Application Note

Class-D Amplifiers Driving High-Inductance Loads in Speakers and Haptics Coils

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ABSTRACT

Class-D audio amplifiers are high-efficiency switching converters widely used in audio applications across consumer electronics. Texas Instruments offers a comprehensive portfolio of Class-D devices — including those with integrated boost converters like TAS2120, TAS2572 and TAS2563 and those driven by an external PVDD supply like TAS2320, TAS2780 and TAS2781. These amplifiers support a diverse range of actuators including micro speakers, woofers, sub-woofers, tweeters, bone conduction actuators, LRAs, ERMs, haptic coils, and piezo/MEMS speakers, each with distinct electrical characteristics. When driving highly inductive loads, amplifiers may run into boost over-voltage (OV) faults caused by reverse inductive kickback current, and Over-Current shutdowns due to insufficient Y-Bridge switching hysteresis. The over current scenario can also occur when using a Y-Bridge with a large LC (EMI) filter on the Class-D output. This application note identifies the root causes of these modes and provides practical, quantitative design solutions to mitigate them.

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1 Introduction

Class-D audio amplifiers are switching converters that are used for audio because of their high efficiency. The class-D amplifiers devices from TI can have either an integrated boost converter, to generate the Class-D switching supply rail (ex.11V/13V) from a low voltage battery supply: (example 2.5V-5.5V) or the Class-D can be driven with an external power supply rail directly.

Further, some TI class-D amplifiers devices use an integrated Y-bridge to dynamically change the power supply rail on which the class-D switches based on the audio dynamically. For example, the: TAS2572 and TAS2780 have an integrated Y-bridge where at low power the amplifier switches on either the 1.8V & 3.8V rail respectively and at higher power operates on the Boosted/external PVDD rail respectively.

The class-D amplifier can be used to drive different kinds of actuators: microspeakers (used in applications like Smartphones, wearables, or PCs), large loudspeakers: woofers/tweeters/mid-range speakers, bone conduction actuators, LRAs/ERMs, coils and piezo/MEMS speakers to produce audio. Each of these actuators offer a different level of electrical inductance/impedance. Electrically, micro speakers are typically more resistive loads which offer relatively low inductances, while large loudspeakers, woofers/sub woofers & haptics coils (LRAs & ERMs) are a combination of mid-low resistance and high inductance. Electrically tweeters are capacitive coupled speaker loads & Piezo/MEMS speakers are almost purely capacitive loads.

The table below shows the approximate range of speaker resistance (R) & inductance (L) & capacitance (C) for different types of actuators and the electrical nature of the actuator.

Table 1-1. Actuator Types and Ranges for Different Audio Applications

Actuator type	**Typical application**	**Series (DC resistance)**	**Electrical nature of actuator**	**Series inductance/ capacitance**
Microspeakers	Mobile & PC speakers	4Ω-32Ω	R	≤ 200uH
Woofers & Mid-Full Range speakers	Bluetooth speakers & TVs , Soundbars, Party boxes	3Ω-8Ω	R+L (slightly inductive)	≤ 500uH (Mid-range) ≤ 1.5mH (Woofers)
Sub-woofers	Bluetooth speakers, Soundbars, TVs, Party boxes	2Ω-8Ω	R+L (highly inductive)	≤ 50mH
Tweeters	Soundbars, Party boxes	4Ω-15Ω	R+L+C (Cap coupled)	≤ 1.5mH 10uF-80uF (Series Cap)
Bone conduction actuators	Headphones, Audiometry, Hearing devices	4Ω-50Ω	R+L (slightly inductive)	≤ 3mH
LRAs/ ERMs/Haptics coils	Gaming controllers, Trackpads, Smart wearables	LRA: 10Ω-30Ω ERM: 25Ω-60Ω Haptics coils: 4Ω-12Ω	R+L (slightly inductive)	≤ 1.5mH
Piezo speakers/ Buzzers	Alarms, Sirens, Doorbells, GPS trackers, Appliances (Beepers)	Very high >1MΩ	Capacitive (C)	≤ 1.5uF
MEMS speakers	Headphones, Smart wearables (AR/VR headsets, Glasses), Hearing aids	Very high >1MΩ	Capacitive (C)	≤ 150nF

Due to the highly nature inductive loads such as: LRAs/ ERMs/Haptics coils, woofers/sub-woofers & some mid-full range speakers there are design considerations required to ensure the amplifier operates smoothly without triggering boost over voltage or Class-D over current faults.

2 Detailed Description

2.1 Boost over voltage fault considerations for highly inductive speakers

For highly inductive audio actuators the key problem is that they resist sudden changes in the current through the actuator even if there is a change in the polarity of the voltage through the actuator. Due to this there is a large phase lag between the voltage & the current when driving a highly inductive speaker/haptics actuator. For example, as shown in the following figure, the Class-D amplifier outputs OUT_P & OUT_N are used to drive a full-scale input differential PWM into a speaker coil whose R= 4ohm & L= 1mH with a PVDD supply voltage=13V, as shown in the following equation:

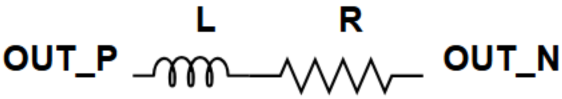


Figure 2-1. Class-D outputs connected to inductive speaker

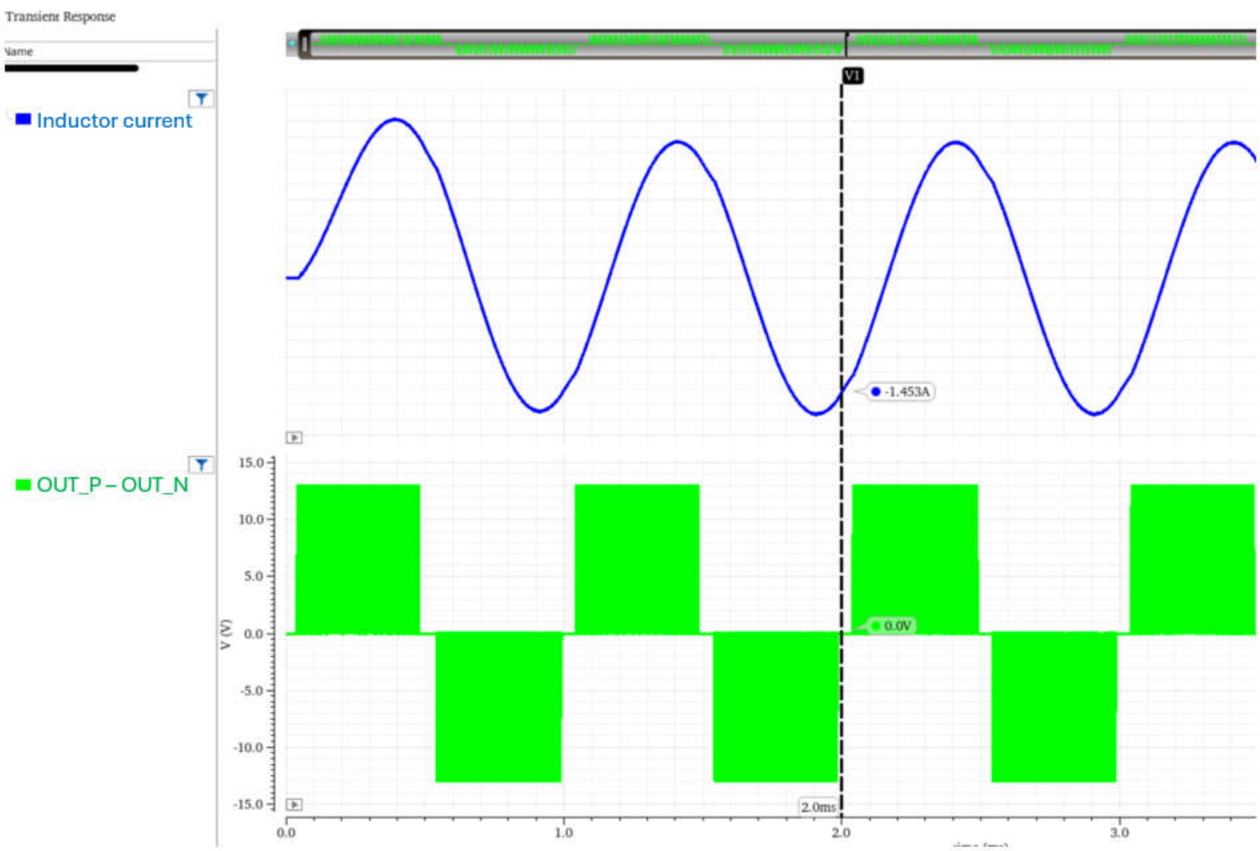
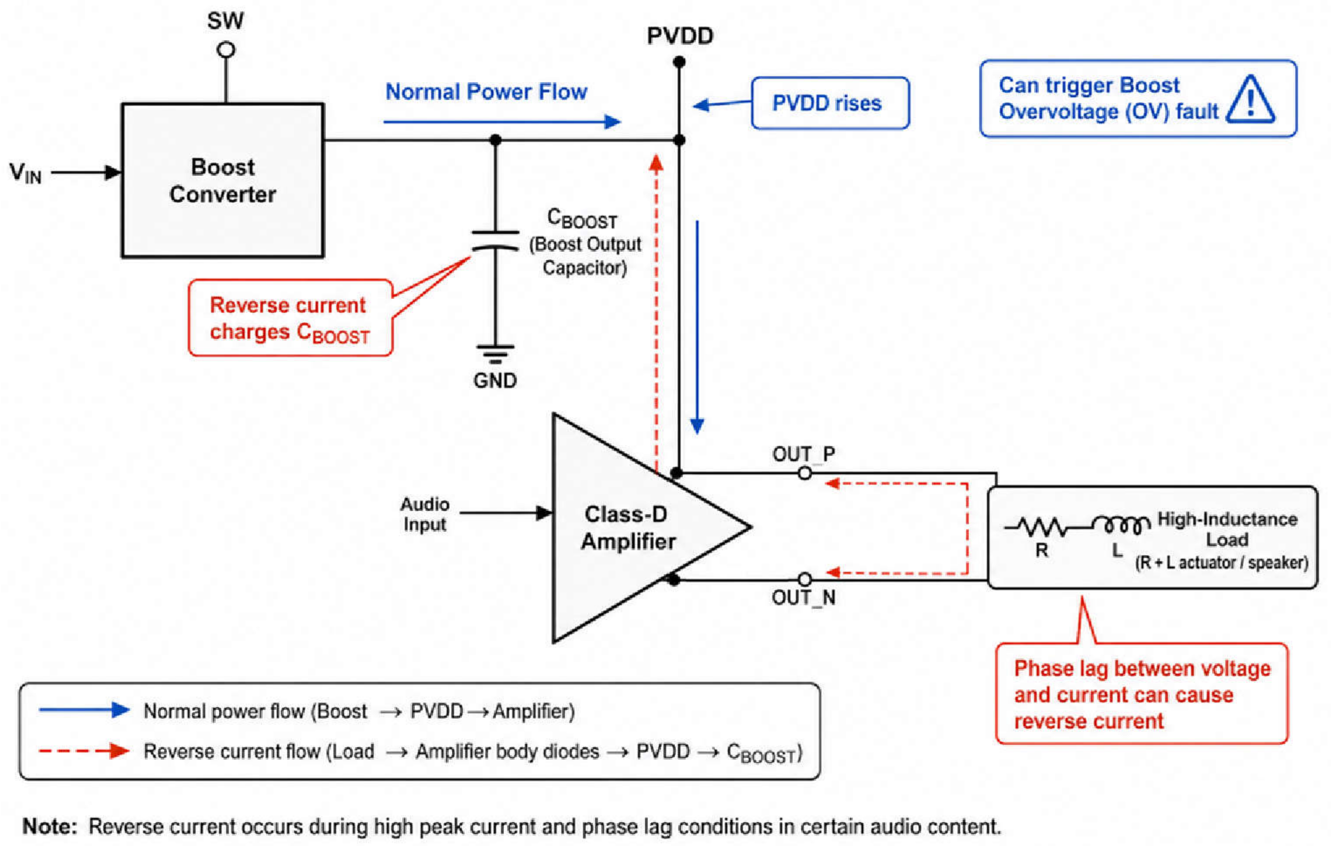


Figure 2-2. Example waveform of actuator current when driving a differential PWM showing phase lag between voltage & current across the actuator

As can be observed from the figure, there are scenarios where the Class-D output OUT_P-OUT_N has crossed zero however due to high inductance, the current has a lag in responding to change in the voltage and there is a high negative current of -1.45A.

Due to this phase lag, there are scenarios for certain kinds of input audio files, where if the amplifier is operating at a high peak current and there is a sudden change of phase of the Class-D output the reverse current from the actuator gets pushed into the Boost output through the Class-D FETs. This phenomenon is shown in the image in Figure 2-3. Since boost converters are typically designed to only source an output current & aren't designed to sink any current hence this reverse current ends up overcharging the boost output capacitor to a higher voltage causing the Boost over voltage fault to eventually trigger & shutdown the device.



Note: Reverse current occurs during high peak current and phase lag conditions in certain audio content.

Figure 2-3. Class-D amplifier with integrated boost converter showing the reverse current path

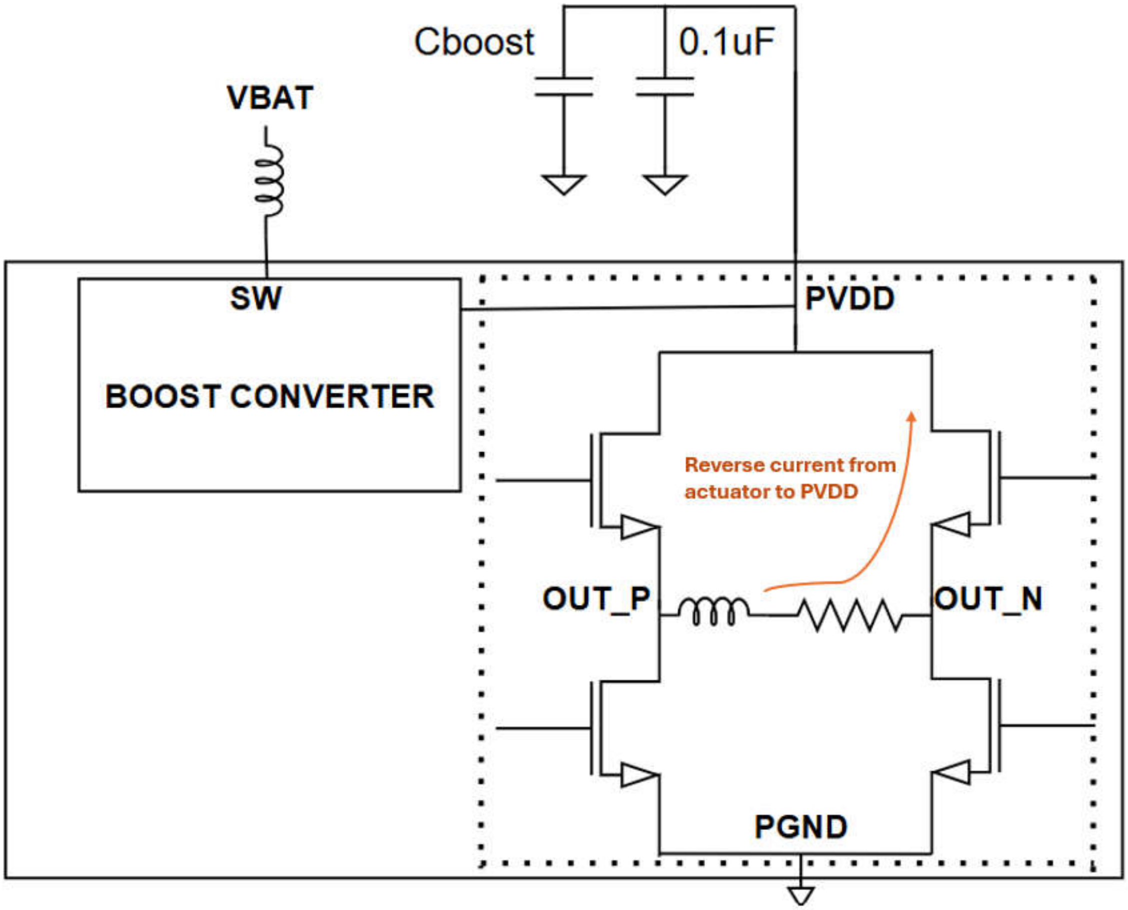
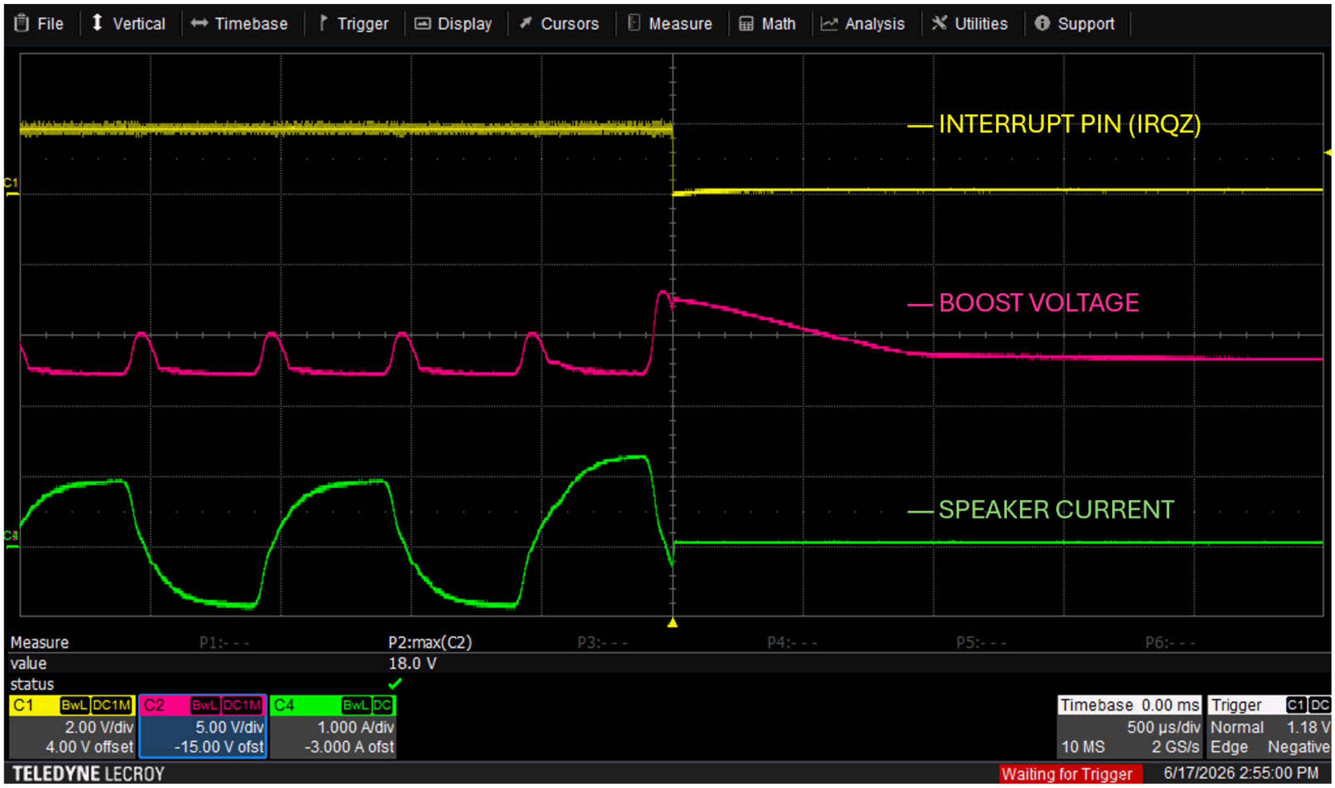


Figure 2-4. Class-D amplifier with integrated boost converter showing internal FET current path

The worst-case scenario of such an occurrence, is a large current has built up and suddenly the signal amplitude reduces to a very small value, but the large reverse current causes the boost to charge up and trip an overvoltage. To mimic this scenario, square wave input signals were provided to the amplifier and swept in amplitude from low -9dBFs to -6dBFs to trigger the negative current & OV. Figure 2-5 shows a scope capture of the Boost voltage & speaker current at the time when the OV is triggered due to this kind of audio input to the device with an actuator load of 6ohm+500uH inductance.



Measure P1:- - - P2:max(C2) P3:- - - P4:- - - P5:- - - P6:- - -
value 18.0 V
status ✓
C1 BwL DC1M 2.00 V/div 4.00 V offset
C2 BwL DC1M 5.00 V/div -15.00 V ofst
C4 BwL DC 1.000 A/div -3.000 A ofst
Timebase 0.00 ms 500 µs/div 10 MS 2 GS/s
Trigger C1 DC Normal 1.18 V Edge Negative
6/17/2026 2:55:00 PM

Figure 2-5. Boost Over voltage fault observed on TAS2572 EVM with default 20uF capacitor with 6ohm+500uH load

There are 2 Solutions, either of which can be used to avoid Boost Over voltage faults on Integrated boost Class-D amplifier devices with highly inductive loads:

1. **Solution 1:** Ensure there is sufficient boost capacitance to prevent the boost inductor current from over-charging the boost capacitor beyond the OV threshold. To calculate the amount of boost capacitance required it must be ensured that the energy stored in the inductor at the worst case peak load current doesn't cause the boost capacitor to over-charge.

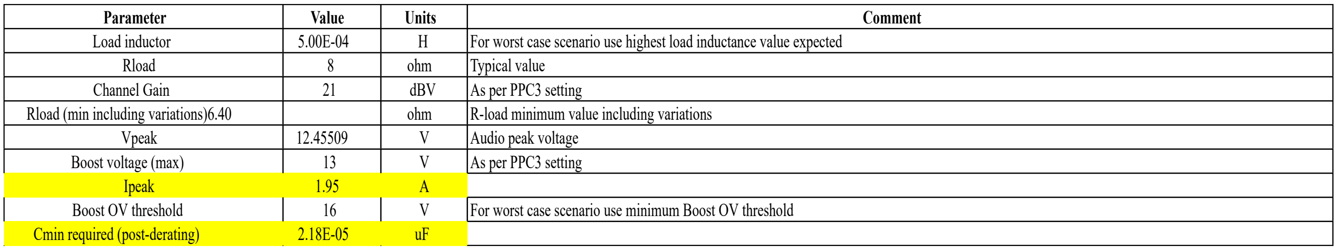
   Lets assume the channel gain programmed by the user is "CH" dBV, the speaker resistance is "Rspk" & inductance is "Lspk" and the boost voltage is "Vbst", & the maximum boost voltage OV threshold is "Vov". Let's assume the amplifier has an rdson of Rdson. To calculate the minimum boost capacitance Cmin required to prevent the Boost OV, the follow equations can be applied:

   - The peak voltage across the load (Vpk) = Min(Vbst*Rspk/(Rspk+Rdson), 10^((CH+3)/20))
   - The peak current through the speaker Ipk = Vpk/Rspk
   - Energy stored in the inductor = ½*Lspk*Ipk^2
   - To ensure that the energy in the inductor can be dissipated through the capacitor without triggering boost OV fault the ½*C* (Vov^2 -Vbst^2) > ½*Lspk*Ipk^2
   - Cmin (derated) ≥ Lspk*Ipk^2/(Vov^2 -Vbst^2)

   The user must check the appropriate de-rating of the capacitor at DC bias of "Vov" as per the datasheet.

   To ensure that the de-rated capacitance is sufficient to meet the minimum requirement

   To reduce complexity the user may also use the excel sheet calculator included in this TI-E2E post.



Parameter	Value	Units	Comment
Load inductor	5.00E-04	H	For worst case scenario use highest load inductance value expected
Rload	8	ohm	Typical value
Channel Gain	21	dBV	As per PPC3 setting
Rload (min including variations)6.40		ohm	R-load minimum value including variations
Vpeak	12.45509	V	Audio peak voltage
Boost voltage (max)	13	V	As per PPC3 setting
Ipeak	1.95	A	
Boost OV threshold	16	V	For worst case scenario use minimum Boost OV threshold
Cmin required (post-derating)	2.18E-05	uF	

Figure 2-6. Snapshot of excel calculator

The Cmin (post-derating) & Ipeak highlighted in yellow are the outputs of this excel sheet-based calculator that directly calculates this using the inputs provided by the user. All items not marked in Yellow are inputs to the sheet that must be provided by the user.

As an example, in the above scenario shown in Figure 6, the load inductance assumed is maximum 500uH & the minimum load impedance assumed is 6.4ohm and the user has programmed the channel gain to 21dBV. The ipeak calculated as output is 1.95A and the minimum capacitance required post-derating to avoid Boost OV trip is ≥21.8uF.

25V Ceramic capacitors de-rate very heavily at 16V DC bias, hence to realize a ≥21.8uF capacitance this would warrant ≥181uF ceramic capacitance pre-derating, which isn't optimal for cost/footprint.

To realize this capacitance, it may be more sensible in terms of cost & footprint to utilize:

- 47uF aluminum electrolytic capacitor (if solution is not height constrained, example Part number: UCM1V470MCL1GS)/ Stacked ceramic capacitors of 50uF (example Part number: ST125C506MAJ10)

OR

- 5x10uF capacitors 50V ceramic capacitors (if solution is height constrained, example Part no: GRM21BR61H106ME43L)

2. **Solution 2:** Adding a Zener diode voltage clamp on the boost supply to sink the flowback current from the Class-D FET and prevent the boost from triggering OV. This Zener diode voltage tolerance must be relatively low to ensure that it doesn't trigger during normal boost operating conditions but also ensure that the maximum clamping voltage is less than the minimum boost OV threshold. For TAS2572 the boost OV threshold is programmable using: pvdd_ovlo_th_sel[1:0] as per the datasheet for internal boost mode with default set to 16V. Accounting variation of ±2% the minimum threshold is 15.68V. Hence it must be ensured that the Zener diode must activate only >13V & <15.86V. So, either a 14V or 15V Zener diode can be used with +-5% tolerance. (example part number: 4878-SZ3C15). Ensure the power rating of the Zener diode is sufficient to tolerate high currents for short duration.

2.2 Class-D Y-Bridge hysteresis minimum requirement to prevent over current shutdown

Devices like TAS2120, TAS2780, TAS2781 have an integrated Y-Bridge where the Class-D amplifier switches on VBAT supply (3.8V) at low power levels and dynamically switches over to a PVDD supply (18V) at high power based on audio. Similarly TAS2572 device has an integrated AVDD Y-bridge where the amplifier switches off a low voltage (1.8V) supply for <100mW power levels & switches over to Boosted rail PVDD (2.5V-13V) for higher power levels. The low voltage AVDD Y-Bridge output FET circuitry is designed to handle a peak current of <0.95A & the switchover from PVDD rail to AVDD rail on TAS2572 for example happens with certain hysteresis (ex. 500us).

Hence if there is an audio profile where the Class-D was switching on the PVDD bridge with a high peak current and there is a high inductance which takes long duration to discharge > 500us to <0.7A it can trigger the AVDD bridge over current and cause the device to shut down. To prevent this, it must be ensured:

- Y-bridge time hystersis > 2*Lspkr / Rspkr

This is to ensure that the peak current dies down to a sufficiently low value before the Bridge switchover to avoid triggering an AVDD bridge over current error. For example if the Lspk= 10mH & R= 4ohm, it is recommended to set the Y-bridge time hysteresis to > 5ms.

Similarly, in TAS2764, TAS2780, TAS2781 the VBAT Y-bridge is designed to handle a maximum current of 2A while the PVDD bridge can handle >4.9A. Hence it is recommended that while using a high inductance load for example as mentioned above the LVS_HYS[3:0] register is programmed to meet the minimum requirement for hysteresis to avoid Over current related shutdowns. Alternatively, the Y-bridge feature may also be disabled at the cost of efficiency performance, however all devices support hysteresis settings upto 50ms for the Y-bridge which should be sufficient to avoid these issues.

2.3 Class-D Y-Bridge over current shutdown when using EMI filters on the class-D output

A scenario may also occur when connecting a low frequency LC filter (<< switching frequency of the Class-D amplifier output) at the Class-D output since this generates a ripple current which propagates through the Class-D FETs. In such a scenario the AVDD Y-bridge may also have to be disabled or the AVDD Y-bridge threshold may need to be reduced, depending on the amount of ripple current through the LC filter to avoid triggering an AVDD Y-bridge Over current error.

To avoid OC errors, it must be ensured that peak audio current + Ripple current through the LC filter < AVDD Bridge Over current threshold. Assuming that the amplifier was switching on PVDD bridge,

The ripple current through the LC filter for TAS2572 can be calculated as:

- ΔI= PVDD/(4*L*Fsw) (Operating in PVDD bridge)

Where PVDD= PVDD supply voltage, L= Inductor value & Fsw= switching frequency of the Class-D amplifier.

For example, if the L=1uH & C=0.68uF and Fsw=384KHz, PVDD=13V the ripple current is ±0.84A, when the Class-D switches from PVDD rail into AVDD bridge, which will trigger the Over current error, irrespective of AVDD Y-bridge threshold. This forces the AVDD bridge to be disabled always.

However, if the Boost voltage is sufficiently low <9V, it may be possible to still utilize the AVDD Y-bridge to save efficiency at low power levels. Alternatively, the user can increase the Inductance value & reduce the capacitance to still achieve the same LC filter cutoff frequency and mitigate the high ripple current (at the cost of BOM size & cost for the inductor).

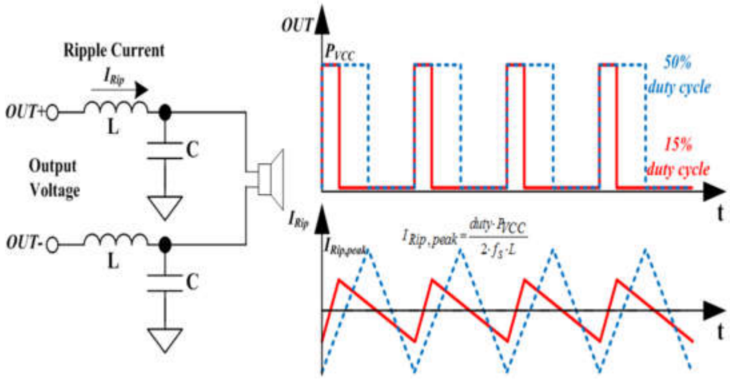


Figure 2-7. Image showing the Class-D output ripple current with LC filter

3 Summary

This application note addresses critical design considerations for Class-D amplifiers when driving highly inductive loads such as subwoofers, LRAs, haptic coils, and when using LC-EMI filters at the amplifier output. Highly inductive actuators exhibit significant phase lag between voltage and current, leading to two primary fault conditions: Boost Over-Voltage (OV) faults caused by reverse inductive kickback current, and Over-Current (OC) shutdowns due to insufficient Y-Bridge switching hysteresis.

This application note covers TI Class-D devices with integrated boost converters (like TAS2572, TAS2574, TAS2562, TAS2563 orTAS2564) and those with external PVDD supplies (like TAS2764, TAS2770, TAS2780 or TAS2781). It provides an electrical characterization of various actuator types ranging from microspeakers (≤200µH) to highly inductive subwoofers (≤50mH) and haptic coils.

Two practical solutions are presented for Boost OV mitigation: (1) Calculating and implementing sufficient boost capacitance to absorb inductive energy without exceeding OV thresholds, with a provided design calculator tool, and (2) Adding a Zener diode voltage clamp to sink reverse current. For Y-Bridge OC prevention, the note establishes minimum hysteresis requirements to ensure adequate current decay before bridge transitions.

The note also addresses OC issues when using LC-EMI filters on Class-D outputs, providing ripple current calculation methods and design trade-offs between Y-Bridge operation, filter component values, and system efficiency. These quantitative design guidelines enable robust amplifier operation across diverse inductive loads without triggering protection faults.

4 References

1. TAS2572 - 6.5-W Boosted Class-D Audio Amplifier With Integrated DSP, Datasheet
2. TAS2574 - 10.5-W Boosted Stereo Class-D Audio Amplifier With IV Sense, Datasheet
3. TAS2562 - 5.7-W Boosted Class-D Audio Amplifier, Datasheet
4. TAS2563 - 5.7-W Boosted Class-D Audio Amplifier With Integrated DSP, Datasheet
5. TAS2564 - 5.7-W Boosted Class-D Audio Amplifier With IV Sense, Datasheet
6. TAS2764 - 4.5-W Boosted Class-D Audio Amplifier, Datasheet
7. TAS2770 - 5.6-W Mono Class-D Audio Amplifier, Datasheet
8. TAS2780 - 5-W Boosted Class-D Audio Amplifier, Datasheet
9. TAS2781 - 5-W Boosted Class-D Audio Amplifier With Integrated DSP, Datasheet
10. Efficiency Improvement With Y-Bridge in TAS2x20, TAS257x
11. Y-Bridge in TAS278x Class-D Amplifiers for Improving Efficiency

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Last updated 10/2025