and its ESR are not the limiting factors. Instead, the dominant limitation arises from the transformer's inability to sustain the sinusoidal voltage peak under load.

D. Increased DC Load (≈2.57 A)

As the DC load current was increased to **2.571 A**, a pronounced degradation in performance was observed (see **figures 8, 9 and 10**):

- Peak secondary voltage: **24.06 V**
- DC output voltage: **23.36 V**
- Ripple voltage: **925 mVpp**

Figure 8. Output current measured at the positive rail of the PS-4700 power supply.
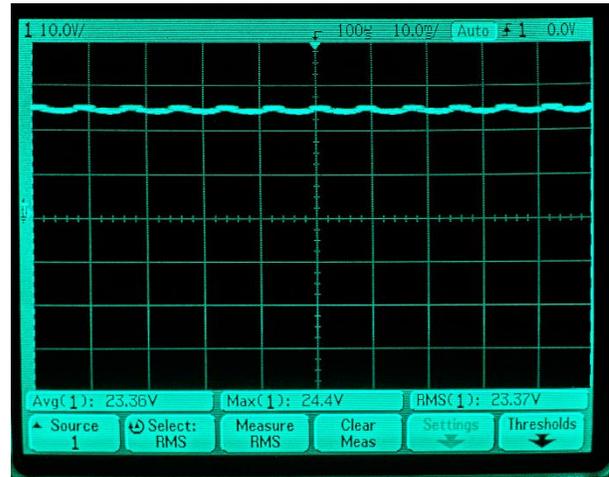

Figure 10. DC output voltage of the PS-4700 power supply under a load current of 2.571 A.

Relative to the no-load condition, the peak voltage has now collapsed by approximately **33%**, while the DC output voltage has dropped by **35%**.

Interestingly, the measured ripple voltage is **lower than the theoretical prediction** of approximately **1.43 Vpp**. This apparent discrepancy indicates that the system no longer behaves as an ideal capacitor-input rectifier. Instead, the reduced peak voltage forces wider conduction angles, effectively flattening the waveform—a clear signature of transformer-limited operation rather than improved filtering.

E. Severe Load Condition (≈4.03 A)

Under heavy DC loading approaching **4.03 A**, the EI laminated transformers exhibit near-collapse behavior (see **figures 11 and 12**):

- Peak secondary voltage: **21.56 V**
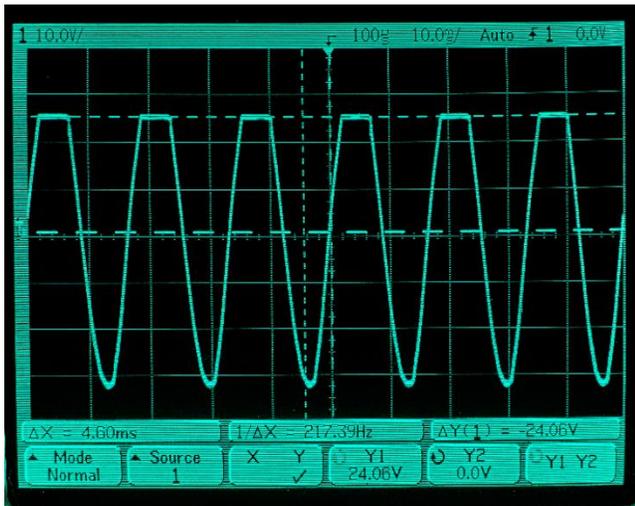- DC output voltage: **18.94 V**
- Ripple voltage: **1.18 Vpp**

Figure 9. Peak voltage at the secondary winding of the EI laminated transformer, showing a progressive reduction in peak amplitude at a load current of 2.571 A.
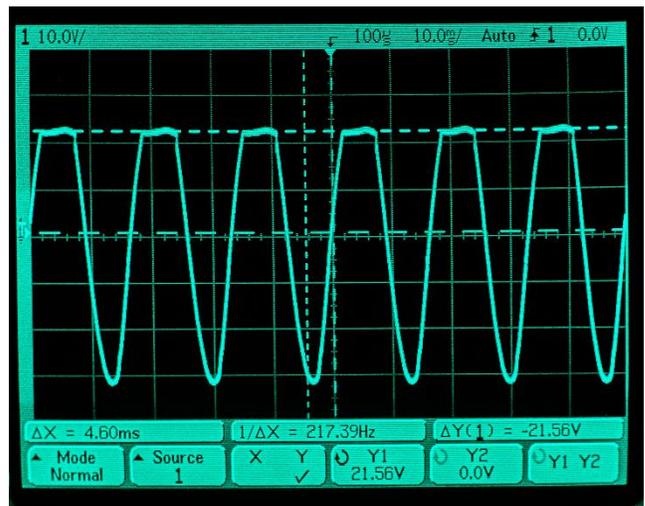

Figure 11. Peak voltage at the secondary winding of the EI laminated transformer at a load current of 4.03 A, showing severe waveform distortion and pronounced peak deformation.
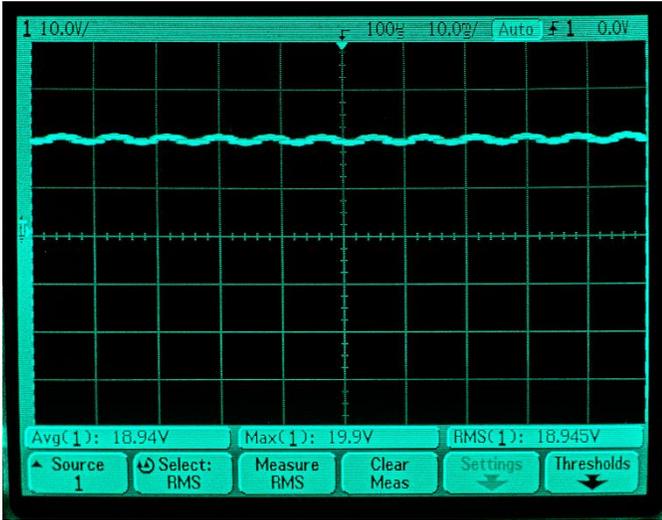
Figure 12. DC output voltage of the PS-4700 power supply unit under a load current of 4.03 A.

At this operating point, the DC output voltage has fallen by nearly **47%** relative to the no-load value. The ripple voltage represents approximately **6.2%** of the DC level, a magnitude that directly couples into the amplifier supply rails and is known to degrade audio performance.

This regime exceeds the practical DC current capability of a transformer rated at **5 Arms** when used with a capacitor-input rectifier, confirming that the effective DC current limit is significantly lower than the nominal RMS rating.

F. Interpretation and Implications for Audio Applications

Across all load conditions, the measurements consistently show that voltage sag in the EI laminated transformers is dominated by the collapse of the secondary voltage peak rather than by insufficient reservoir capacitance. As a result, increasing capacitance alone cannot compensate for the observed regulation deficiencies.

From an audio perspective, this behavior directly translates into:

- Reduced dynamic headroom
- Increased THD under load
- Compression of low-frequency transients
- Degraded damping factor and bass control

These effects become increasingly pronounced as output power increases.

IV. EXPERIMENTAL RESULTS: TOROIDAL TRANSFORMER (ANTEK AS-4222)

It is important to note that the toroidal transformer used in this work has a higher nominal VA rating (400 VA) than the EI laminated transformers evaluated earlier. As such, this is not intended to be a one-to-one comparison at equal VA ratings. The purpose of these measurements is instead to characterize the real-world performance of a low-cost EI laminated transformer in a typical audio power supply, and to use the higher-VA toroidal unit as a practical reference for expected behavior when transformer limitations are no longer dominant.

A. Transformer Description and Test Conditions

The toroidal transformer evaluated in this section is the **AnTek AS-4222**, a commercially available unit manufactured in the United States and rated at **400 VA**. According to the manufacturer's datasheet, the transformer is specified for **22 V secondaries** and demonstrates strong load regulation when operated at 120 VAC and 60 Hz, with secondary windings connected in parallel during characterization.

In the present study, the transformer was configured with **22–0–22 Vrms secondaries**, supplying a linear power supply with full-wave bridge rectification and a **15,000 µF reservoir capacitor**, identical to the setup used for the EI laminated transformer tests. Measurements were performed on a **single DC rail**, using an active DC electronic load to emulate realistic amplifier current demands.

Key parameters:

- Transformer type: Toroidal (AnTek AS-4222)
- Secondary voltage: 22–0–22 Vrms
- Nominal current rating (windings in series): 9.1 Arms
- Rectification: full-wave bridge
- Reservoir capacitance: 15,000 µF
- Mains frequency: 60 Hz

B. No-Load Performance

Under no-load conditions, the following values were measured:

- Secondary RMS voltage: **23.72 Vrms**
- Peak secondary voltage: **33.44 V**
- DC output voltage: **33.11 V**
- DC load current: **0 A**

The measured DC voltage closely matches the theoretical peak value:

$$V_{peak} = V_{rms} \cdot \sqrt{2} \approx 33.55 \text{ V}$$

The small deviation is attributed to normal diode conduction losses and winding resistance, confirming an efficient RMS-to-DC conversion. The near coincidence of peak and DC voltages indicates very low secondary series resistance and operation far from core saturation—typical characteristics of a well-dimensioned toroidal transformer.

C. Light Load Operation (≈1.07 A DC)

With a DC load current of **1.066 A**, the measured values were (see **figures 13, 14 and 15**):

- Peak secondary voltage: **32.19 V**
- DC output voltage: **30.7 V**
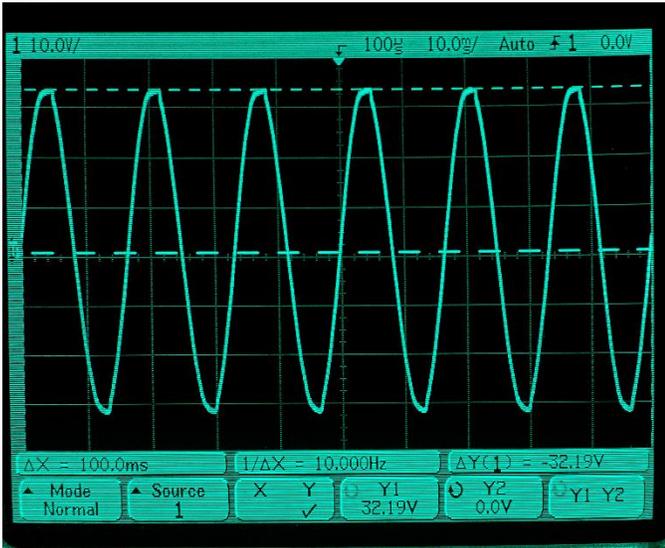- Ripple voltage: **668 mVpp**

Figure 13. Peak voltage at the secondary winding of the AnTek toroidal transformer under a load current of 1.066 A. The waveform remains largely undistorted, indicating good voltage regulation under this load condition.
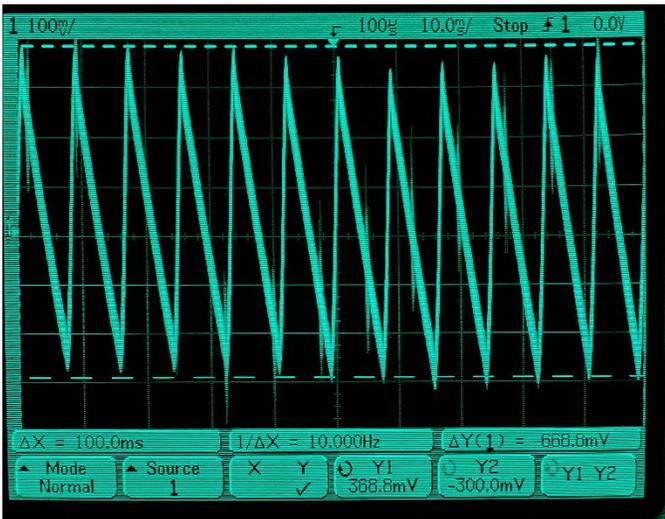

Figure 14. Ripple voltage measured at the positive rail of the PS-4700 power supply unit under a load current of 1.066 A when using the AnTek toroidal transformer.
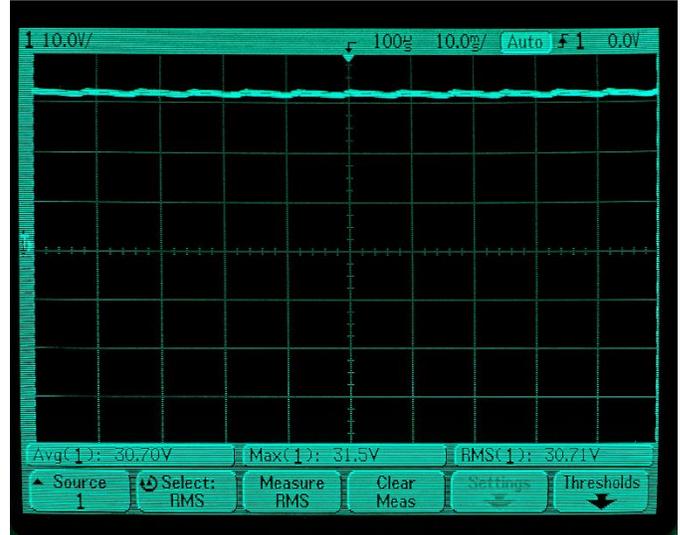

Figure 15. DC output voltage of the PS-4700 power supply unit under a load current of 1.066 A using the toroidal transformer.

The DC voltage drop relative to no-load is **2.41 V**, corresponding to approximately **7.3%**, which represents excellent regulation for an unregulated linear supply with capacitor-input rectification.

Theoretical ripple voltage:

$$V_{ripple(pp)} \approx \frac{I_{DC}}{f \cdot C} \approx 0.59 \text{ Vpp}$$

The measured ripple closely matches the calculated value, confirming that the supply behavior is dominated by the reservoir capacitor and not by transformer limitations. At this operating point, the transformer utilizes only about **10% of its nominal RMS current rating**, resulting in wide conduction angles, low current distortion, and minimal magnetic stress.

D. Moderate Load Operation (≈2.64 A DC)

Increasing the DC load current to **2.642 A** yields:

- Peak secondary voltage: **31.88 V**
- DC output voltage: **30.11 V**
- Ripple voltage: **1.36 Vpp**

The DC voltage drop increases modestly to **9.1%**, while the ripple voltage nearly doubles, as predicted by theory. The measured ripple remains within **8%** of the theoretical value, confirming linear scaling:

$$V_{ripple} \propto I_{DC}$$

No evidence of peak voltage collapse or saturation is observed, indicating that the transformer continues to operate with low effective series impedance.

E. High Load Operation (≈5.03 A DC)

At a DC load current of **5.033 A**, the transformer exhibits the following behavior (see **figures 16 and 17**):

- Peak secondary voltage: **30.63 V**
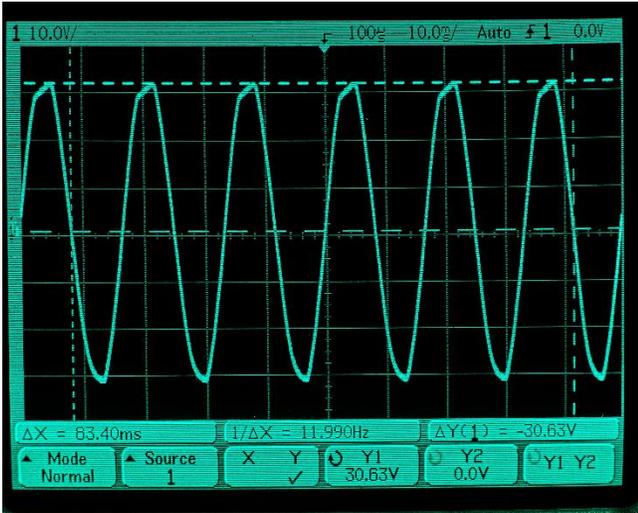- DC output voltage: **28.52 V**
- Ripple voltage: **2.375 Vpp**

Figure 16. Peak voltage at the secondary winding of the AnTek toroidal transformer under a load current of 5.033 A. No signs of magnetic saturation or abrupt regulation degradation are observed, indicating stable operation under conditions representative of high-power audio amplifier use.

Figure 17. DC output voltage of the PS-4700 power supply unit under a load current of 5.033 A using the AnTek toroidal transformer.

The DC voltage drop remains below **14%**, while the measured ripple is slightly lower than the theoretical estimate of **2.80 Vpp**. This deviation is attributed to widening conduction angles and non-ideal current waveforms, indicating that the simplified ripple model becomes conservative at higher currents.

Importantly, the transformer shows no signs of magnetic saturation or abrupt regulation degradation, maintaining stable operation under conditions representative of high-power audio amplifier use.

F. Very High Load Operation (≈7.15 A DC)

At **7.149 A DC**, the measured performance remains robust (see **figures 18 and 19**):

- Peak secondary voltage: **29.69 V**
- DC output voltage: **26.57 V**
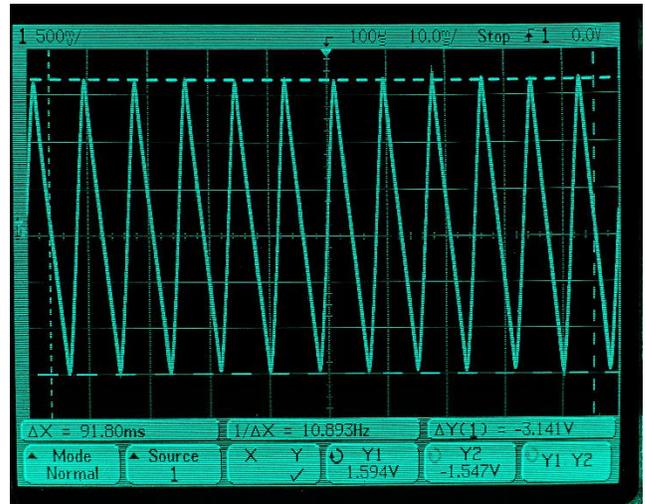- Ripple voltage: **3.14 Vpp**

Figure 18. Ripple voltage measured at the positive rail of the PS-4700 power supply unit under a load current of 7.149 A when using the AnTek toroidal transformer.
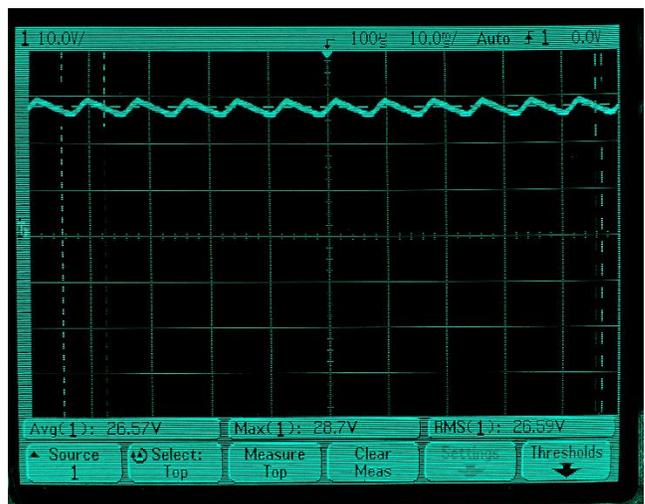

Figure 19. DC output voltage of the PS-4700 power supply unit under a load current of 7.149 A using the AnTek toroidal transformer.

Despite the high DC current—well above the classical $0.62 \cdot I_{rms}$ guideline for capacitor-input supplies—the transformer maintains strong voltage regulation. Ripple growth begins to compress relative to the linear model, a signature of a transformer with low internal resistance and high magnetic headroom.

G. Extreme Load Condition (≈9.09 A DC)

Under extreme loading approaching **9.087A DC**, the transformer exhibits the following results (see **figures 20 and 21**):

- Peak secondary voltage: **29.38 V**
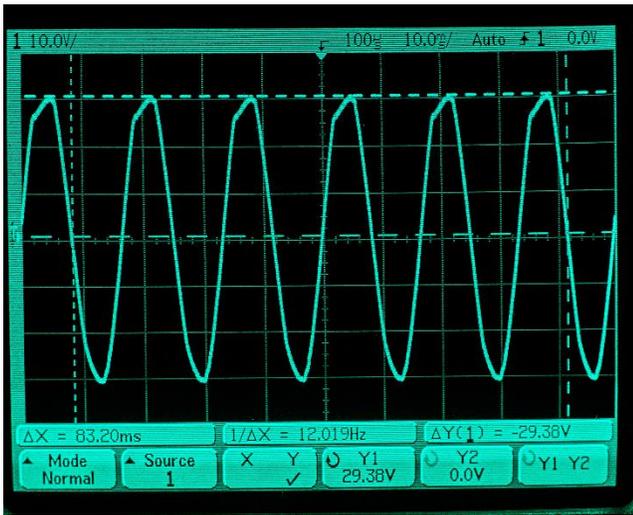- DC output voltage: **25.62 V**
- Ripple voltage: **3.84 Vpp**

Figure 20. Peak voltage at the secondary winding of the AnTek toroidal transformer under a load current of 9.087 A. Although the waveform remains distorted, the transition with increasing load is smooth, with no abrupt voltage collapse or signs of transformer instability observed.

Figure 21. DC output voltage of the PS-4700 power supply unit under a load current of 9.087 A using the AnTek toroidal transformer.

The total DC voltage drop reaches approximately **22.6%**, as expected near the upper operating limit. However, the transition remains smooth, with no abrupt collapse or instability. The measured ripple is significantly lower than the theoretical estimate of **5.05 Vpp**, confirming that the transformer continues to sustain effective capacitor recharge even at very high current levels.

This behavior aligns well with the manufacturer's load-regulation data and demonstrates that the AS-4222 is conservatively rated for audio applications.

H. Interpretation and Comparison with EI Laminated Transformers

Across all tested load conditions, the toroidal transformer consistently maintains:

- Higher sustained DC voltage
- Predictable, near-linear ripple scaling
- Absence of peak voltage collapse
- No observable saturation under pulsating loads

In contrast to the EI laminated transformers evaluated earlier, the toroidal unit remains firmly in a **capacitor-limited regime**, even at high DC currents. This distinction is critical: while ripple magnitude increases with load as expected, the underlying supply voltage remains sufficiently stiff to preserve amplifier headroom and dynamic performance.

Implications for Audio Power Amplifiers

From an audio engineering perspective, the measured behavior translates directly into:

- Preserved dynamic headroom
- THD dominated by amplifier circuitry rather than power supply limitations
- Superior low-frequency control and damping factor
- Robust handling of musical crest factors and transient peaks

These characteristics confirm that the toroidal transformer operates with substantial electrical and magnetic margin, making it particularly well suited for high-performance and high-power audio amplifier applications.

V. TRANSLATION OF POWER SUPPLY MEASUREMENTS TO A COMPOSITE AUDIO AMPLIFIER SYSTEM

Based on the previous measurements obtained from the PS-4700 linear power supply feeding a composite audio amplifier, the relevance of raw power supply behavior to actual audio performance can be evaluated. The amplifier under test consists of:

- **Signal stage:** LM4562 powered by LM317 / LM337 linear regulators with an adjustment-pin bypass capacitor
- **Power stage:** LM3886 powered directly from an unregulated DC supply

Two transformer technologies were evaluated—EI laminated and toroidal—under multiple load conditions, allowing direct correlation between measured supply ripple, load current, and effective ripple at the active devices.

EI Laminated Transformer Measurements

Two operating points were analyzed to evaluate power supply behavior under moderate and high load conditions.

**Case 1 — Moderate Load Condition (EI Laminated)
Measured parameters:**

- Peak secondary voltage: 29.69 V
- DC output voltage (after rectification and filtering): 28.35 V
- Ripple voltage: 512 mVpp
- DC output current: 1.055 A

Under this load condition, the measured ripple corresponds to approximately **1.8% of the DC output voltage**, as given by:

$$\text{Ripple ratio} = \frac{V_{\text{ripple,pp}}}{V_{\text{DC}}} \times 100$$

$$\frac{0.512}{28.35} \times 100 \approx 1.8\%$$

This value is fully consistent with expectations for a linear, unregulated power supply operating under moderate load.

To estimate the actual impact of this ripple on the audio output, the power supply rejection ratio (PSRR) of the LM3886 must be considered. At mains-related frequencies (120 Hz), a conservative PSRR value of **80 dB** may be assumed. The effective ripple contribution at the amplifier output can be approximated as:

$$V_{\text{out,ripple}} = \frac{V_{\text{ripple,pp}}}{10^{\frac{\text{PSRR}}{20}}}$$

$$V_{\text{out,ripple}} = \frac{512 \text{ mV}}{10^{\frac{80}{20}}} \approx 51 \text{ μVp}$$

This ripple level is well below both the intrinsic noise floor of the LM3886 and any threshold of audibility.

**Case 2 — High Load Condition (EI Laminated)
Measured parameters:**

- Peak secondary voltage: 21.56 V
- DC output voltage (after rectification and filtering): 18.94 V
- Ripple voltage: 1.18 Vpp
- DC output current: 4.03 A

Applying the same PSRR-based attenuation:

$$V_{\text{out,ripple}} = \frac{1.18 \text{ V}}{10^{80/20}} \approx 118 \text{ μVpp}$$

Although the raw ripple voltage more than doubles relative to the moderate-load case, the resulting ripple at the LM3886 output remains on the order of **hundreds of microvolts peak-to-peak**, which remains negligible in practical audio operation.

Toroidal Transformer Measurements (AnTek AS-4222)

The same power supply and composite amplifier architecture were evaluated using an AnTek toroidal transformer. As before, the signal stage operates from regulated rails, while the power stage is supplied from an unregulated DC source.

**Case 3 — Moderate Load Condition (Toroidal)
Measured parameters:**

- Peak secondary voltage: 32.19 V
- DC output voltage (after rectification and filtering): 30.7 V
- Ripple voltage: 668 mVpp
- DC output current: 1.066 A

The effective ripple contribution at the LM3886 output is therefore:

$$V_{\text{out,ripple}} = \frac{0.668 \text{ V}}{10^{80/20}} \approx 66.8 \text{ μVpp}$$

Despite the higher raw ripple voltage compared to the EI transformer under similar load, the output-referred ripple remains extremely small due to the high PSRR of the power amplifier stage.

**Case 4 — High Load Condition (Toroidal)
Measured parameters:**

- Peak secondary voltage: 29.38 V
- DC output voltage (after rectification and filtering): 25.62 V
- Ripple voltage: 3.84 Vpp
- DC output current: 9.087 A

The corresponding output-referred ripple is:

$$V_{\text{out,ripple}} = \frac{3.84 \text{ V}}{10^{80/20}} \approx 384 \text{ μVpp}$$

Even under this extreme load condition—representative of sustained high-power operation—the ripple appearing at the LM3886 output remains below **0.4 mVpp**, which is still far below the signal levels involved in real audio reproduction.

Impact on the LM4562 Signal Stage

It is important to note that the LM4562 signal stage is powered from regulated rails (LM317/LM337) with an adjustment-pin bypass capacitor. At 120 Hz, these regulators typically provide **65–80 dB of ripple rejection**, which is then compounded by the intrinsic PSRR of the LM4562 itself (exceeding 100 dB at low frequencies).

As a result, the effective ripple voltage reaching the LM4562 supply pins is reduced to the **nanovolt range**, rendering power supply ripple completely irrelevant to signal integrity at the voltage amplification stage.

Final Conclusion

Across all measured conditions, the results demonstrate that:

- Increasing load current leads to higher raw ripple voltage and reduced DC rail voltage, regardless of transformer topology.
- Toroidal transformers maintain higher DC output voltage under heavy load but may exhibit larger ripple amplitudes due to narrower rectifier conduction angles and higher peak charging currents.
- EI laminated transformers exhibit greater voltage sag but comparatively moderate ripple growth at high load.

However, when evaluated in the context of a properly designed composite amplifier:

- The **LM3886**, with a PSRR of approximately 80 dB at mains frequencies, attenuates even multi-volt ripple to **sub-millivolt levels** at the output.
- The **LM4562**, powered from regulated rails, is effectively isolated from supply ripple altogether.

Consequently, despite large differences in raw ripple magnitude and load current between EI laminated and toroidal transformers, **no measurable or audible degradation of audio performance is expected**. These results confirm that, in modern composite amplifier architectures, transformer selection primarily affects thermal behavior, efficiency, and mechanical considerations, while its influence on final audio performance is strongly mitigated by circuit topology and power supply design.

VI. DC RAIL SAG UNDER DYNAMIC AUDIO LOAD — EI VS. TOROIDAL

A. Measurement Objective

The objective of this experiment is to quantify the **dynamic DC rail sag** of an unregulated linear power supply under realistic audio operating conditions, when feeding a composite audio power amplifier based on an LM4562 voltage stage and an LM3886 output stage (see **figures 22 and 23**).

A continuous sinusoidal excitation was deliberately used, as it represents a **worst-case condition** for an unregulated supply with capacitive input filtering. Compared to music program material, a steady sine wave exhibits a minimal crest factor, sustained current demand, and maximum capacitor discharge. Therefore, the results presented here should be interpreted as an **upper bound** on DC rail modulation under real audio operation.
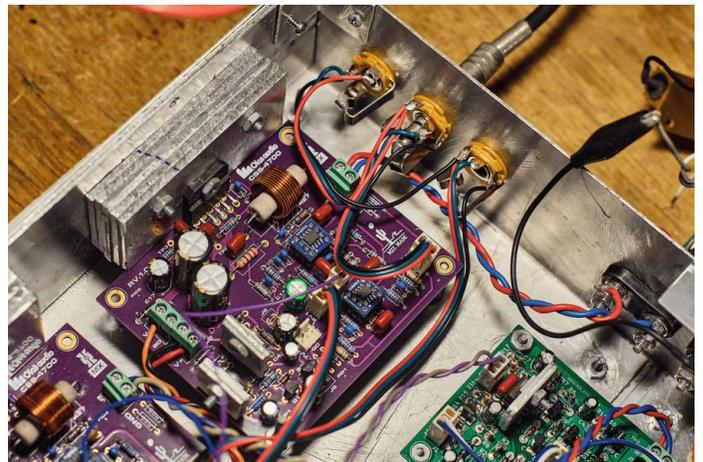

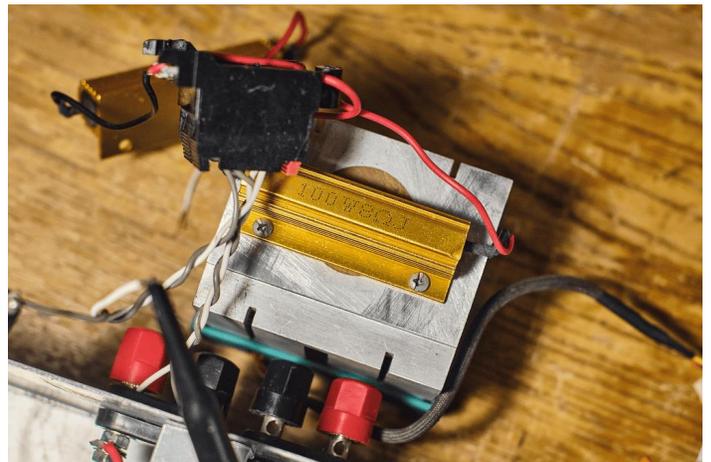**Figure 22.** A CSS-4700 board of my stereo audio amplifier was used to measure the dynamic DC rail sag.

Figure 23. Resistive load (100 W, 8 Ω) connected to the CSS-4700 amplifier output during dynamic DC rail sag measurements.

B. Common Test Conditions

The following conditions were identical for all measurements:

- **Amplifier:** CSS-4700 (LM4562 + LM3886 composite topology)
- **Power Supply:** PS-4700, full-wave bridge rectifier with reservoir capacitor
- **Load:** 8 Ω resistive
- **Signal:** Continuous sinusoidal waveform
- **Operating State:** Steady-state (several seconds)
- **Target Output Power:** ~26–27 W RMS
- **Test Frequencies:** 50 Hz and 1 kHz

C. EI Laminated Transformer Results

Configuration
- **Transformers:** 2 × EI laminated, 24 Vrms @ 5 Arms
- **Primary windings:** Connected in parallel
- **Secondary windings:** Connected in series

Table I. Measured results for DC rail sag under dynamic audio load (EI laminated transformers).

Frequency	Output Power	V_idle	V_min	ΔV	Sag
50 Hz	~27 W	33.37 V	28.1 V	5.27 V	**15.8%**
1 kHz	~27 W	33.37 V	28.4 V	4.97 V	**14.9%**

Key Observation

The DC rail sag remains nearly constant across frequency, indicating that the supply behavior is no longer dominated by the reservoir capacitor. Instead, the performance is primarily limited by the **intrinsic regulation of the EI transformer**, including secondary winding resistance and magnetic stiffness (see **figures 24-27**).
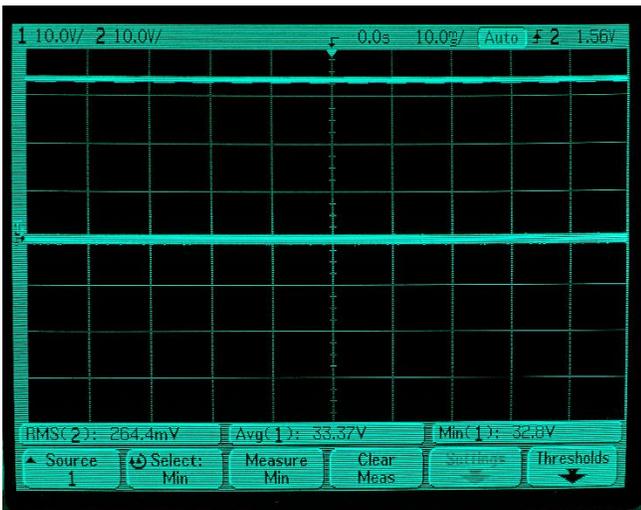

Figure 24. Positive DC rail voltage of the PS-4700 power supply with the CSS-4700 audio power amplifier output unloaded.

Figure 25. Sinusoidal 50 Hz test signal measured at the output of the CSS-4700 amplifier, together with the minimum voltage observed on the positive supply rail.

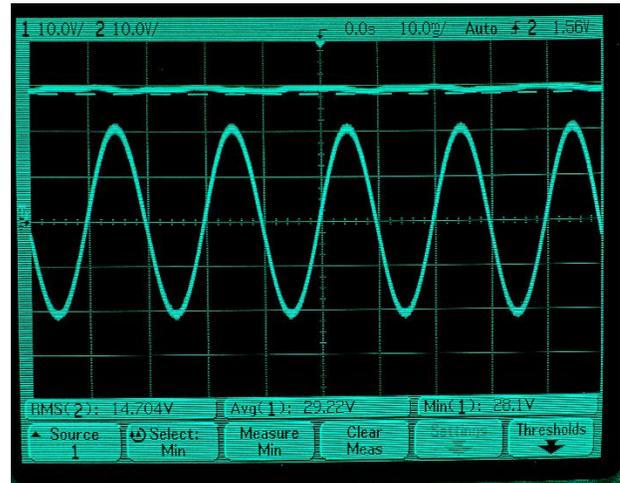**Figure 26.** Sinusoidal 1 kHz test signal measured at the output of the CSS-4700 amplifier, together with the minimum voltage observed on the positive supply rail.
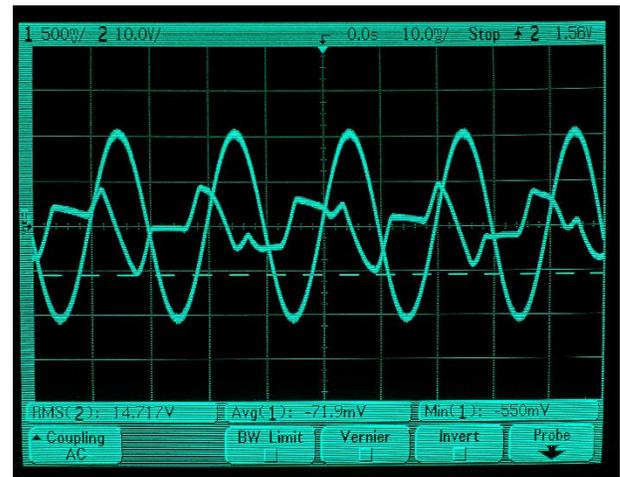
Figure 27. Output waveform of the CSS-4700 amplifier driven by a 50 Hz sinusoidal test signal (Channel 2), with Channel 1 AC-coupled showing audio-frequency modulation of the positive supply rail due to load current rather than mains ripple.

D. Toroidal Transformer Results (AnTek)

Configuration
- **Transformer:** Toroidal AnTek (22–0–22 Vrms nominal)
- **Rectification and filtering:** Identical to the EI transformer tests

D.1 Measurement at 50 Hz (see figures 28 and 29)

- $V_{out,rms} = 14.612$ Vrms
- $P_{out} = 26.68$ W
- $V_{idle} = 31.56$ VDC
- $V_{min} = 29.1$ VDC

Figure 28. Positive DC rail voltage of the PS-4700 power supply with the CSS-4700 audio power amplifier output unloaded, when powered by the AnTek toroidal transformer.

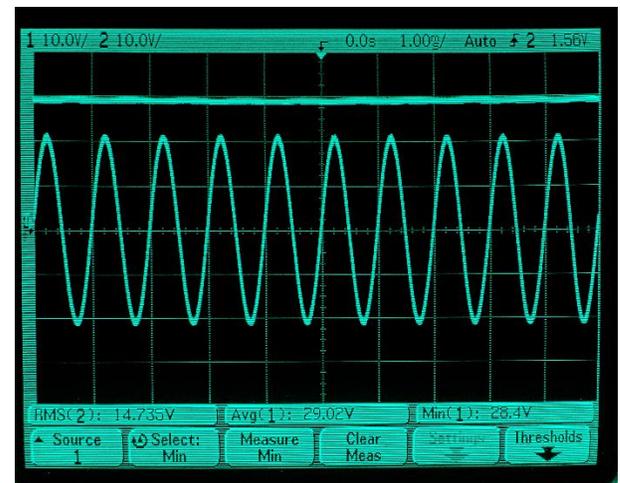**Figure 29.** Sinusoidal 50 Hz test signal measured at the output of the CSS-4700 amplifier, together with the minimum voltage observed on the positive supply rail, when powered by the AnTek toroidal transformer.

$$\Delta V = 31.56 - 29.1 = 2.46 \text{ V}$$

$$\text{Sag}_{50Hz} = 7.8\%$$

This level of sag is fully consistent with a healthy unregulated supply under continuous low-frequency excitation.

D.2 Measurement at 1 kHz (see figure 30)

- $V_{out,rms} = 14.66$ Vrms
- $P_{out} = 26.86$ W
- $V_{idle} = 31.56$ VDC
- $V_{min} = 29.7$ VDC

$$\Delta V = 31.56 - 29.7 = 1.86 \text{ V}$$

$$\text{Sag}_{1kHz} = \frac{\Delta V}{V_{idle}} = \frac{1.86}{31.56} = 5.89\%$$

Compared to the 50 Hz case, a clear reduction in sag is observed.

Figure 30. Sinusoidal 1 kHz test signal measured at the output of the CSS-4700 amplifier, together with the minimum voltage observed on the positive supply rail, when powered by the AnTek toroidal transformer.

E. Direct EI vs. Toroidal Comparison

All measurements were performed at comparable output power levels (~26–27 W RMS).

Table II. Comparison of DC supply rail sag for EI laminated and toroidal transformers.

Transformer	Frequency	Output Power	DC Rail Sag
EI laminated	50 Hz	~27 W	**15.8%**
EI laminated	1 kHz	~27 W	**14.9%**
Toroidal	50 Hz	~26.5 W	**7.8%**
Toroidal	1 kHz	~26.9 W	**5.89%**

The toroidal transformer exhibits approximately **half the DC rail sag** of the EI laminated transformers under identical operating conditions.

F. Physical Interpretation

The improved performance of the toroidal transformer can be attributed to:

- Lower secondary winding resistance
- Superior intrinsic voltage regulation
- Reduced leakage flux
- Higher magnetic stiffness under pulsed load conditions

The reduction in sag at 1 kHz relative to 50 Hz is explained by the shorter discharge interval of the reservoir capacitor, resulting in improved conduction angle and reduced peak current stress.

These results confirm that **continuous low-frequency excitation represents the worst-case operating condition**, while real music signals will produce significantly lower effective DC rail modulation.

G. Impact on Audio Performance

For the EI laminated transformers (≈15% sag):

- Reduced dynamic headroom
- Increased rail modulation
- Degraded low-frequency control
- Higher distortion at elevated output levels

For the toroidal transformer (≈6–8% sag):

- DC rail remains well above the required output swing
- No supply-induced clipping
- Distortion dominated by amplifier linearity rather than the power supply
- Improved bass control and transient response

Under typical music program material, the effective sag would be substantially lower than the values reported here.

H. Final Statement

Under continuous sinusoidal excitation delivering approximately 27 W into an 8 Ω resistive load, the toroidal transformer exhibited DC rail sag values of 7.8% at 50 Hz and 5.89% at 1 kHz, roughly half those observed with EI laminated transformers under identical conditions. This reduced rail modulation indicates superior dynamic stiffness and confirms the suitability of toroidal transformers for high-power/high-performance audio amplifier applications.

VII. RIPPLE-RELATED LOW-FREQUENCY SPECTRAL CONTENT

Measurement Scope and Limitations

Although the appearance of spectral components at frequencies of the form

$$f = 1 \text{ kHz} \pm n \cdot 60 \text{ Hz}$$

is consistent with ripple-induced intermodulation mechanisms, the measurements presented in this work were **not intended to constitute a standardized intermodulation distortion (IMD) test**, such as SMPTE RP120-1994 or CCIF methods.

In particular, the SMPTE approach employs two deliberate excitation tones (typically 60 Hz and 7 kHz with a defined amplitude ratio), whereas the present measurements use **a single audio excitation tone (1 kHz)** and rely on the **natural residual ripple of the power supply** as the low-frequency modulating component.

As a result, while sideband components were observed, their absolute levels may be influenced by additional mechanisms such as passive intermodulation, cabling effects, external electromagnetic interference, or analyzer noise floor limitations. Therefore, these results are interpreted qualitatively and comparatively rather than as absolute IMD figures.

What Is Reliably Measured

What *is* measured with high confidence—and forms the core of this analysis—is the **absolute spectral content of mains-related components** appearing at the amplifier output under identical operating conditions.

Specifically, the following quantities were directly and repeatably measured:

- Fundamental mains component at 60 Hz
- Second, third, and fourth harmonics (120 Hz, 180 Hz, 240 Hz)
- Measured in absolute terms (dBV)
- Referenced to a constant output level of 15 Vrms into 8 Ω
- Using a low-distortion 1 kHz excitation with intrinsic THD ≤ 0.000015% (with a 40 dBV of post notch filter amplification)

These measurements provide a **robust and unambiguous comparison** of how different transformer types influence the injection of line-frequency artifacts into the signal path.

Measured Mains-Related Spectral Components (see figures 31-33)

Table III. Noise floor reference measurement of the spectrum analyzer.

Component	Level (dBV)
60 Hz	−99
120 Hz	−128.9
180 Hz	−133.7
240 Hz	−139.4
Noise floor	-150

This establishes that the analyzer noise floor is well below the measured levels at the amplifier output.
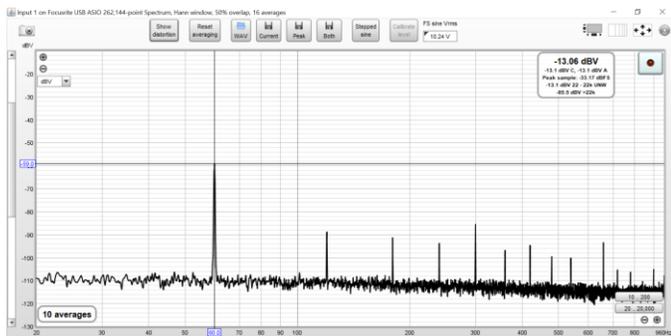

Figure 31. Noise floor reference of the spectrum analyzer. A 1 kHz notch filter and a post-amplification gain of 40 dBV are used in the measurement setup; therefore, this gain must be subtracted to determine the true amplitude of the spectral components.
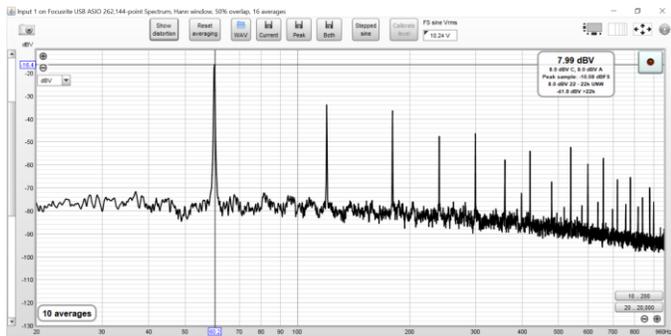

Figure 32. Spectrum analysis of the output sinewave at 15 Vrms into an 8 Ω load while powered by the EI laminated transformers.
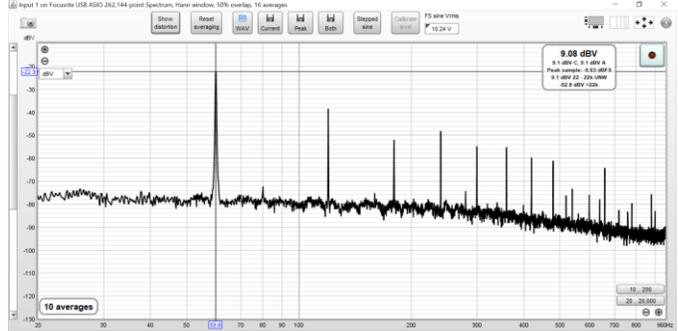
Figure 33. Spectrum analysis of the output sinewave at 15 Vrms into an 8 Ω load while powered by the AnTek toroidal transformer.

Table IV. Spectral content measurement of the amplifier output using EI laminated transformers (15 Vrms / 8 Ω).

Component	Level (dBV)
60 Hz	−56.4
120 Hz	−73.7
180 Hz	−87.6
240 Hz	−107.3
Noise floor	-120

Table V. Spectral content measurement of the amplifier output using the AS-4222 AnTek toroidal transformer (15 Vrms / 8 Ω).

Component	Level (dBV)
60 Hz	−62.3
120 Hz	−78.3
180 Hz	−88.6
240 Hz	−101.1
Noise floor	-120

Comparative Interpretation

Across all measured mains-related spectral components, the toroidal transformer consistently exhibits **lower absolute amplitudes** than the EI laminated transformers.

Key observations:

- The 60 Hz fundamental is approximately **6 dB lower** with the toroidal transformer.
- The 120 Hz component shows a reduction of approximately **4–5 dB**.
- Higher-order harmonics are similarly reduced or remain close to the measurement noise floor.

- These differences persist under identical load, output power, and measurement conditions.

Because **intermodulation mechanisms scale with the absolute magnitude of the modulating signal**, lower mains-related spectral content directly implies reduced susceptibility to ripple-induced modulation effects, regardless of whether sidebands are explicitly quantified as standardized IMD metrics.

Relation to Intermodulation Effects

While sideband components near 1 kHz $\pm$ n·60 Hz were observed and showed a reduction of approximately 9–10 dB when using the toroidal transformer, these results are presented as **supporting evidence** rather than as definitive IMD figures.

The physically relevant conclusion is that:

Lower absolute mains-related spectral content reduces the available modulation energy that can mix with the audio signal.

This relationship holds independently of the specific test methodology and explains why improvements in supply stiffness and ripple suppression translate into lower distortion audibility.

Implications for Audio Performance

From an audio engineering perspective, the measured reductions in 60 Hz and harmonic content imply:

- Reduced hum-related modulation of low-frequency program material
- Lower generation of ripple-induced intermodulation products
- Improved low-frequency clarity and stability
- Reduced congestion under sustained or complex signals

Importantly, **both transformer types operate within acceptable limits** for many applications. However, the toroidal transformer provides a measurable and repeatable advantage in minimizing power-supply-related spectral contamination.

Concluding Clarification

This work does not claim compliance with standardized IMD measurement protocols. Instead, it demonstrates—through absolute spectral analysis—that toroidal transformers introduce significantly lower mains-related components into the amplifier output than EI laminated transformers under identical conditions. These reductions directly support improved power-supply behavior and reduced susceptibility to ripple-induced distortion mechanisms in high-fidelity audio applications.

Influence of Transformer Topology on Low-Frequency Spectral Content

Despite the higher DC ripple voltage measured on the supply rails when using the toroidal transformer under high current demand, the resulting ripple contribution at the audio output remains in the microvolt range due to the high-power supply rejection ratio (PSRR) of both the LM3886 power stage and the LM4562 signal stage. Consequently, this ripple does not significantly affect the spectral purity of the output signal.

Conversely, measurements performed with the EI laminated transformer reveal a higher absolute spectral content at 60 Hz and its second harmonic, even though the measured DC ripple voltage is lower. This behavior indicates that the dominant noise coupling mechanism in this case is not conducted ripple through the power supply rails, but rather direct electromagnetic coupling from the transformer to the audio circuitry.

The EI laminated transformer exhibits higher stray magnetic flux and less effective field containment compared to the toroidal topology. This stray field can induce low-frequency interference directly into sensitive circuit nodes, ground loops, and wiring, bypassing the power supply rejection mechanisms of the amplifier. As a result, mains-related spectral components become more prominent in the output spectrum.

These results demonstrate that, in high-performance audio amplifier systems, transformer magnetic radiation and physical coupling can be more critical than raw ripple voltage magnitude when evaluating low-frequency noise performance. Proper transformer selection and layout are therefore essential to achieving optimal spectral cleanliness at mains-related frequencies.

This study highlights that low-frequency spectral purity in composite audio amplifiers is governed more by transformer electromagnetic behavior than by absolute DC ripple levels alone.

VIII. TABLE VI — SUMMARY OF MEASURED PERFORMANCE PARAMETERS

Parameter	EI Laminated Transformer	Toroidal Transformer (AnTek AS-4222)
Declared / estimated apparent power	≈240 VA (estimated from 2×24 V, 5 A)	400 VA (manufacturer rated)
Core type	EI laminated steel	Toroidal
Nominal secondary voltage	24–0–24 Vrms	22–0–22 Vrms
No-load secondary voltage (Vrms)	Higher overshoot	Moderate overshoot
No-load DC rail voltage	Higher than nominal	Closely matches theoretical peak
Regulation (indirect, DC, light load)	Inferior	Superior
Regulation (indirect, DC, high load)	Noticeable voltage sag	Gradual, controlled sag
Ripple voltage @ low DC current	Comparable	Comparable
Ripple voltage @ moderate DC current	Slightly lower	Slightly higher
Ripple voltage @ high DC current	Increases rapidly	Predictable, near-linear increase
Positive rail sag under dynamic load	Clearly observable	Significantly reduced
Low-frequency load handling	Limited stiffness	High stiffness
Evidence of magnetic saturation	Approaching at high load	Not observed
Mains-related spectral components (60 Hz, harmonics)	More pronounced	Lower amplitude
Line-frequency intermodulation products	More evident	Reduced
Mechanical hum / vibration tendency	Possible	Minimal
Cost (relative)	Low	Moderate
Availability	High	High

IX. GENERAL DISCUSSION

Design Implications for Audio Engineers

The experimental results presented in this work provide a practical framework for evaluating the suitability of EI laminated and toroidal transformers in high-performance audio power amplifiers. Rather than treating transformer topology as a binary "good vs. bad" choice, the measurements highlight the conditions under which each option can be technically justified, as well as the limitations that must be acknowledged.

The discussion below is intentionally grounded in measured behavior—regulation, ripple, rail sag, spectral content, and ripple-induced intermodulation—rather than traditional assumptions or audiophile folklore.

When an EI Laminated Transformer *Can* Be Used

The measurements demonstrate that a low-cost EI laminated transformer is **not inherently unusable** for audio applications, even in relatively demanding power amplifier scenarios.

Under moderate output power levels, the EI transformer:

- Provides acceptable DC regulation when properly sized.
- Maintains ripple voltage at levels that remain below clearly audible hum thresholds.
- Does not catastrophically degrade the amplifier's intrinsic THD performance.
- Produces ripple-induced intermodulation products that, although measurable, remain very low in absolute terms.

From a practical standpoint, EI laminated transformers **can be used** in the following cases:

- Cost-sensitive designs where ultimate noise floor is not the primary constraint.
- Amplifiers operating primarily at moderate power levels rather than sustained high output.
- Systems where additional mitigation techniques are applied, such as:
  - Increased reservoir capacitance
  - CRC or CLC filtering
  - Local rail decoupling close to the output stage
  - Amplifier topologies with strong low-frequency PSRR

In these contexts, an EI transformer may deliver performance that is entirely acceptable for many Hi-Fi applications, particularly where system noise is dominated by other factors (loudspeaker sensitivity, room noise floor, or upstream electronics).

When a Toroidal Transformer Is Clearly Superior

While EI transformers can function adequately, the measurements consistently show that the toroidal transformer offers **clear technical advantages** in applications targeting high-resolution audio performance. Compared to the EI laminated transformer, the toroidal unit exhibits:

- Reduced rail sag under dynamic low-frequency load conditions.
- Lower spectral amplitude of 60 Hz and harmonic components.
- Approximately **9–10 dB lower ripple-induced intermodulation sidebands** around a 1 kHz test tone.

These advantages are not merely academic. They directly translate into:

- Reduced modulation of the supply rails.
- Lower injection of low-frequency artifacts into the audio band.
- Improved low-frequency clarity and bass definition.
- Reduced "hum-related" intermodulation products, which are particularly audible in high-resolution systems.

For these reasons, a toroidal transformer is clearly preferable in:

- High-performance or "reference-grade" amplifiers.
- Designs intended to operate near maximum output power.
- Systems using wide-bandwidth, low-distortion amplifier topologies.
- Applications where microdetail, low-level resolution, and transparency are prioritized.

Practical Limits and Required Precautions

The results also define **where EI transformers begin to impose real constraints**.

As output power increases and low-frequency content becomes more demanding:

- Rail modulation becomes more pronounced with EI transformers.
- Ripple-induced IMD products rise proportionally with ripple amplitude.
- The power supply increasingly becomes the dominant performance limiter rather than the amplifier circuit itself.

To safely employ EI laminated transformers in audio amplifiers, designers must therefore accept and manage these constraints through:

- Conservative transformer loading (avoiding operation near rated VA).
- Oversized reservoir capacitors.
- Careful grounding and layout to minimize hum coupling.
- Realistic performance targets aligned with the transformer's electrical behavior.

Ignoring these precautions does not lead to catastrophic failure—but it does result in diminishing returns from otherwise excellent amplifier circuitry.

Final Conclusions

Based on the combined FFT analysis, ripple measurements, regulation data, rail sag evaluation, and ripple-induced intermodulation results, the following conclusions can be drawn:
- EI laminated transformers are **not inherently unsuitable** for Hi-Fi audio applications.
- Their use is viable when performance expectations are realistic and appropriate filtering and design margins are applied.
- Toroidal transformers, however, provide **measurable and repeatable advantages** in terms of ripple, reduced rail modulation, and significantly lower ripple-induced IMD.
- The key differentiator is not classical THD, but the **absolute spectral content of power-supply noise and its interaction with the audio signal**.

A Measurement-Driven Perspective (Without Dogma)

This study reinforces an important design principle: **audio performance should be evaluated through measured mechanisms, not assumptions.**

Transformer choice should not be guided by dogma, price alone, or tradition, but by:

- Measured ripple behavior
- Dynamic load response
- Spectral contamination of the audio signal
- The intended performance envelope of the final system

When viewed through this lens, EI and toroidal transformers are not competitors in a binary sense—but tools with different strengths, limitations, and appropriate use cases.

About the author

Andrés Sánchez received the B.Sc. degree in Communications and Electronics Engineering from the Escuela Superior de Ingeniería Mecánica y Eléctrica (ESIME), Instituto Politécnico Nacional (IPN), Mexico, in 2010, and the M.Sc. degree in Applied Sciences from the Universidad Politécnica de Sinaloa, specializing in power electronics and electrical energy conversion in 2023.

From 2010 to 2013, he worked in digital and analog design at the Electromagnetic Compatibility Laboratory of the Graduate Studies Section (SEPI) at ESIME. He later served as a power electronics design engineer, developing switch-mode power supplies and LED lighting systems from concept to production.

He is the founder and hardware designer of Olas Audio, focused on professional and high-fidelity audio equipment (https://olasaudio.com/).