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Class D IC amps: Ready for audio prime time

It's now OK—and easy—to use the "bad boy" of audio amplifiers if you modify some traditional audio-design guidelines.

Bill Schweber, Technical Editor

In the early days of electronics, when triode vacuum tubes appeared and enabled engineers to manipulate the flow of a larger current in proportion to a smaller controlling signal, amplifiers were available in classes of performance. Class A was the best and the brightest. Biased in the middle of its active region, with relatively high bias current and small excursions around its bias point, it featured superior fidelity but with roughly 10% efficiency. Class B was somewhat inferior in sound quality but had better efficiency, and Class C was even more inferior but offered still higher efficiency (see sidebar "Revisiting the class struggle").

Then there was Class D: It was biased to well beyond its cutoff point in the absence of an input and thus operated in the on/off mode. Its primary application was for switching power to motors and relays—what we now call a digital function—albeit at low speed. You wouldn't even consider using this binary-state amplifier for audio applications. Despite audio designers' getting a better understanding of Class D by the 1960s, they could use this architecture for high-performance audio only if they were willing to carefully work on all the details. The audio systems that Bose Corp (www.bose.com) mass-produced in the 1970s for OEM automotive installations demonstrate that these designs could succeed.

AT A GLANCE

- Class D audio ICs can provide audio quality comparable with Class AB but with much higher efficiency for realistic audio signals.
- The mandatory passive output filter is a key element of the Class D design, and you must design the filter for a specific load.
- You have to consider switching and RF design guidelines in any Class D system.

But times have changed. Basic Class D amplifiers were previously relegated to applications such as limited-bandwidth public-address systems, which tolerate THD of several percentage points. Now, an IC audio amp that rates only a D in class needs no longer suffer from low self-esteem. You can get high efficiency plus high fidelity in a Class D IC or module, comparable with Class AB designs (see sidebar "Efficiency numbers may vary"). You're no longer subject to a sharp fidelity-versus-efficiency trade-off, removing a major dilemma in your design approach. Meanwhile, you must adapt your design to the needs of high-frequency switching circuitry and related issues.

Using an on/off signal to capture and accurately render a faithful but more powerful reproduction of an analog signal may seem counterintuitive at first glance, especially when you think of the audiophile world and specifications such as 0.1% THD. After all, what's more distorted than a rectangular waveform approximating a sinelike wave shape?

Consider the simple case of a sine-wave input. Suppose your digital signal uses +V and –V to represent the two logic levels. Next, use the digital states to drive transistor or MOSFET switches, which connect to each side of the output speaker; when one switch is on, the other is off. Because the switches are either on or off, they operate efficiently with virtually no steady-state loss except for R_{ON} loss.

When you switch from one binary state to the other as the sine input passes through the zero-crossing level, you have a rectangular wave approximation—admittedly crude—of a sine wave. Lowpass-filtering helps somewhat, but distortion is still about 10 to 20%, depending on the filter.

But, instead of just waiting for the zero crossings of the input to make an output determination, compare the bandwidth-limited input with a precise triangle clock signal that is at a frequency much higher than the audio bandwidth. Now, the comparator output is a square wave with a duty cycle that is proportional to the input-signal amplitude (Figure 1). Designers developed this classic Class D design in the late 1940s and early 1950s; it's the principle underlying pulse-width modulation (PWM), which nonaudio amplifier applications also use.

Although the duty cycle of this Class D or PWM waveform relates to the input amplitude, the waveform is still a poor representation of the input. Fortunately, the solution to this problem is simple—at least in concept. You put a pair of lowpass filters between the Class D driver outputs and the load inputs. With the right filter, matched to the load, you can achieve THD of less than 1%. Your selection and design of this filter and matching it to the switching frequency of the amplifier, as well as the load characteristics, are critical parts of successful overall Class D design.

Design issues are no longer just analog

Using a Class D IC audio amp makes your design effort much simpler than using a discrete approach. However, you should consider some new factors if your experience is with Class A, AB, or B. First, you no longer deal with low- and moderate-level analog signals with bandwidth only as high as 20 kHz. You now have switching waveforms of 100 kHz to 1 MHz, so you must provide adequate ground planes. Equally important, you need power-rail bypassing very close to the Class D IC.

You also have to keep all leads short. This requirement is especially important between the high-level Class D driver outputs and the lowpass filters; otherwise, you source RFI that you don't want in your system. Components in the filter section should also be close together to minimize track length.

Though you need to follow good high-frequency design and layout guidelines, you may not need to be overconcerned about these switching waveforms. For audio subsystems of laptop PCs, the RFI from the system clock and CPU is a greater threat to electronic integrity than your audio amplifier. Even if your design uses a slower CPU, such as an embedded microcontroller managing a security panel with user-voice-prompt features, you can minimize RF concerns by using shielded or toroidal inductors in the lowpass filters to reduce emissions from the filter components themselves.

A bridge to the load

Nearly all Class D amplifiers drive their loads via an H-bridge configuration, which alternately switches the load between the positive and negative rails. Unlike Class A through C loads, the Class D load is therefore ungrounded. You have to make sure that your design and mounting configuration allows for ungrounded loads and that the Class D amplifier you choose can tolerate inadvertent grounding of one side of the load if this situation is possible. You can connect most real-world audio loads as floating loads; a standard headphone is one of the few loads that assume that one side is grounded, so you would have to use a separate low-power, single-ended headphone amplifier in this situation.

These floating, bridge-tied-load (BTL) configurations serve another purpose: They boost potential output power by a factor of four over a grounded load. A single-ended load sees a maximum voltage differential of V_{SUPPLY}, whereas a BTL sees a maximum voltage differential of $–V_{SUPPLY}$ to $+V_{SUPPLY}$, or $2XV_{SUPPLY}$.

Because the power delivered for a fixed load resistance is proportional to the square of the voltage, doubling the output voltage quadruples the power. It’s almost like getting something for nothing here, so don’t complain about needing bipolar supplies.

Even if you have only a unipolar supply in your system, you don’t lose out. Many of the Class D amplifier ICs contain internal charge-pump circuitry to develop a local negative supply; even if they don’t, you can build your own with a basic dc/dc-converter IC and obtain more than 90% negative-supply efficiency.

For outputs up to about 10W, IC vendors now build the output switches as part of the IC. This approach saves you space and cost and minimizes interconnection and interface issues because the bridge’s param-eters—rise and fall times as well as on-resistance—match the amplifier control circuitry and drivers. For higher power designs, as well as those in which you need to match unusual loads, you may prefer to provide your own MOSFET or other switches, using drivers that are in the IC.

Vendor parts diverge in practice

Although the latest Class D ICs significantly reduce your design challenge compared with discrete designs, each vendor’s offerings differ significantly from the others, so you need to carefully choose the power levels and the number and type of external components you can accept in your design (Table 1).

For example, Texas Instruments offers the stereo TPA005D02, a 2W-average/5W-peak power (per channel) IC, which includes on-chip DMOS power-output transistors that can drive 4 Ohm loads (Figure 2). This 48-pin device has balanced differential inputs for input flexibility with various audio-interface situations. Its nominal operating frequency is 250 kHz; THD+ noise is less than 0.5% across the audio band with a 5V supply. You can also put the amplifier into a shutdown mode in which it consumes just 400 µA. You do not need a heat sink at these single-watt power levels running at 80 to 90% Class D efficiencies with realistic audio signals, because the surface-mount IC also includes a thermal pad that conveys dissipated heat to the pc board.

To help you use this IC, TI also provides a SLOP223 evaluation module that is compatible with the company’s audio-power amplifier plug-and-play platform. The user’s guide offers reference designs, schematics, and Gerber plot files. The design software lets you enter desired parameters and evaluate audio and thermal performance under a variety of conditions.

Linfinity Microelectronics introduced its LX1720 stereo-controller IC with the notebook-PC market in mind, optimized for 20-Hz to 20-kHz operation and 10W rms output. This 44-pin SSOP IC, which requires external MOSFETs, operates at around 350 kHz. Fed by a 1-kHz sine-wave test input with an 8 Ohm load per channel and 0.1 Ohm MOSFETs, the measured THD+distortion is less than 1%, and efficiency is greater than 92%. With a real-world music signal, such as the first 20 sec of *Hold On Tight* from the Electric Light Orchestra, the efficiency is approximately 60%.

Because the output drivers are external, you can use larger external MOSFETs and a higher voltage supply to get even more power. Linfinity Microelectronics also supplies a step-by-step design application note and reference design, as well as the $49.95 LXE1720-01 amplifier module, which plugs into the $19.95 LXE1700 evaluation kit and provides audio-input jacks, power connections, volume control, and output connections (Figure 3).

STMicroelectronics recognizes that many audio applications need high efficiency but not stereo output (that is, they are monophonic) and can accept moderate distortion levels. To meet this need, the company has developed a trio of Class D parts, the TDA7480, TDA7481, and TDA7482, which offer 10, 18, and 25W outputs, respectively. The smallest of these 100-kHz ICs is available in a power DIP package with a heat-spreading lead frame, and the larger two ICs come in 15-pin packages with heat-sink tabs (Figure 4). The application note that STMicroelectronics supplies gives detailed design steps, concluding with both second- and third-order Butterworth filter design options; the individual part data sheets show detailed pc-board layouts.

A lot of similarities exist between a Class D amplifier and a dc/dc switching regulator. Recognizing this fact, Micro Linear Corp’s (www.microlinear.com) Application Brief 7 shows you how to use the company’s

ML6552 switching regulator, which can both source and sink current, as a Class D amplifier. The design, which switches at around 600 kHz, requires 10 passive components and yields THD of 0.8% from 20 Hz to 30 kHz; efficiency is 55% for this single-watt configuration.

Not all high-efficiency ICs are Class D. Philips Semiconductors goes the Class H route with the TDA1562Q. This 17-lead SIP operates as a Class AB amplifier at low levels and automatically switches to Class H mode when its case temperature exceeds 120°C, corresponding to approximately 18W output power. It delivers 50W into a 4 Ohm load from a 12V supply (nominal car battery), 70W from a 14.4V supply (a car battery fully charged), and 100W from a 17V supply. The mono IC also includes a status output that tells you which class of operation the device is in and a diagnostic pin that informs you of excessive dynamic distortion, short circuits, or open circuits at the output.

Pesky passive filters affect efficiency

Your lowpass-filter design is an opportunity for you to make your design trade-offs—it's those analog signals again in an on/off world. Work with the application group and literature from the IC vendor to see what the company recommends; there's no use covering the same ground by yourself. The vendors' design kits, evaluation units, and modeling software should help you explore topology and component selections.

The vendors can't make all decisions for you, however. A two-pole Butterworth topology is effective for many applications, but designs that call for lower distortion—less than about 0.5%—may need a four-pole filter, which costs more and involves more components and matching (Figure 5). You need two identical filters, one for each leg of the H-bridge and its BTL outputs.

Your design life would be much easier if you simply buffered the filter output, thus making the filter design relatively independent of the load. Sorry: Because the buffer would have to operate as a power-hungry Class A or Class AB function to provide the fidelity you need, it would negate the major virtue of the Class D amplifier. If you must accommodate loads that vary over a wide resistance or reactance range, be sure to model and analyze your filter design accordingly.

You also have to balance the Class D frequency you choose against the perform-ance you can achieve and the filter components you need. On one side, a higher switching frequency is easier to filter with smaller value and smaller physical-size capacitors and inductors that can have greater tolerance from their nominal values. However, switching losses increase with frequency, so you may not get the overall efficiency you expect. Around 750 kHz to 1 MHz, the design reaches the point of diminishing returns in efficiency. Similarly, high-frequency losses in the passive components and even RF "skin effect" contribute to inefficiency. RF-layout concerns are more evident at higher frequencies.

Conversely, lower frequencies minimize RF but need larger passive filter components or more complex filters to achieve the same THD as a higher frequency implementation. Your layout and component selection are easier, however. Lower frequency filters usually have larger inductors with more turns and longer linear conductors, so their resistance may be higher. The fact that inductor vendors offer larger gauge (hence, lower resistance) wire for these larger value inductors balances out this resistance. In contrast, higher frequency inductors have fewer turns and shorter linear conductors but are often of thinner wire with high resistance. Use the make and model components that the IC vendor recommends or be prepared to dig into the component data sheets to get additional parameters for a more realistic model. For better filter analysis, you should include the dc resistance of the filter inductor as part of your filter model.

For your first-pass estimate, start your Class D implementation with a switching frequency that's at least 10 times the audio bandwidth; that is, 200 to 250 kHz for a full audio band. If your design requires lower audio bandwidth, as in many applications that need low-THD audio but only over a limited band, you can either reduce the switching frequency or loosen your filter requirements to achieve the same final THD. If you're unsure of your final switching frequency, be sure that the IC you select supports the frequency range you wish to explore.

Reference

1. Dapkus, Don, "Class D Audio Amplifiers for Compact, Portable Equipment," presented at the Audio Engineering Society 105th Convention (AES '98), Sept 26 to 29, 1998.

Revisiting the class struggle

Some references to analog-amplifier classes appeared by the mid-1930s. (The triode was invented in 1906 and was in widespread use by 1920.) However, I cannot find the original paper or source that cited these now-common class designations. To add to the alphabet soup, other amplifier classes exist besides the well-known Classes A, B, AB, C, and D. Here's a brief review of the class schedule:

Class A operation gives superior linearity but yields efficiency of only 5 to 25%. As you progress from Class A to Class AB to Class B and to Class C, you lose linearity but gain efficiency. Each succeeding class moves the bias point farther away from the active, linear region and closer to cutoff when there's no input signal and lets the input signal swing the output over a wider range (Figure A). Class B offers a nice balance between performance and distortion, but you have to watch out for crossover distortion, which results from timing asymmetry as each half of the output transistor pair alternates between its on (active) and off states.

You use Class C amplifiers in nonaudio applications in which power efficiency is critical—for RF power amplifiers, for example, in which it's difficult to generate a large, linear amount of RF power. A Class C design may be inexpensive and efficient but requires careful RF filtering using an LC tank circuit to suppress harmonics. Class C audio amplifiers are rare because they generate large amounts of hard-to-filter harmonics at relatively low frequencies.

With Class D, the input signal drives the output either off or fully on, pushing transistors either into cutoff or saturation, respectively, and no pretense exists of following the input waveform shape. Therefore, Class D devices offer high efficiency, because the main sources of inefficiency are the switching loss, charge injection, and on-resistance, rather than the quiescent bias-state current consumption of the amplifier itself.

Class D is essentially the same as pulse-width modulation (PWM); the different names come about because of the designator's frame of reference. If you think the digital world is more attractive, you can call the PWM amplifier a 1-bit amplifier, and some commercially available consumer-amp vendors do that to lure leading-edge customers. Although PWM is the most common switching-amplifier implementation, other varieties, such as pulse-amplitude, pulse-density, and pulse-position-modulation, exist.

Less well-known are Class E, G, H, and S. (Apparently, the Class F designation is still available if you want to claim it for something you develop. Does anyone want to admit to getting an F in class?) Class E amplifiers operate the output transistor with a low level of current through it or a low voltage across it; whereas this approach can keep dissipation low, no designs use it. Class G is a variation on class AB or B, in which the power stage draws its voltage from one set of voltage rails during lower power operation and then switches to higher level rails when it needs to produce more power.

Engineers sometimes confuse Class H with Class G. In Class G designs, the supply rail itself dynamically grows by drawing on energy stored in a capacitor when the amplifier seeks to deliver more power; this technique eliminates the high-rate switching waveforms of Class D and minimizes potential EMI radiation. Finally, Class S amplifiers have a Class A stage followed by a Class B stage, configured so that the load appears as a higher resistance than it is; this approach simplifies load-driving requirements for the amplifier. (See references A and B for good descriptions of the various classes and their implications.)

Leading to considerable confusion, common British and Japanese audio usage reverse the American usage of classes G and H (Reference B). (I haven't checked out this claim, but the author appears knowledgeable and experienced, so this note seems worthwhile to keep in mind!)

References

A. Self, Douglas, Audio Power Amplifier Design Handbook, Newnes/Butterworth-Heinemann, 1996.
B. Duncan, Ben, High Perform-ance Audio Power Amplifiers, Newnes/Butterworth-Heinemann, 1996.

Efficiency numbers may vary

The driving factor for Class D amplifiers, compared with their class A and AB counterparts, is efficiency. Higher efficiency translates into longer battery life, reduced heat dissipation, and smaller designs. The development of fast-switching, low-loss switches was a major factor in allowing engineers to implement practical Class D designs. Before the existence of these switches, the losses were excessive even at relatively low switching frequencies of 50 kHz.

The major power loss occurs during the switching process itself, which should be a relatively small part of the overall switching period. Other sources of loss are switch on-resistance and RF-related losses in the filter because of imperfect inductors, "skin effect," and undesired coupling between components.

What efficiency improvement can you expect from a Class D amplifier? As with so many other questions, the answer is, "It depends." For a properly designed Class AB amplifier that a sine wave drives to maximum output level, efficiency is about 67%, whereas a Class D design under the same conditions yields approximately 80% efficiency—not much difference there.

However, few audio amplifications have just full-scale sine-wave inputs; they make a pretty dull sound. Many music applications have signal-crest factors—the ratio of the highest to the average signal—of 10 to 15 dB, so the typical signal is one-tenth to one-thirtieth of the maximum. At these lower levels, the Class D efficiency remains near its maximum and can even increase to about 90%, whereas Class AB efficiency drops dramatically to 30 to 45%.

In a controlled test with music, Texas Instruments compared its TPA0202 linear amplifier with its TPA005D02 Class D IC, both 2W devices. The dramatic results demonstrate an increase in playing time from 111 minutes for the linear approach to 283 minutes for the Class D technique (Figure A). The difference between the two designs represents a lot of wasted battery power plus more heat that your design must dissipate. Some Class D designs with even higher power boast more than 90% efficiency when they are properly matched to the application (see sidebar "Class D goes beyond basic battery applications").

Precise efficiency measurements may involve special test setups and consideration of the type of signal: music, voice, continuous, or intermittent. Reference A provides some insight into these issues.

Reference

A. Nalbant, Mehmet K, "Performance Analysis of High Efficiency Stereo Multimedia Audio Amplifiers," Portable by Design Conference, February 1998.

Class D goes beyond basic battery applications

Although Class D designs are attractive for low-power, battery-constrained systems, engineers did much of the pioneering work in applying them at higher output levels, at which efficiency is not optional. Many of these applications are in the full- or limited-audio band but may not involve sound reproduction itself. Representative applications include motor control, magnetic bearings, vibration-canceling systems, and large-area sound systems.

For example, Apex Microtechnology Corp packs a 500-kHz amplifier with an H-bridge into a hybrid component that occupies less than 1 sq in. (Figure A). The device operates from a 5 to 40V supply (80V component that occupies less than 1 sq in. (Figure A). The device operates from a 5 to 40V supply (80V p-p) and supplies 5A of continuous output current (7A peak) at 94% efficiency. To further simplify using this 50-kHz- bandwidth amplifier, the SA07 includes shutdown control and fault protection, and you can synchronize its clock to an external source if you want to minimize undesired interactions with other signals. Apex also offers hybrids with other power ranges and bandwidths to match the needs of different applications.

If you're serious about audio-band power, you can step up from that smaller hybrid device to Copley Controls' (www.copleycontrols.com) Model 263P, a 19-in., rack-mounted unit (Figure B). Designed for inductive loads such as the magnetic coils of shake tables and vibration-free platforms (which are finding increasing use in precision manufacturing, semiconductor fabrication lines, and electron-microscope stations), this $13,000 unit develops 38 kW of power from dc to 3.5 kHz. Its output is rated ±300V at ±128A continuous (±266A p-k), and the 51-kHz switching frequency unit thankfully operates at 94% efficiency. If you need more power than this unit can deliver, rest easy: You can parallel as many as 20 identical units for fractional-megawatt power!

Recognizing other specialty markets, Harris Semiconductor offers parts and subsystems designed for the heart-thumping audio subwoofer. The HIP100DCREF is a 100W rms circuit that drives a 0.75 Ohm subwoofer from a nominal 12V car battery over the 20- to 900-Hz band. You get THD+noise lower than 0.08% and 95% efficiency with this circular-pc-board design, which mounts on the back of the woofer itself. If you're at home rather than in your car, you can use the similar HIP200ACREF parts and design to achieve 200W rms into a 2 Ohm speaker from 10 to 450 Hz from a 32V bus supply.

Table 1—Sources of Class D audio ICs and hybrid devices

Vendor	Model	Features	Price (quantity)
Apex Microtechnology Corp Tucson, AZ 1-520-690-8600 fax 1-520-888-3329 www.apexmicrotech.com Circle No. 364	SA07	80V/5A 500-kHz hybrid, includes bridge output	$274 (100)
Harris Semiconductor Melbourne, FL 1-407-727-9207 www.semi.harris.com Circle No. 365	HIP100DCREF	Full-bridge 100W for automotive subwoofers	$85 (OEM)
Linfinity Microelectronics Garden Grove, CA 1-714-898-8121 fax 1-714-893-2570 www.linfinity.com Circle No. 366	LX1720	Stereo-controller IC, external switches	$11.75 (1000)
Philips Semiconductors Sunnyvale, CA 1-800-447-1500 www.semiconductors.philips.com Circle No. 367	TDA1562Q	Class H, 50 to 100W for automotive applications	$3.50 (OEM)
STMicroelectronics Lexington, MA 1-781-861-2650 fax 1-781-861-2687 www.st.com Circle No. 368	TDA7480, TDA7481, TDA7482	10, 18, 25W single-channel; include drivers	$1.40 to $2.45 (10,000)
Texas Instruments Inc Dallas, TX www.ti.com/sc/class_d.htm Circle No. 369	TPA005D02	2W (continuous)/5W (peak) stereo IC with integral switches	$3.48 (1000)

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