Applying Ferrite-Based Inductors in the Design of Class D Amplifiers

Application Information

1 Introduction

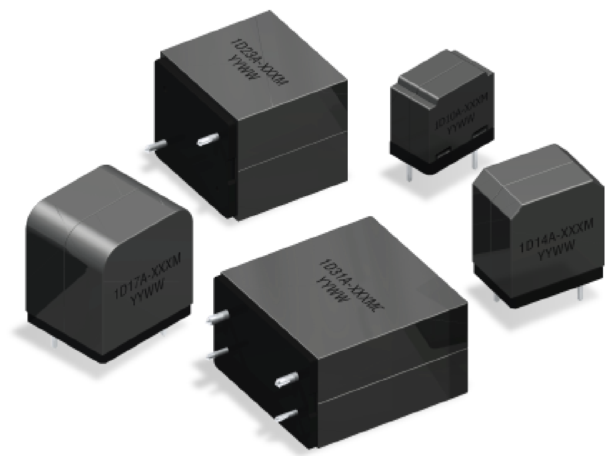
Class D amplifiers offer lightweight and high efficiency, making them ideal for modern audio applications, from high-power sound reinforcement to compact, battery-powered devices. Selecting the output filter inductor is the most critical design decision, directly impacting audio quality, thermal performance, and EMI.

This application note discusses the role of the output inductor, the specific advantages of using ferrite-based cores, and key parameters for selecting an optimal component. It will reference the ICE Components **1D Series** of Class D Inductors as a practical example of components engineered for this application.

2 Introduction to Class D Amplifiers

A Class D amplifier operates by converting the analog audio input signal into a high-frequency Pulse-Width Modulated (PWM) square wave. This PWM signal rapidly switches a set of output power MOSFETs fully on or off. Because the transistors (ideally) spend no time in the linear region, they dissipate very little power, leading to theoretical efficiencies from 80% to 97%..

This high-frequency switched signal is not suitable for driving a loudspeaker directly. Demodulating the signal requires a passive low-pass filter, typically an LC (inductor-capacitor) filter. This filter removes the high-frequency PWM carrier, recovering the amplified, low-frequency audio signal and delivering it to the load (the speaker).



3 The Role of the Output Inductor

The inductor is the heart of the Class D output filter. It serves two primary functions:

- **Energy Storage:** The inductor stores energy during one part of the switching cycle and releases it during the other, averaging the high-frequency pulses back into the desired audio waveform.
- **Current Limiting:** It presents a high impedance to the high-frequency switching carrier (typically 300 kHz to >1 MHz), blocking it from reaching the speaker, while presenting a very low impedance to the audible frequency range (20 Hz to 20 kHz), allowing the audio to pass through.

The design of this single component directly dictates the amplifier's performance:

- **Audio Fidelity:** A well designed inductor prevents non-linearity (e.g., saturation) which introduces distortion.
- **Efficiency:** Power lost as heat in the inductor's winding (DCR and ACR) and core (AC losses) directly reduces the amplifier's wall-to-speaker efficiency.
- **EMI Performance:** A poorly shielded inductor can radiate significant electromagnetic interference (EMI) from the high-frequency switching currents.

4 Why Ferrite-Based Inductors?

The choice of inductor core material is a trade-off between cost, size, and performance. While powdered-iron cores are common, designers often prefer ferrite-based inductors for high-performance Class D applications.

- **Low Core Losses at High Frequencies:** Ferrite materials inherently have very low core losses (hysteresis and eddy current losses) at the typical PWM switching frequencies. This is their single greatest advantage. Lower core loss means the inductor dissipates less heat, higher amplifier efficiency, and less thermal stress on components.
- **High Permeability:** Ferrite's high magnetic permeability allows designers to achieve the required inductance with fewer turns of wire in a smaller component package.
- **Stable Characteristics Over Time:** Ferrite materials exhibit excellent thermal and magnetic stability, maintaining consistent inductance across wide temperature swings and aging cycles. This predictability is crucial in Class D amplifier designs, where filter performance must remain tightly controlled to avoid distortion or EMI drift. Unlike some core materials that degrade or shift with prolonged exposure to heat or high currents, ferrite's crystalline structure resists thermal expansion and magnetic fatigue, ensuring long-term reliability in demanding environments.

The main challenge with ferrite is its "**hard saturation**" characteristic. Unlike powdered iron, which loses inductance gradually (soft saturation), a ferrite core can saturate abruptly. If the peak current exceeds the inductor's saturation rating (I_{SAT}), the inductance will collapse, causing a large current spike, potentially destroying the output MOSFETs and causing severe audio distortion.

This characteristic is not a flaw, but a critical design parameter. It necessitates careful selection of an inductor with a saturation current rating that can handle the absolute peak currents of the application with sufficient margin.

5 Key Design Considerations for Inductor Selection

When selecting a ferrite inductor for a Class D amplifier, designers must evaluate several key parameters.

5.1 Inductance Value (L)

The inductance value, in conjunction with the output capacitor (C), sets the cut-off frequency (f_C) of the low-pass filter. This frequency must be high enough to pass the entire audio band (< 20 kHz) but low enough to effectively attenuate the PWM carrier frequency (f_{sw}).

Calculate the cut-off frequency (f_C) using:

$$f_c = \frac{1}{2\pi\sqrt{LC}}$$

A common approach is to select an inductance value that permits a peak-to-peak current ripple (ΔI_{ripple}) of 20-40% of the maximum rated output current. The inductance can be calculated based on the supply voltage (V_{BUS}), switching frequency (f_{sw}), and desired ripple. The maximum ripple occurs at a 50% duty cycle (D = 0.5).

$$L = \frac{V_{BUS}}{4 \cdot f_{sw} \cdot \Delta I_{ripple}}$$

5.2 Saturation Current (I_{SAT})

This is arguably the most critical parameter for ferrite inductors. I_{SAT} is the peak current at which the inductance drops by a specified percentage. The inductor's I_{SAT} rating *must* be higher than the total peak current (I_{peak}) expected under any load condition.

The total peak current is the sum of the peak audio load current and half the peak-to-peak ripple current:

$$I_{peak} = I_{load(peak)} + \frac{\Delta I_{ripple}}{2}$$

Where the peak load current ($I_{load(peak)}$) for a given output power (P_{out}) and load resistance (R_L) is:

$$I_{load(peak)} = \sqrt{\frac{2 \cdot P_{out}}{R_L}}$$

A design rule of I_{SAT} > 1.25 · I_{peak} provides a safe operating margin.

5.3 RMS Current (I_{DC}) or Rated Current

This rating is thermal-based. It specifies the maximum continuous DC or AC current the inductor can handle before its temperature rises by a specified amount (e.g., ΔT = 40°C). The total RMS current ($I_{L(rms)}$) in the inductor is the quadratic sum of the RMS load current and the RMS ripple current.

$$I_{L(rms)} = \sqrt{I^2_{load(rms)} + I^2_{ripple(rms)}}$$

Where:

- $I_{load(rms)} = \frac{I_{load(peak)}}{\sqrt{2}}$
- $I_{ripple(rms)} = \frac{\Delta I_{ripple}}{2\sqrt{3}}$ (for a triangular wave)

The inductor's IDC rating must be greater than this calculated ($I_{L(rms)}$) to prevent overheating.

5.4 DC Resistance (DCR)

DCR is the resistance of the copper winding. This resistance causes I^2R power loss (conduction loss), which dissipates as heat and lowers efficiency. A lower DCR is always better.

$$P_{DCR} = I^2_{L(rms)} \cdot DCR$$

This conduction loss is typically dominant at high output power. Designers must factor this in with the AC core losses (P_{core}) which are frequency-dependent and dominant at idle (no signal).

$$P_{TotalLoss} = P_{DCR} + P_{core}$$

Choosing a ferrite core, as discussed, helps minimize P_{core}.

5.5 Shielding (EMI)

The inductor carries large, high-frequency switching currents and can act as an antenna. A shielded inductor contains the magnetic field within the core structure. This "low EMI design" is essential for passing EMC regulations and preventing interference with other nearby electronics.

6 Practical Design Example: 150W / 4Ω BTL Amplifier (TI's SLAA701A)

Let's apply these principles to select an inductor for a high-performance, 2-channel BTL amplifier based on TI's SLAA701A application note.

Design Parameters:

- Output Power (P_{out}): 150 W per channel
- Load Resistance (R_L): 4 Ω
- Supply Voltage (V_{BUS}): 36 V
- Switching Frequency (f_{SW}): 600 kHz

Step 1: Recommended Inductance (L)

For 4 Ω Bridge-Tied Load (BTL) with a Type-2 filter, TI's quick guide recommends:

- **Option A (Most Common):**
  L_{BTL} = 10 µH, C_G = 1.0 µF, $Q \approx 0.79$,
  $f_0 \approx$ 50 kHz.

- **Option B (More Bandwidth / More Ripple):**
  L_{BTL} = 7 µH, C_G = 1.0 µF, $Q \approx 0.76$,
  $f_0 \approx$ 60 kHz.

Either meets the flat-ish Butterworth goal; 10 µH gives lower ripple and is easier on EMI.

Step 2: Calculate Ripple Current (ΔI_{ripple})

Using the recommended 10 µH inductance, we can calculate the actual peak-to-peak ripple current by rearranging the formula introduced in Section 5.1.

$$\Delta I_{ripple} = \frac{V_{BUS}}{4 \cdot f_{sw} \cdot L} = \frac{36V}{4 \cdot 600,000Hz \cdot 10\mu H} = 1.5A$$

Step 3: Calculate Peak Current (I_{peak}) for I_{SAT}

First, find the peak load current required to deliver 150 W into 4 Ω:

$$I_{load(peak)} = \sqrt{\frac{2 \cdot 150W}{4\Omega}} = \sqrt{75} = 8.66A$$

Next, find the total peak current the inductor will see:

$$I_{peak} = I_{load(peak)} + \frac{\Delta I_{ripple}}{2} = 8.66A + \frac{1.5A}{2} = 9.41A$$

Applying the 1.25x safety margin, the inductor's I_{SAT} value must be: 1.25 × 9.41 A = **11.76 A**

Step 4: Calculate RMS Current ($I_{L(rms)}$) for I_{DC}

This calculates the "worst-case" continuous thermal load. First, find the RMS load current and RMS ripple current:

$$I_{load(rms)} = \frac{I_{load(peak)}}{\sqrt{2}} = \frac{8.66A}{1.414} = 6.12A$$

$$I_{ripple(rms)} = \frac{\Delta I_{ripple}}{2\sqrt{3}} = \frac{1.5A}{3.464} = 0.43A$$

The total RMS current is the quadratic sum:

$$I_{L(rms)} = \sqrt{(6.12A)^2 + (0.43A)^2}$$
$$= \sqrt{37.45 + 0.18} = 6.13A$$

The inductor's I_{DC} rating must be greater than this value to prevent overheating under a continuous sine-wave test. Required **I_{DC} > 6.13 A**.

Step 5: Component Requirements

- L = 10 µH
- I_{SAT} > 11.76 A
- I_{DC} > 6.13 A
- P_{DCR} *per channel* ≈ 2 × I_{rms}^2 × DCR
  - At I_{RMS} ≈ 6.13 A, P_{DCR} ≈ 74.9 × DCR(Ω) per channel. So every 10 mΩ is ≈ 0.75 W heat/channel, ≈ 0.38 W heat/inductor.

Step 6: ICE Recommended Parts

For a high-performance 150 W amplifier, the superior recommendations are:

- **1D31A-100MC — Best Overall**
  - 10 µH, DCR ≈ 6.3 mΩ, I_{SAT} ≈ 50 A
  - P_{DCR} per channel (at 150 W) ≈ 0.47 W
  - Low Loss, Big Headroom
  - Great thermal margin; Large package.
- **1D23A-100M — Balanced Efficiency**
  - 10 µH, DCR ≤ 9.6 mΩ, I_{SAT} up to ~38 A
  - P_{DCR} per channel (at 150 W) ≈ 0.72 W
  - Balanced Size vs. Performance
  - Smaller than 1D31A with plenty of I_{SAT} for low total harmonic distortion.
- **1D17A-100M — Space-Saving**
  - 10 µH, DCR ≤ 18 mΩ, I_{SAT} up to ~31 A
  - P_{DCR} per channel (at 150 W) ≈ 1.35 W
  - Compact and Cost-Lean
  - Electrically OK; Plan for extra thermal margin.

Step 7: Design Summary

- **Load Current**
  - I_{RMS} = √(150/4) = **6.12 A**, I_{peak} = **8.66 A**
- **Idle Ripple (10 µH)**
  - 36 V / (8·10 µH × 600 kHz) ≈ **0.75 A** peak
- **DCR Loss per Channel**
  - 1D31A-100MC (6.3 mΩ each): 2×(6.12²)×0.0063 ≈ **0.47 W**;
  - 1D23A-100M (9.6 mΩ each): 2×(6.12²)×0.0096 ≈ **0.72 W**;
  - 1D17A-100M (18 mΩ each): 2×(6.12²)×0.0180 ≈ **1.35 W**;
- **Capacitor (Type-2, 4 Ω)**

  C_G = 1.0 µF with L = 7–10 µH.
  Use polypropylene film with adequate AC current rating; X7R ceramics derate with DC bias.

7 Applying ICE Components' Ferrite-Based Class D Inductors

The **ICE Components 1D series** provides a practical case study for applying these principles. These components are specifically engineered for Class D audio applications and exhibit the key features discussed.

- **Ferrite Core Construction:** The 1D series utilizes efficient ferrite cores with a core shape engineered to optimize performance for Class D switching topologies. This construction provides the low AC core losses necessary for high-efficiency amplification.
- **Low EMI Design:** The series features a shielded construction that minimizes radiated magnetic fields, simplifying the system-level challenge of EMI compliance.
- **Clear Current Ratings:** The product tables clearly delineate between I_{SAT} (Saturation Current) and I_{DC} (DC Current / RMS).
  - For example, the **1D17A-100M** has an I_{SAT} of 31.0 A and an I_{DC} of 6.0 A.
  - This tells a designer that while the component can handle continuous RMS audio currents up to 6.0 A (thermal limit), it can withstand signal peaks up to 31.0 A before saturating (magnetic limit). This high-headroom I_{SAT} is essential for handling musical transients without distortion.

- **Optimized DCR:** The series offers very low DCR values (e.g., 6.3 mΩ for the **1D31A-100MC**) to minimize conduction losses P_{DCR} and maximize amplifier efficiency.

- **High-Temperature Operation:** A maximum temperature rating of 130°C provides significant thermal headroom for high-power, space-constrained designs.

- **Small Footprint:** The components are designed as thru-hole (TH) devices with a small board footprint, balancing power handling with density.

When selecting from this series, a designer would first calculate the required L, I_{peak} (for I_{SAT}), and $I_{L(rms)}$ (for I_{DC}) using the formulas in Section 5.0. They could then select the smallest part in the 1D series (e.g., **1D10A**, **1D14A**, **1D17A**) that meets these criteria with an appropriate safety margin.

8 Conclusion

The output inductor is not a simple passive component but a critical piece of the Class D amplifier's "engine." By choosing a high-performance, ferrite-based inductor, designers can minimize losses, ensure audio fidelity, and control EMI. Ferrite cores offer superior performance at high switching frequencies, but demand careful attention to peak current ratings to avoid hard saturation.

Component families like the ICE Components 1D series, which are designed specifically for this application, simplify the selection process by providing low-loss ferrite cores in shielded, small-footprint packages with clear I_{SAT} and I_{DC} ratings, enabling the design of efficient, reliable, and high-fidelity Class D amplifiers.

For more details about our Class D Inductors, please visit:
https://www.icecomponents.com/product-category/inductors/class-d-inductors/

Reference: TI SLAA701A - LC Filter Design
https://www.ti.com/lit/pdf/sloa119?keyMatch=SLAA701A&tisearch=universal_search