Class D Audio Using the PE29102

Application Note 72



Summary

The objective of this application note is to provide pSemi customers with a general overview of Class D audio techniques as well as to show how one or two PE29102 gallium nitride field effect transistor (GaN FET) drivers may be used to each drive a pair of GaN FET devices for audio applications.

Introduction

Class D audio amplifiers were first proposed as far back as the 1950s, though it is only relatively recently that their implementation has become increasingly commonplace. Semiconductor technology has finally come of age to meet the performance levels Class D is capable of, many decades after its conception. This is because, until GaN FETs were introduced circa 2008, most metal oxide semiconductor (MOS) devices were either too slow or had finite "on" resistance of an order that limited their uses for high-power, fast and reliable designs. The great benefit of Class D is efficiency, and achieving efficiency requires using switching devices with high specifications in terms of both low loss and switching speed.

In the Class D mode of operation, the transistors are not used in their linear (triode) mode but are used instead as switches: either fully saturated or cut-off. This way, they dissipate very little heat as there is either minimum voltage or minimum current present across each device in either extreme state. The "D" in Class D is sometimes said to stand for "digital". This is not correct because the operation of the Class D amplifier is based on analog principles, and there is no digital coding of the signal.

Pulse Width Modulation

In its basic form, an audio signal is fed into a fast comparator, whose other input is referenced to a free-running, highly linear ramp or triangle waveform of ultrasonic frequency (that is to say, the frequency of the ramp/triangle wave must be at least two times higher than that of the highest frequency in the sampled input audio signal). The comparator samples the audio precisely against the ramp/triangle wave, resulting in an output square wave whose frequency is the same as the carrier but whose pulse width (duty cycle) is modulated by the amplitude of the audio signal. The quality of the pulse width modulation (PWM) depends upon the linearity of the encoding system used. PWM quality is of paramount importance to the degree of audio quality that can be achieved and will limit the performance achievable with the subsequent Class D amplifier.

More sophisticated implementations may be found using delta-sigma modulators and/or pulse density modulation (PDM). In some designs, the PWM high frequency carrier is produced by self-oscillation owing to positive feedback (this self-oscillating Class D amplifier topology is known as "SODA"), yet the audio signal may be further linearized with another negative feedback loop operating in the relatively lower frequency audio band. With the latter approach, the Class D amplifier becomes a self-contained, free-running, high frequency astable multivibrator, nominally resonating at just below 400 kHz. The audio signal is used to modulate this oscillation by injecting it into the oscillator's integrating feedback node. This technique works very well and is popular in commercial designs as it is also relatively simple and does not require a highly linear, high frequency triangle wave oscillator, which is both difficult and costly to implement. The results are quite respectable and not offensive to the ear, even when operated open loop where total harmonic distortion + noise (THD+N) is typically around <1.5%. THD+N maybe reduced using carefully applied negative feedback, an established technique

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which is often used to improve circuit performance by proportionally canceling and reducing non-linearities, by feeding back a proportion of the output signal, mixed out of phase with the input signal.

High Fidelity

High fidelity—or its better-known contraction, "hi-fi"—is a term that generally refers to high-quality reproduction of sound. This term is applicable to sound-reproducing equipment that gives a realistic recreation of the original sound. The human ear is said to be barely able to perceive a distortion level below one percent; since the advent of hi-fi, distortion levels of 0.1 percent have been achievable with good design. This percentage has been advertised as a "very good" level of distortion and, therefore, a benchmark of sorts. Today, we can expect levels an order of magnitude better than this (that is to say, 0.01 percent, which could be said to be "audiophile" quality) provided the other key requirements of a wide, flat frequency response, good transient response, and very low noise are also met and maintained throughout the audio system.

Output Stage Filtering and Audio Demodulation

The output switching devices are driven with a modulated, high frequency square wave. Think of the output devices as being an efficient switch that is behaving as a push-pull power buffer, routing the power supply proportionally into the load. The high switching frequency used in Class D amplifiers with the inherently fast rise times of square waves and resulting harmonic spectra is a potential source of radio frequency interference toward other equipment. There is a particular requirement to suppress radio frequency radiation from entering the loudspeaker cables, which would otherwise act as dipole antennas due to the fast switching. Class D amplifiers must also be properly shielded and grounded to prevent radiation of the switching harmonics emerging from the amplifier's (metal) enclosure; low-pass filters must be used not only on the loudspeaker outputs but also ideally on all input and power connections.

The components used in the low-pass filter (usually a second-order/12 dB per octave type comprising an inductor and at least one capacitor) will have some impact on the audio quality. This is because the audio signal is demodulated (that is to say, recovered) by filtering out the higher frequency square wave "carrier" using the aforementioned filter network, whose electrical characteristics will, to an extent, affect the linearity of the (deliberately) residual audio signal. The losses in the filter inductor will also affect efficiency, as the inductor is connected in series between the switching transistors and the (low-impedance) load. It is the series resistance of the inductor as well as some inherent iron (magnetic) and copper (heating) losses which contribute to this inefficiency. For this reason and also for improved audio quality purposes, it is not uncommon to see special formulation iron cores or even air cores being used in the inductors with this kind of application. High-quality capacitor dielectrics with low loss and good pulse performance (such as polypropylene) are preferable to further minimize losses in the filter network.

Distortion

Distortion must be minimized, and this improvement in linearity is achieved both by reducing the switching deadtime and by using global negative feedback from the analog output right back to the PWM input.

Advantages of Both Class D and GaN FETs

An advantage of Class D circuits is that they are relatively simple to implement with modern components, require simpler power supplies for the full-bridge topology, and have at least double the efficiency of the best linear designs. GaN FETs are preferred as the switching devices because they offer significant advantages over MOSFETs. Because GaN FETs are faster, smaller and do not have a body diode, they have fewer switching losses versus conduction losses, resulting in superior linearity and efficiency.



Full Bridge

A fully bridged configuration combines two identical half-bridge channels and, when operating from a unipolar supply, forms a single "floating" bridge-tied load (BTL) output. When operated as a full bridge, the load is tied to the "in phase" half-bridge output at one end and to the "out of phase" half bridge on the other end, referenced to half the unipolar supply voltage. Please note that only with a bipolar power supply (such as mirror-image +ve and –ve rails about ground) is the signal referenced about ground or zero volts. A key advantage of this technique is to increase the output power without having to increase the supply voltage.

The PWM signal modulates toward the positive rail at one end of the load and toward the negative rail at the other end, following the polarity of the PWM input signal. This is a balanced, push-pull arrangement providing full swing to the supply rail limits; a great advantage of full-bridge operation is the full use of the power supply voltage. For a given power supply voltage, the full-bridge/BTL configuration produces double the voltage swing into the load. For the same load impedance, by Ohm's law it can be shown that four times the power is produced as is proportional to the output voltage squared. While full-bridge BTL operation is possible from a unipolar power supply, it is important to note that neither output terminal must be shorted to the supply positive or ground as there is no DC blocking capacitor; otherwise, short circuit damage can occur to the switching devices. Another way of viewing the difference between full- and half-bridge topologies is to consider that amplifiers with BTL outputs can provide twice the peak-to-peak voltage to the load as a single-ended amplifier. The squared term in Ohm's law means that the single-ended amplifier can in fact only supply one-fourth (1/4) of the power to the load when compared with the BTL/full bridge.

A problematic phenomenon found in half-bridge configurations is what is referred to as "bus pumping". This occurs when the stored energy of the load and output filter gets returned to the power supply rails which become temporarily modulated and undergo a variation in supply amplitude when compared with the no signal (quiescent) state.

Full-bridge/BTL mode neatly cancels out this issue, as one output stage is sourcing current while the other is sinking current, with a net result of zero disturbance to the supply rails. Additionally, this mode also offers superior rejection of power supply noise or power supply rejection ratio (PSRR). Disadvantages of the BTL topology are that it requires double the number of active components than for a half bridge in its implementation, plus double the output filter components and their attendant losses. However, these disadvantages are negated by the fourfold increase in available output power and the fact that an unsophisticated and relatively inexpensive power supply may be used and still produce good results. For details, see **Figure 3** on page 5.

Shoot-Through and Dead Time

A problem called "shoot-through" can reduce the efficiency of Class D amplifiers and lead to a potential failure of the output devices. This occurs during the transition when one device is being cut off and another is beginning to conduct. During the transition, both devices are on, and a large current pulse can flow through the two. This can be eliminated by driving each device separately with a deliberate asymmetry (that is to say, a small gap) between the square wave edges so that there is a band of "dead-time" between them, thus eliminating the occurrence of shoot-through. This needs to be just enough, but not excessive, otherwise non-linearities can manifest that will have negative consequences for audio in the form of crossover distortion, so it is a trade-off.

Peak Versus Average Power in Audio Products

Although not confined to Class D, manufacturers of audio products are required by various regulatory agencies to specify the average power rather than peak power for consumer audio products. The root-mean-square (RMS) voltage for an undistorted sinusoidal output is equal to the peak voltage divided by the square root of 2, so the maximum average output power for a Class D amplifier with an undistorted sinusoidal output is equal to the peak-to-peak output power divided by 2 x the square root of 2; that is to say, divided by 2.83 approximately.



Amplifier manufacturers sometimes specify the output power at a higher level of THD in order to allow them to advertise a higher output power. For example, it may be shown that a clipped sinusoidal output waveform with 10% THD has an average output power almost 30% higher than an undistorted sine wave output from the same amplifier.

Determining Average Power Supply Requirements

Consumers rarely require more than 40% power on a continuous basis. Most will operate their amplifiers well below the maximum rated power, with full output only being required for short periods during music peaks. As a guideline, an amplifier for consumer audio use may be rated for continuous operation at one-eighth (1/8) of its full output power; however, the power supply should still be rated to comfortably provide the maximum output current, which is due to the amplifier's peak output power rather than its (much lower) continuous power capability.

Studio-quality audio has historically aimed for an ideal overload margin (headroom) of 10x or 20 dB within the dynamic range between the average signal level and the threshold of signal clipping. This should be borne in mind when considering both the sound quality and how robust a design should be, when choosing and specifying a power supply for any type of audio amplifier.

Figures 1 through 4 refer to an evaluation kit that has a Class D full-bridge output stage using GaN Systems GS61004B GaN FETs driven by pSemi PE29102 drivers.

The PWM input is transistor-transistor logic (TTL) level-compatible, and the recommended maximum supply voltage is 60V. Dead times and overcurrent limit protection are fully adjustable, and various options for configuring the PWM signal drive and inversion are made possible using jumper links.



Figure 1 • View of the EK29102-03 pSemi / GaN Systems Evaluation Kit



Figure 2 - Block Diagram of the EK29102-03



Figure 3 Internals and Connectivity of the PE29102 Driver





Figure 4 - Schematic of the EK29102-03







The circuit shown in **Figure 5** is for a simple, self-oscillating modulator that encodes the incoming audio as a high quality PWM signal, suitable for driving a Class D amplifier.







Benefits to Class D

Dealing with Distortion

One of the traditional problems with Class D amplifiers is their high transient intermodulation distortion (TIM), which results in part from the characteristics of silicon MOSFETs, whose switching anomalies, high on-state resistance, and very high stored gate charge make lowering distortion difficult to achieve. To reduce distortion, Class D amplifiers use large amounts of feedback to compensate for this mediocre open-loop performance. However, the feedback introduces TIM that degrades output signal to what has been described as harsh, colorless, or bland.¹

The use of GaN FETs has a large advantage with respect to MOSFETs—in every regard described above—and facilitates a far better open-loop performance. Aside from careful choice in the output low-pass filter (especially the specification of the inductor), the reduction of jitter and dead time in the switching device, as well as carefully applied minimal negative feedback, also play a large part in achieving optimal audio quality.



Figure 6 • Causes of Distortion

^{1.} Manz, Barry, "Automotive Applications Drive Class D Audio Amplifier Performance," http://innovation-destination.com/2018/06/22/automotive-applications-drive-class-d-audio-amplifier-performance/, June 22,2018



In **Figure 7**, the PE29102 is simply connected to the GaN FETs by means of small fixed resistors to tailor the on/ off parasitics and a bootstrap capacitor for the high-side switching.







Figure 8 shows that the relationship between the dead-time resistance value and the dead time is linear and easy to set accurately with the aid of an oscilloscope.





GaN FETs switch more cleanly than MOSFETS due to lack of body diode parasitic minimizing jitter and distortion. The jitter range for a Gan FET switched by the PE29102 is impressively narrow, with a low standard deviation figure.



Figure 9 - Jitter Graph



Dead time adjustments preserve the integrity of the underlying signal by not introducing skew.





The following graph shows the relationship of THD+Noise vs. jitter in Class D amplification.²

Figure 11 • THD+Noise vs. Jitter in Class D Amplification



Fig. 4. THD+Noise vs. Jitter [$V_{tri} = 1 V$, $V_{SP} = 0.5V$, $T_{tri} = 1 \mu s$, $f_{in} = 1 KHz$, $f_{bw} = 15 KHz$]

^{2.} Source: Kelleci, Burak, Edgar Sanchez-Sinencio, and Aydin Ilker Karsilayan, THD+Noise Estimation in Class-D Amplifiers, 2007 IEEE International Symposium on Circuits and Systems



pSemi has collaborated with EAS to produce a daughterboard using EPC2016C GaN FETs and the pSemi PE29102 driver. This plugs into the EAS motherboard (which has a power supply, filtering and DSP PWM encoding on-board). The result is a high quality, powerful stereo audio amplifier with impressive performance.

Figure 12 • EAS Motherboard with Daughterboards Removed



Figure 13 • Modular Daughterboard Using the PE29102 to Drive EPC2016C GaN FETs





Figure 14 • EAS Motherboard with Modular Class D Daughterboard Output Stages Fitted for Performance Evaluation





An Audio Precision[©] AP2700 audio analyzer was used to measure the plots shown in **Figure 15** and **Figure 16**; namely, THD vs. input signal level and output power, and also the noise floor relative to an output level of 100W RMS into an 8Ω load vs. input level. Both plots show open-loop (yellow lines) and closed-loop (cyan lines) performance. These plots were taken from the Elegant Audio Solutions (EAS) Class D amplifier, consisting of the EAS-designed motherboard (power supply, filters and DSP PWM encoder) driving their daughterboard Class D power output stage design built around pSemi PE29102 drivers and EPC2016C GaN FETs













Conclusion

We have looked at the principles of Class D audio amplification with particular regard to the benefits of using GaN FET output devices driven by the pSemi PE29102 driver. We have explored the difficulties of producing a sufficiently linear PWM signal to drive a Class D output stage from a standard (linear, analog) audio input signal. We have explored techniques for addressing the attendant non-linearities in the encoding process as well as those found in the Class D circuit, namely distortion and noise, which may be reduced by using negative feedback, whereas jitter, dead time and shoot-through are issues that may be addressed or minimized by careful circuit design and the use of high quality, fast devices. We have also seen how the configuration of the output stage affects power supply requirements. All of these criteria need to be understood, applied and optimized to produce an efficient, reliable and listenable Class D audio amplifier.

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