12

Class D Audio Amplifiers

12.1 Introduction

Until recently, in order to achieve high-quality sound from an audio amplifier thousands of dollars would have had to be spent on a large, heavy, power-hungry amplifier built with a class A amplifier topology. The class A amplifier is the benchmark for sound quality. It is composed of a current source and a transistor operating in its linear region where small-signal analog is directly converted to large-signal power to drive the loudspeaker. A key advantage of the class A amplifier is that it is unipolar, where the amplifier stays in a constant mode and only component nonlinearity causes distortion [1]. A drawback is that class A amplifiers operate as a constant power dissipater with efficiencies in the 15–30% range. Figure 12.1a shows a schematic of a class A amplifier [2].

The class AB amplifier uses a push–pull output with the transistors operating in their linear region. While each half cycle behaves like a class A amplifier, circuitry and components are complimentary between the positive and negative cycles, leading to variations in distortion. Class AB amplifiers reduce distortion by biasing the output stage such that there is always current flowing [3]. Class AB amplifiers have a lower sound quality compared with class A amplifiers, but efficiency can be 50–70% [4]. Even at 70%, 200 W of output power dissipates over 85 W of heat, requiring large, heavy heatsinks. Figure 12.1b shows a schematic of a class AB amplifier.

The processor for a class D amplifier creates a high-frequency, pulse-width-modulated small signal that represents the audio signal. Power transistors in either a half bridge or full bridge convert the small signal to a large signal to drive the speakers through a filter. A diagram of a single channel, bridge-tied load (BTL), class D amplifier with a split supply (±HV) is shown in Figure 12.2. Since each pulse is a square wave, increasing frequency gives a better representation of the audio signal. With each switching cycle, power is dissipated through both switching losses and conduction losses, creating a tradeoff between sound quality, operating frequency, and power dissipation.

Discerning listeners suffered with mediocre audio quality coming out of TVs, car stereos, and boom boxes where sound quality was described as “good enough.” Even moderate-cost, class D amplifier rack systems lacked richness and color of the sound. The potential for improvement relied heavily on overcoming imperfections of the silicon power MOSFET [5]. To meet targeted total harmonic distortion plus noise

GaN Transistors for Efficient Power Conversion, Third Edition. Alex Lidow, Michael de Rooij, Johan Strydom, David Reusch and John Glaser.

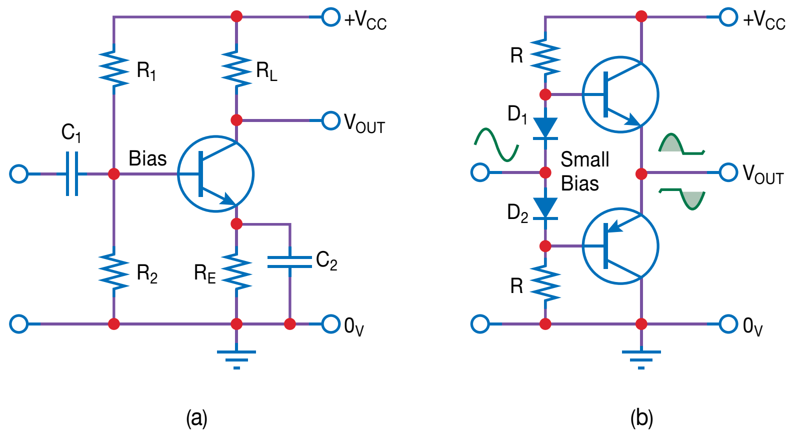


Figure 12.1 Schematic diagrams for (a) class A amplifier and (b) class AB amplifier.

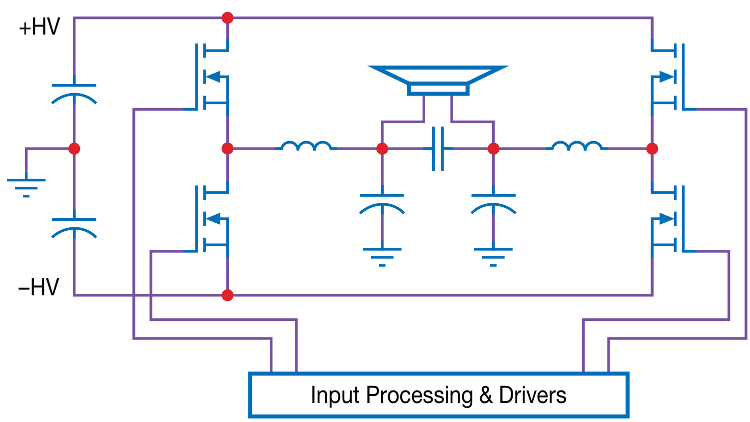


Figure 12.2 Diagram for a single channel of a BTL class D amplifier with a split supply (±HV).

(THD + N) numbers, high gain was required in the feedback loop, which introduced dynamic intermodulation distortion (DIM) that suppresses the subtle richness and color of the music.

The objective of the power stage of the class D amplifier is to create an exact large-signal replication of the small-signal source while dissipating little heat. Chapter 7 details the theory and practice of hard-switching commutation with a buck converter example, which is relevant to the efficiency and linearity of a class D amplifier. A significant difference is that each transistor in a class D amplifier spends half of its time functioning as a control switch and half of its time operating as a rectifier switch. While a transistor in a buck converter socket can be optimized for its function, a transistor in a class D amplifier is required to perform all functions well [6]. There is no room for functional compromises as the transistor must have both outstanding on-state and switching characteristics.

Each parasitic element of the transistor that is dissipative creates distortion. For example, $R_{DS(on)}$ prohibits the output waveform from reaching either rail while dissipating

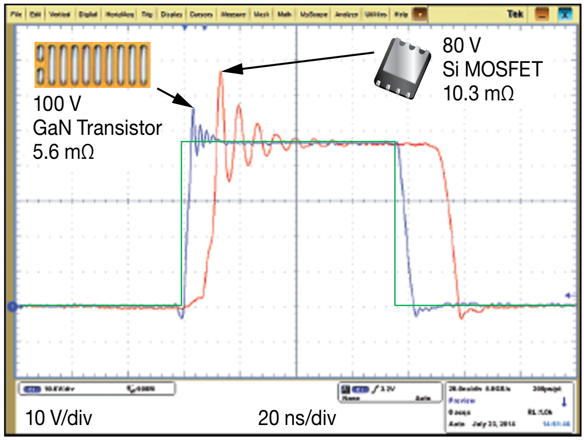


Figure 12.3 EPC2001C [8] GaN transistor (blue) and BSC123N08NS3 [9] MOSFET (red) waveforms compared with an ideal waveform (green) [10].

power that is proportional to the square of the current. Input charge and gate resistance slow the switching transition, while applying both current and voltage to the transistor simultaneously. Stray inductance and reverse recovery charge cause overshoot and ringing while the associated energy is dissipated in each cycle [7]. Figure 12.3 compares an ideal waveform with measured waveforms of both a GaN transistor and a silicon MOSFET.

12.1.1 Total Harmonic Distortion

Total harmonic distortion (THD) is defined as the ratio of the equivalent root mean square (RMS) voltage of all the harmonic frequencies (beginning with the second harmonic) over the RMS voltage of the fundamental frequency [11] and is given by

$$\mathrm{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} V_{\mathrm{N\_RMS}}^{2}}}{V_{\mathrm{Fund\_RMS}}} \tag{12.1}$$

where $V_{\mathrm{N\_RMS}}$ is the RMS voltage of the nth harmonic, and $V_{\mathrm{Fund\_RMS}}$ is the RMS voltage of the fundamental frequency.

Another major contributor to THD is dead-time distortion. Dead time is the time where both high-side and low-side transistors of the class D amplifier are commanded off. During dead time, commutation is delayed, preventing shoot-through of current caused by differences in propagation delay between the high side and the low side. The propagation delay differences are due to the variation in delay of the gate drivers along with variations in delay due to inductance common to the power loop and the gate drive loop. The GaN transistors in LGA or BGA wafer level chip-scale (WLCS) packages eliminate most common source inductance, while the wire-bonds, clips, and cans of packaged GaN or Si-MOSFETs have significant common source inductance. Low common source inductance and the choice of a gate driver with low propagation delay mismatch allows dead-time distortion to be minimized.

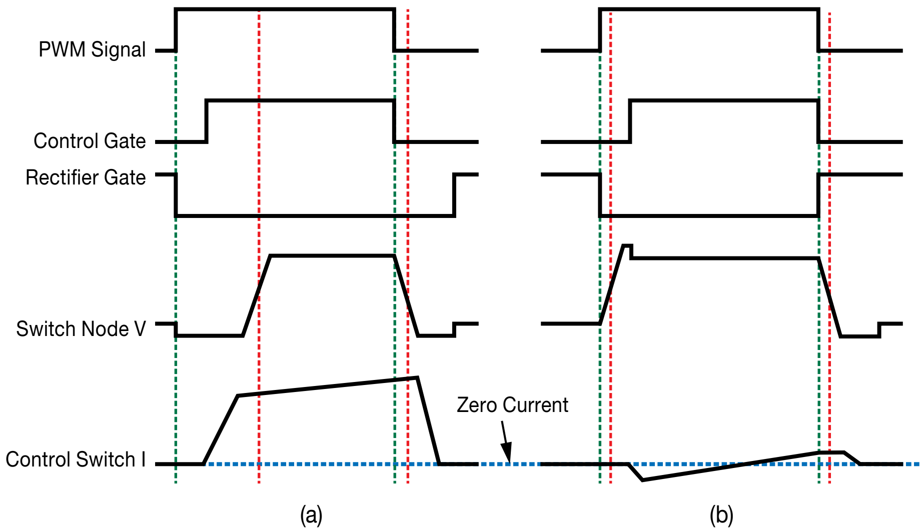


Figure 12.4 Detail of voltage and current commutation for (a) unidirectional current and (b) where current reverses direction.

During most of the half-cycle, current flows in a single direction because output current is higher than ripple current. In this case, one transistor acts as the control switch and the other acts as the rectifier switch, similar to a buck converter at high current. The voltage transition lags the dead time and current transition during control switch turn-on, but leads them during turn-off. The result is that the on-time of the switch node is less than that of the PWM signal, as shown in Figure 12.4a. When the current is near zero, the ripple current is higher than the output current. In this case, the rectifier turn-off causes voltage commutation before the dead time and current commutation. Control switch turn-off occurs in the same manner as in the high current condition. At low current, switch-node voltage on-time nearly matches PWM on-time. Figure 12.4b shows detailed commutation when the inductor current changes direction. Half-bridge commutation is described in much more detail in Chapter 7.

The impact of a reduced duty cycle due to dead-time PWM is a reduction of the output voltage as the PWM is averaged over many of its cycles. Near the zero crossing, the ripple current reverses direction, greatly reducing dead-time error. Figure 12.5 shows the error due to dead time in a large signal compared with the theoretical waveform without dead time.

Many of the small-signal analog and digital components produce low levels of distortion at zero input, which is defined as noise. A common measure of sound quality is THD plus noise (THD + N). THD + N is typically measured with a 1 kHz signal with target performance varying by product grade and cost.

12.1.2 Intermodulation Distortion

A fault of using THD + N as a sound quality metric is that the signal is constant. With a constant signal, feedback can be used to reduce THD + N to a level that meets design requirements but produces other undesirable side effects. In closed-loop systems, negative

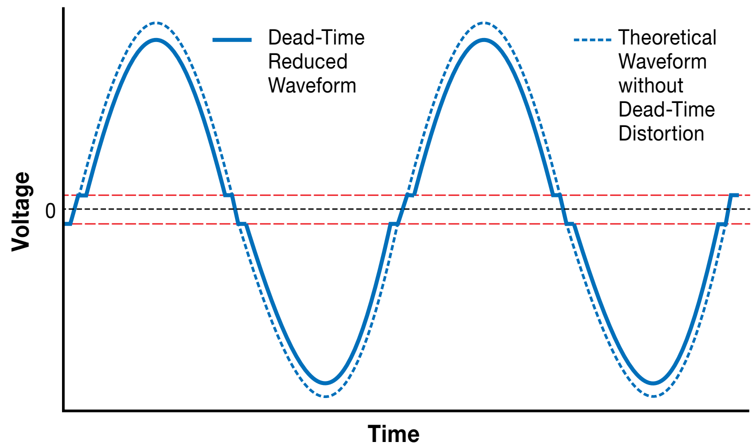
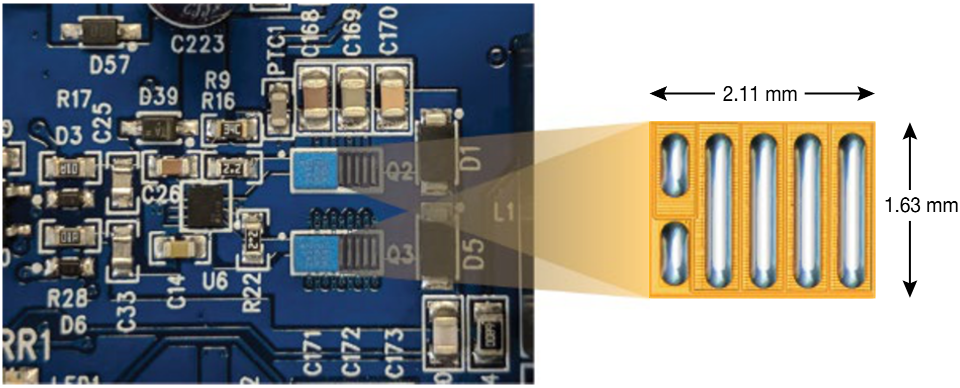


Figure 12.5 Error due to dead time compared with theoretical.

feedback is used to correct for open-loop nonlinearity. The fault of feedback is that it mixes the old sound with the new sound. This is not a problem at constant frequency, but music is dynamic with much color and richness in the intended harmonics [12]. The distortion caused by the frequencies of the old sound mixing with the new sound is DIM, also called transient intermodulation distortion (TIM), and our sense of hearing is apparently very sensitive to it [13]. DIM is measured in several ways. One method combines a low-frequency, low-pass filtered square wave with a 15 kHz sine-wave. The sine-wave and single-pole low-pass filter frequencies are 30 kHz for DIM 30 and 100 kHz for DIM 100. DIM is calculated as the ratio of the sum of the RMS levels of the intermodulation components to the level of the sine wave [14]. Intermodulation distortion (IMD) is a measure of signal errors due to two dissimilar but simultaneous signals. Another method to measure IMD is based on the Society of Motion Picture and Television Engineers® (SMPTE) standards. A 60 Hz signal and a 7 kHz signal that is not a harmonic are combined in a 4 : 1 amplitude ratio. Other frequencies and amplitudes can also be used. With the signal applied to the input, the output is measured over a range of frequencies. The distortion is evident in the 60 Hz sidebands of 7 kHz. The modulation components of the upper signal appear as sidebands spaced at multiples of the lower frequency tone. The amplitudes of the sidebands are RMS summed and expressed as a percentage of the upper frequency level [15].

12.2 GaN Transistor Class D Audio Amplifier Example

A GaN transistor-based class D system, an amplifier capable of 200 W driving an 8 Ω speaker or 400 W into a 4 Ω speaker, will be used as an example. It is configured as a bridge-tied load with a PWM frequency of 364 kHz. It uses the 100 V rated, 16 mΩ EPC2016C GaN transistors, with an LMG1205 driver IC from Texas Instruments as the half-bridge gate driver. A photograph of the power stage of the amplifier is shown in Figure 12.6a, which is approximately 10 mm × 15 mm, with the EPC2016C GaN transistor (Figure 12.6b).



(a) (b)

Figure 12.6 (a) Class D power stage and (b) solder bump view of EPC2016C GaN transistor [16].

12.2.1 Closed-Loop Amplifier

The 200 W closed-loop amplifier module is 10 cm × 5.5 cm and is shown in Figure 12.7 [17]. Its 96% system efficiency allows operation without a heatsink.

This class D amplifier has very low THD + N across both frequency and power ranges due to the precise switching of the GaN transistors. The amplifier has a maximum of 0.012% THD + N from 20 Hz to 20 kHz at −9 dBr, 200 W out, into an 8 Ω speaker load, as shown in Figure 12.8. Figure 12.9 shows a THD + N at 1 kHz of less than 0.05% at full

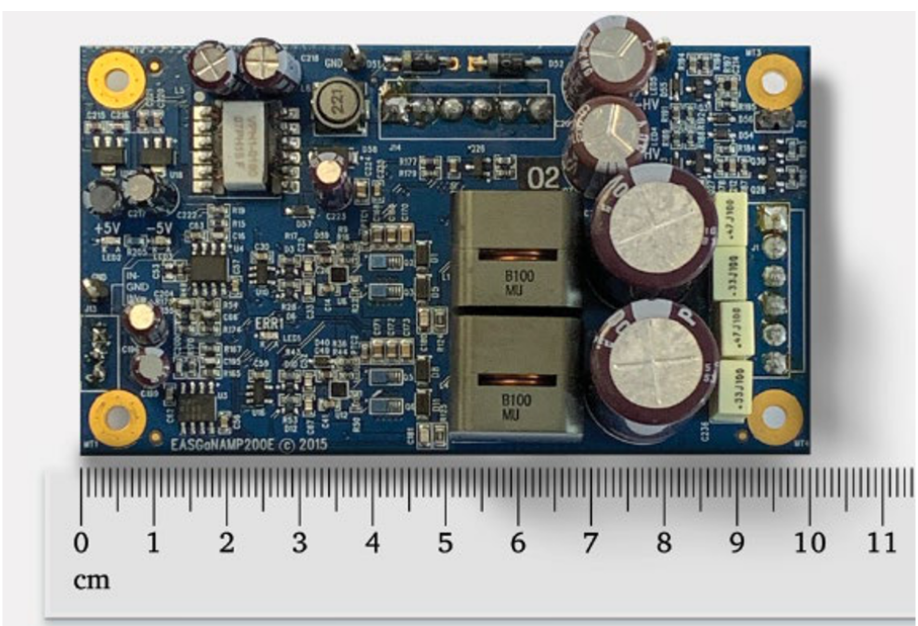


Figure 12.7 This class D amplifier can deliver 200 W into 8 Ω (400 W into 4 Ω) without a heatsink.

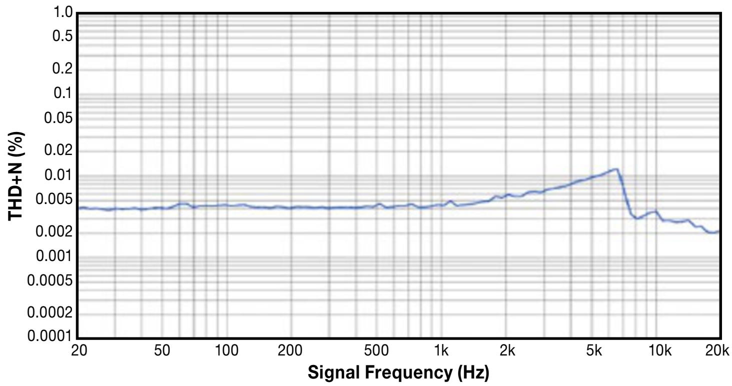


Figure 12.8 GaN transistor-based class D amplifier THD + N versus output frequency.

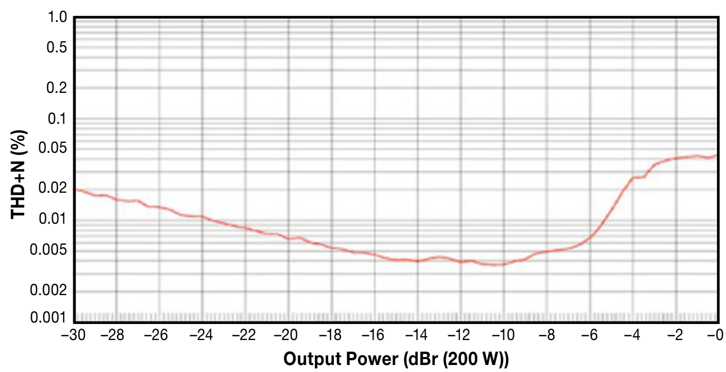


Figure 12.9 GaN transistor-based class D amplifier THD + N versus output power level at 1 kHz.

power, and approximately 0.005% at −10 dBr (200 W). The low distortion is achievable with only 20 dB of feedback. The low magnitude of the feedback helps to give this amplifier a very clear, rich sound.

Frequency analysis by applying a fast Fourier transform (FFT) to a 1 kHz, −60 dBr (200 W) signal from 20 Hz to 20 kHz yielded the result shown in Figure 12.10. Frequencies outside of the fundamental show −145 dBr (200 W) A-weighted to −125 dBr (200 W) A-weighted. A-weighing is commonly applied by acoustical engineers to a filter to model the responsiveness of the human ear at varying frequencies [18]. The low magnitude of all frequencies outside of the fundamental frequency indicate good suppression. In addition, there are no harmonics of 1 kHz appearing in the FFT.

Figure 12.11 shows the noise floor of the closed-loop class D amplifier system. The noise floor was measured from full power to low power. It is done in this manner to ensure the amplifier is operating. When running at very low power, some of the components might be in sleep mode, giving a measurement of ambient noise and not the amplifier noise. The noise floor is less than −102.5 dBr (200 W) unweighted and – 107 dBr (200 W) A-weighted.

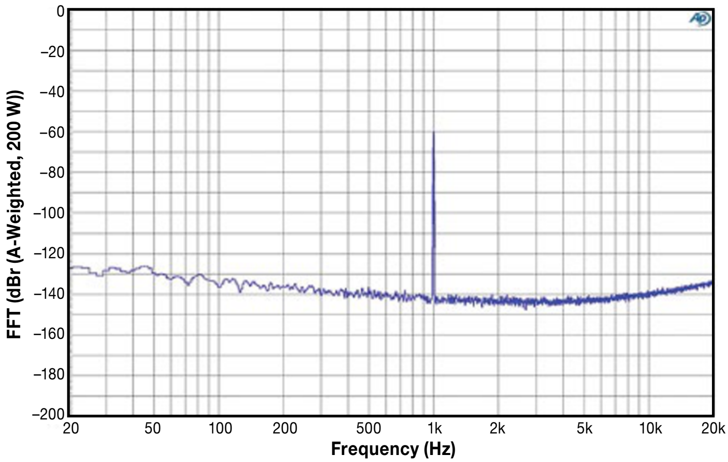


Figure 12.10 Fast Fourier transform (FFT) of GaN transistor-based class D amplifier from 20 Hz to 20 kHz of a 1 kHz signal at −60 dBr (200 W).

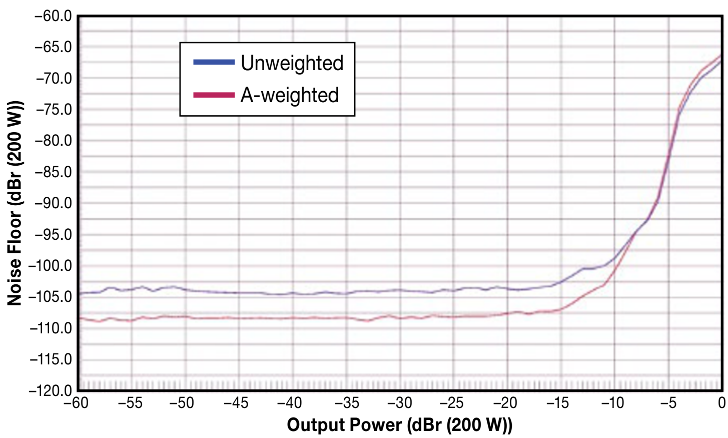


Figure 12.11 Noise floor versus output power of GaN transistor-based class D amplifier.

12.2.2 Open-Loop Amplifier

A similar amplifier was developed as an open-loop amplifier to characterize and compare with the closed-loop solution using similar components and configuration [19]. Open-loop THD + N is less than 0.12%, but there are distinct differences. Figure 12.12 shows that the THD + N performance of the open-loop system is superior to that of the closed-loop system at low power, and closed-loop performance is superior at high power. This is mainly due to the increase in noise contribution of the feedback at low power, and the increased benefit of feedback as power is increased. As the audio signal level is increased, and hence the output power increased, the benefit of the closed-loop architecture is evident. However, the THD + N of the open-loop architecture compares very favorably, mainly due to the excellent switch characteristics of the GaN transistors

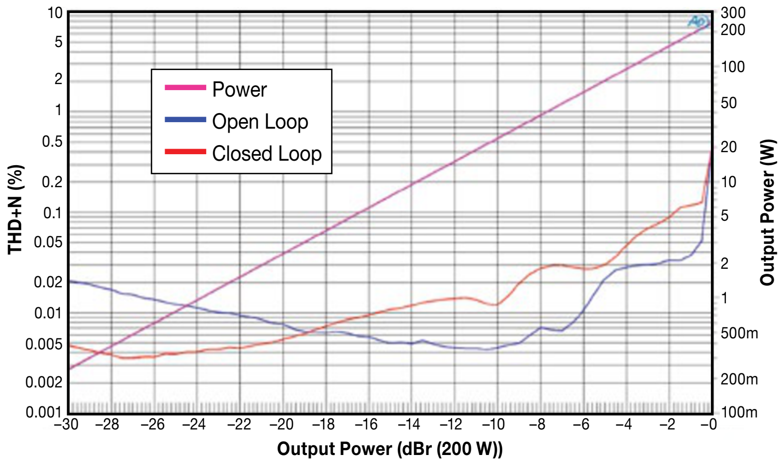


Figure 12.12 Open-loop and closed-loop, THD + N versus power into 8 Ω at ±32 VDC.

in the output stage. By using an open-loop architecture with the ability to tightly control the dead-band timing, near closed-loop THD + N performance can be achieved.

One technique available in digital amplifiers to reduce all distortion is to introduce pre-distortion [20]. Amplifier distortion is characterized across frequency and power and stored digitally. It is then inverted and summed with the input signal at appropriate frequency and power.

Intermodulation was also characterized on both open-loop and closed-loop amplifiers. Figure 12.13 shows IMD (SMPTE), 60 Hz/7 kHz, 4 : 1 FFT for both open-loop and closed-loop systems. Open-loop performance is vastly superior with distortion reductions of up to 18 dBr (200 W) A-weighted. The low gain of the feedback loop gives the closed-loop system excellent results as well, and the difference shows the impact of feedback on DIM. It should be noted that the 60 Hz (and harmonics of 60 Hz) are due to

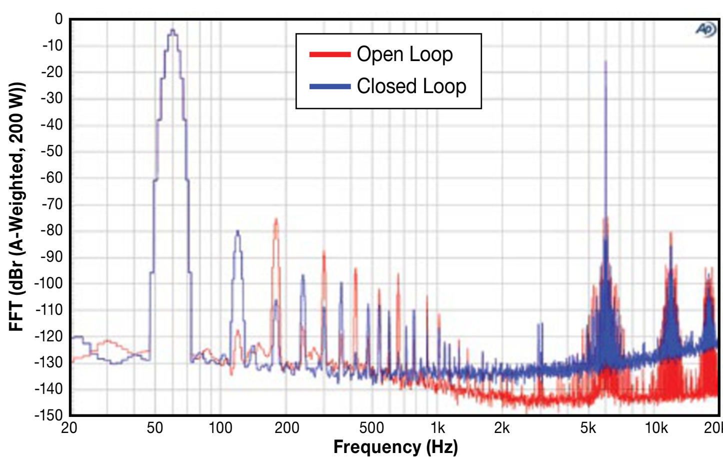


Figure 12.13 Dynamic intermodulation distortion (DIM) Society of Motion Picture and Television Engineers® (SMPTE), 60 Hz/7 kHz, 4 : 1 FFT comparison plots (open-loop versus closed-loop).

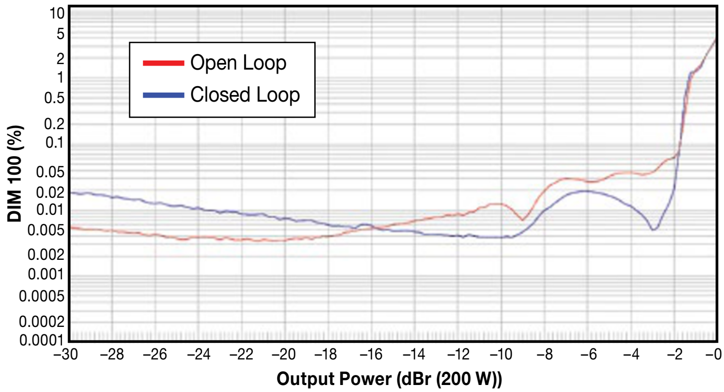


Figure 12.14 Dynamic intermodulation distortion (DIM) 100 versus power level comparison plots (open-loop versus closed-loop).

intermodulation of the AC power supply. With reduced feedback, the power supply becomes a more important component in the overall audio system. The peaks at 7 kHz and its harmonics are from the 7 kHz test frequency.

Figure 12.14 shows DIM 100 versus power. The benefits of reduced feedback are seen at lower power, and decreased power supply rejection is seen at higher power. This is similar to THD + N.

12.3 Summary

GaN transistors increase sound quality in class D audio systems by producing a much more accurate PWM replication of the large output signal, giving much higher open-loop linearity. The benefit of the open-loop linearity is lower harmonic distortion and noise. Since THD + N is a key design parameter, feedback can be reduced, and even eliminated, to reduce dynamic distortion for a more pleasurable and realistic listening experience, while still meeting THD + N marketing requirements. The small size and power efficiency enable audiophile quality in moderate-cost consumer applications such as smart speakers and sound bars. Further improvement can be realized by improving the power supply and introducing digital pre-distortion into digital amplifiers.

In Chapter 13 the application of GaN transistors to light detection and ranging (lidar) systems found on autonomous vehicles, drones, robots, mapping, and security systems will be explored.

References

1 Pas, N. (February 1977). Build a class-A amplifier. Audio. http://www.firstwatt.com/pdf/art_classa_20.pdf.
2 Electronics Tutorials. Amplifier classes. https://www.electronics-tutorials.ws/amplifier/amplifier-classes.html.
3 Poduva, N.S. (August 2016). Class-AB amplifier with third order nonlinearity cancellation. Texas A&M University. http://oaktrust.library.tamu.edu/bitstream/handle/1969.1/157896/PODUVAL-THESIS-2016.pdf;sequence=1.

4 Munz, S. (April 20, 2014). Audio amplifier classes (A, A/B, D, G, and H): What are the differences? *Audioholics Online A/V Magazine*. https://www.audioholics.com/audio-amplifier/amplifier-classes.

5 Taylor, S. (September 17, 2016). Why we'll soon be living in a class D world. http://AudiophileReview.com and https://audiophilereview.com/cd-dac-digital/why-well-soon-be-living-in-a-class-d-world.html.

6 Colino, S. and Taylor, S. (2017). GaN FETs drive fidelity and efficiency in class-D audio amplifiers. *AES Convention 142*, May 11, 2017. http://www.aes.org/e-lib/browse.cfm?elib=18612.

7 Pavier, M., Sawle, A., Woodworth, A. et al. (2003). High frequency DC:DC power conversion: the influence of package parasitics. *Applied Power Electronics Conference and Exposition, APEC '03, Eighteenth Annual IEEE* 2 (February 2003), 9–13 and 699–704.

8 Efficient Power Conversion Corporation (2018). EPC8009 – Enhancement-mode power transistor. EPC2001C datasheet [Revised 2018]. http://epc-co.com/epc/Portals/0/epc/documents/datasheets/EPC2001C_datasheet.pdf.

9 Infineon Technologies AG (2009). OptiMOS™ 3 power transistor. BSC123N08NS3 datasheet, November 2009 [Revision 2.5]. https://www.infineon.com/dgdl/Infineon-BSC123N08NS3G-DS-v02_05-en.pdf?fileId=db3a30431add1d95011ae80eb8555625.

10 Efficient Power Conversion Corporation (2018). eGaN® FETs and ICs for class-D audio applications. Efficient Power Conversion application brief AB003. http://epc-co.com/epc/Portals/0/epc/documents/briefs/AB003%20eGaN%20FETs%20for%20Class-D%20Audio.pdf.

11 Williams, D. (February 2017). Understanding, calculating, and measuring total harmonic distortion (THD). http://AllAboutCircuits.com and https://www.allaboutcircuits.com/technical-articles/the-importance-of-total-harmonic-distortion.

12 Self, D. (2013). *Audio Power Amplifier Design*, 6e, 25–71. Burlington, MA, USA and Oxon, UK: Focal Press.

13 Otala, M. and Leinonen, E. (1977). The theory of transient intermodulation distortion. *IEEE Trans. Acoust. Speech Signal Process* 25 (1).

14 Audio Precision (May 2009). DIM 30 and DIM 100 measurements per IEC 60268–3 withAP2700.https://www.ap.com/technical-library/dim-30-and-dim-100-measurements-per-iec-60268-3-with-ap2700.

15 Efficient Power Conversion Corporation (2018). EPC8009 – Enhancement-mode power transistor. EPC2016C datasheet. http://epc-co.com/epc/Portals/0/epc/documents/datasheets/EPC2016C_datasheet.pdf.

16 Bohn, D. (January 2003) Audio Specifications. RaneNote 144. https://www.rane.com/note145.html.

17 Taylor, S. EAS™ eGaNAMP2016 product brief class-D high-performance eGaN FET amplifier module. https://epc-co.com/epc/Portals/0/epc/documents/thirdparty/eGaNAMP2016_Consumer-123115.pdf.

18 Vernier Tech Info Library (July 12, 2018). What is the difference between "A weighting" and "C weighting?" https://www.vernier.com/til/3500.

19 Taylor, S. EPC GaN FET open-loop Class-D amplifier design – Final report. http://epc-co.com/epc/portals/0/epc/documents/articles/EPC%20GaN%20FET%20Open-Loop%20Class-D%20Amplifier%20Design.pdf.

20 Aase, S. (2012). A prefilter equalizer for pulse width modulation. *Signal Process.* 92: 2444–2453.