How to Design a Class-D Amplifier

Joey White

Hephaestus Audio

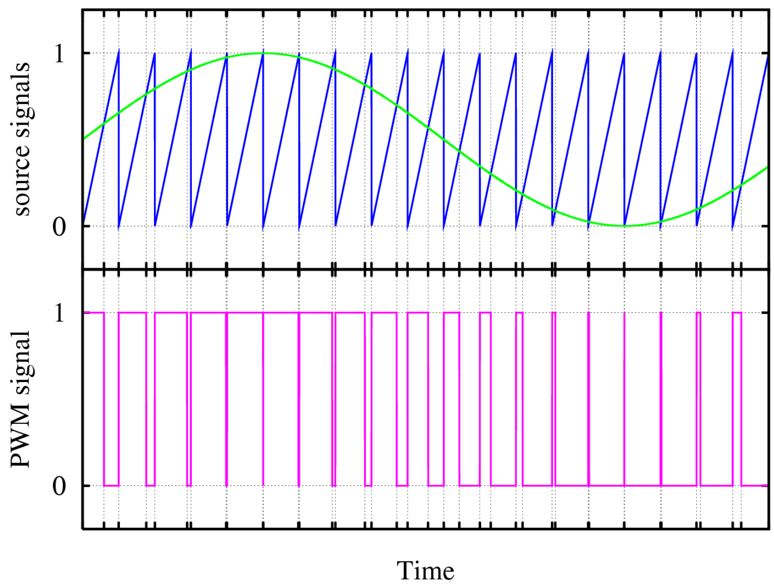
What is a Class-D Amplifier?

A class-D amplifier uses the output devices (MOSFETs, IGBTs, etc.) primarily as **switches**, rather than primarily in their linear region, as in class-A, class-B, class-AB, class-C, class-G, and class-H amplifiers. In other words, the goal is to never have both **voltage** and **current** present on the device at the same time. This is in contrast to a linear amplifier, where the output devices have both voltage and current present at the same time by design.

The reason for doing this is **efficiency**. Power equals voltage times current (P = V x I). With a class-D amplifier we seek to make at least one of these parameters **zero** at any given time, therefore making the power dissipated by the amplifier **zero**. The theoretical efficiency of a "perfect" linear amplifier is 78.5%. Now compare this to the theoretical efficiency of a "perfect" class-D amplifier which is 100%! You can never reach 100%, but as the technology continually improves, you can get closer and closer...

*Many people are familiar with **linear amplifiers**, but **class-D amplifiers** may be new and daunting. Therefore throughout this article, for a given section of a class-D amplifier, I attempt to give the "equivalent" section of a linear amplifier for reference. These parallels are not exact and are intended only to help give an intuitive feel.*

Choices of Modulation Scheme



*The **input stage** of a linear amplifier is very roughly "equivalent" to the **modulator** of a class-D amplifier.*

The choice of modulation scheme is important, but it is often blown out of proportion: A good modulator will not save a poor design - it represents just one piece of the puzzle. This is important to bear in mind when evaluating alternatives.

Several choices are available for the modulation scheme, for example self-oscillating phase shift/hysteresis, delta-sigma, natural PWM, traditional control system approaches – the list is already long and looks as though it will get much longer in the coming years. Each approach offers advantages and disadvantages. For example, **self-oscillating** designs are very simple, but may be challenging when synchronization of multiple channels is necessary. The **delta-sigma** approach pushes the noise out of band (i.e. "noise shaping"), but may suffer in efficiency due to the (sometimes) high switching frequency. **Natural PWM** is easy to grasp intuitively and, due to the use of a clock, synchronization is a non-issue, however it is necessary to generate a high-quality triangle wave for acceptable performance.

There are off-the-shelf controller chips available from Texas Instruments and many others. It is also possible to use a simple self-oscillating design, such as the excellent reference designs from International Rectifier (e.g. the IRAUDAMP series).

Summary of Modulation Schemes

- Self-oscillating
  - Phase shift or hysteresis
  - Simple, but may be difficult to **synchronize**
- Delta-Sigma
  - Noise shaping pushes noise out of band
  - High switching frequency lowers **efficiency**
- Natural PWM
  - Straightforward, intuitive approach
  - Easy to synchronize multiple channels
  - Need to generate high-quality **triangle wave**

The simplest way to get started is to use somebody's controller IC, or to use a self-oscillating reference design. Although, "simple" is probably not the right word to use in conjunction with class-D amplifier design. Even if you follow the guidelines in this article and using a good reference design, some **iteration** will be required. Plan on doing at least a few prototypes using a fast-turn PCB house (no, you can't etch your own boards with this type of design...)

How to Choose a FET

*The **output devices** of a linear amplifier are equivalent to the **output devices** of a class-D amplifier.*

FET selection is critical to the performance of a class-D amplifier. There are many parameters of importance, but luckily it can be boiled down to a few that are really essential. As long as the **voltage rating** is sufficient to handle the bus voltage of the amplifier, then the two main questions are:

How fast can it switch and how much current can it handle?

How Fast Can It Switch?

For a MOSFET this is determined by the choice of FET driver and by the Qg(tot) of the MOSFET. Layout plays a big role too, and all Qg(tot) is not created equal (e.g. “Miller” charge), but these are secondary effects.

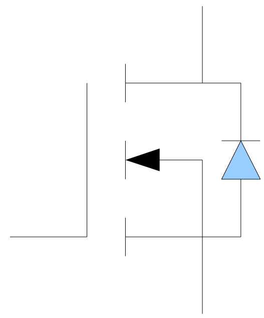
An IGBT is governed by the same parameters as a MOSFET for turn-on speed, but something called the “current tail” comes into play for turn-off speed. The datasheet parameters that indicate turn-off speed of an IGBT are Tfi and Eoff.

How Much Current Can It Handle?

For a MOSFET this is determined by a parameter called the “on resistance” or Rds(on). This parameter, in conjunction with the power handling capability of the package, determine how much current the MOSFET can handle. Note that Rds(on) increases dramatically with temperature – up to 2.5 times at maximum junction temperature! This is an unfortunate situation because it can lead to a runaway temperature rise.

An IGBT has a parameter called the “saturation voltage” or Vce(sat). This parameter, in conjunction with the power handling capability of the package, determine how much current the IGBT can handle. Due to a phenomena called “conductivity modulation” Vce(sat) does not increase proportionally with current (i.e. an IGBT does not act like a resistor like a MOSFET does, but more like a diode). As a further bonus, Vce(sat) tends to stay constant with temperature – sometimes even decreasing a little! Unfortunately, the “current tail” of the IGBT is a result of this conductivity modulation.

MOSFET (**M**etal **O**xide **S**emiconductor **F**ield **E**ffect **T**ransistor):

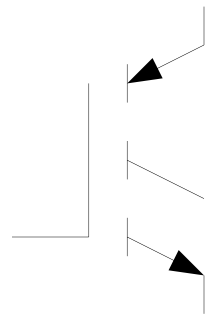


- **Vds(max)** – breakdown voltage (T=25C)
  - Vds(max) increases a little with increasing temperature
  - Choose a high enough Vds(max) to handle the bus voltage plus overshoot
    - Rds(on) increases quickly with increasing Vds(max)
- **Rds(on)** – the resistance of the FET when turned on (Vgs=10V and Tj=25C)
  - Rds(on) increases up to 2.5 times at Tj=175C
  - Choose a low Rds(on) to yield acceptably low *conduction losses*
    - A lower Rds(on) results in a higher Qg(tot) so balance is necessary
- **Qg(tot)** – the total charge needed to turn on the FET (Vgs=10V, Vds=0.75Vds(max))
  - The “Miller” portion of the gate charge is dependent on Vds
  - Choose a low Qg(tot) to yield acceptably low *switching losses*
    - A lower Qg(tot) results in a higher Rds(on) so balance is necessary
- **Qrr/Trr** – intrinsic body diode reverse recovery charge/time (T=25C)
  - Qrr/Trr increases dramatically with increasing temperature
  - Choose a FET with low Qrr/Trr if the body diode will be used
    - Otherwise external steering diodes are necessary

The intrinsic body diode of a MOSFET is generally slow and is often a nuisance in class-D amplifier designs. However, there are an increasing number of MOSFETs that offer a fast intrinsic diode (e.g. the excellent high power offerings from IXYS), but for high-voltage/power MOSFETs this is much less common.

Note: The “CoolMOS” type of MOSFET has excellent parameters and may seem like the perfect candidate for a class-D amplifier, however its severely nonlinear capacitance may be an issue. It tends to make the MOSFET “stick” to the supply rail when switching. This is great for hard-switched applications such as PFC, but not so good for class-D amplifiers.

IGBT (**I**nsulated **G**ate **B**ipolar **T**ransistor):

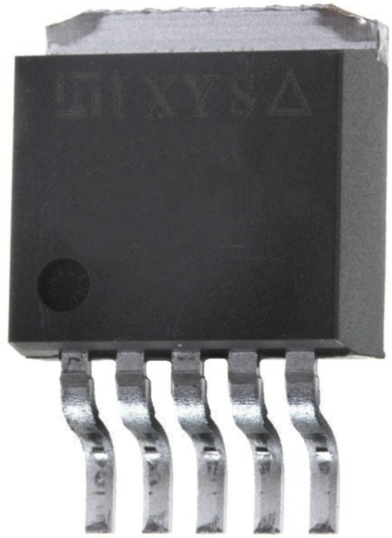


- **Vces** – breakdown voltage (T=25C)
  - Vces increases a little with increasing temperature
  - Choose a high enough Vces to handle the bus voltage plus overshoot
    - Vce(sat) does not significantly increase with increasing Vces
- **Vce(sat)** – saturation voltage (equivalent to on resistance – specified at Ic and Vge)
  - Fairly constant with increasing temperature (yeah!)
  - Choose a low Vce(sat) to yield acceptably low *conduction losses*
    - A lower Vce(sat) results in a higher Qg(tot) and/or Tfi/Eoff so balance is necessary
- **Qg(tot)** – the total charge needed to turn on the FET (Vgs=15V, Vds=0.75Vds(max))
  - The "Miller" portion of the gate charge is dependent on Vds
  - Choose a low Qg(tot) to yield acceptably low *switching losses*
    - A lower Qg(tot) results in a higher Vce(sat) so balance is necessary
- **Tfi/Eoff** – turn off time/energy
  - This is a measure of the IGBT "current tail" – how quickly the IGBT can turn off
  - Choose an IGBT with a low Tfi/Eoff
    - A lower Tfi/Eoff results in a higher Vce(sat) so balance is necessary

The IGBT does not have an intrinsic body diode like the MOSFET, so a fast recovery diode must be placed in parallel with the IGBT. This is a distinct advantage over MOSFETs, where you must often take steps to deal with the slow intrinsic body diode (i.e. it's there whether you want it or not).

Note: There is increasing availability of high-speed IGBTs that may lend themselves to class-D amplifiers. Some have nearly the switching speed of a MOSFET, but with the conductivity modulation of an IGBT. The tradeoff is a Vce(sat) that tends to be higher than that of typical "slow" IGBTs.

How to Choose a FET Driver



*The **voltage amplification stage** (VAS) of a linear amplifier is very roughly "equivalent" to the **FET drivers** used in a class-D amplifier.*

A FET driver must be able to supply adequate current for the high speed switching of a class-D amplifier. The larger the MOSFETs or IGBTs used, the higher the current requirement for a given switching speed. Also, the charging and discharging energy must be dissipated by the FET driver plus any external resistance, so the package used for the FET driver must be up to the task. For example, some FET drivers are packaged in a small SOIC-8 package while others are packaged in a much more thermally capable TO-263-5 package.

Another consideration is the use of two "**low-side**" FET drivers versus the use of a single "**high/low-side**" FET driver. There is a great variety of low-side FET drivers, but only a limited selection of suitable high/low-side FET drivers. This is a shame because level shifting and delay matching are already taken care of in the high/low-side versions. These functions must be addressed by the designer if low-side only FET drivers are used.

Summary of FET Driver Selection

- Current/thermal capability
  - Driving larger FETs requires higher current/thermal capability
    - Choose a higher **drive current** for larger FETs
    - Choose a package with higher **dissipation** for larger FETs
- Low-side versus high/low-side
  - Two low-side FET drivers may be used
    - Some sort of **level shifting** will be required
    - In addition **delay matching** may be a challenge
  - A high/low-side FET driver is convenient
    - Includes level shifting and delay matching
    - Fewer choices and mostly lower voltage/current

The simplest way to get started is to use a high/low-side FET driver. This takes care of the difficulties of level shifting and delay matching. There are some particularly good offerings from International Rectifier (combine this with one of the IRAUDAMP reference designs and you're in business). It may or may not limit how much power you can get out of your amplifier, but if you're just getting started, then it's probably better to learn to walk before you run!

Choices of Output Inductor

*There is no real "equivalent" to a class-D's **output filter** in a linear amplifier. An output inductor is frequently used in linear amplifiers, in conjunction with a RC circuit, for stability into capacitive or light loads (i.e. a **zobel network**). However, this differs from the purpose of the output filter in a class-D amplifier, which is to remove the carrier wave.*

There are two typical choices for the output inductor of a class-D amplifier: a **powdered iron** toroidal core or a **gapped ferrite** core. If a powdered iron toroidal core is used, then there is the option of using an off-the-shelf inductor. There is a wide selection of these off-the-shelf toroidal inductors, but unfortunately most use higher permeability cores, which may result in excessive core losses in high power class-D amplifiers. If a gapped ferrite core is used, then it most likely will be a custom design, which complicates the design process a little.

Powdered Iron versus Gapped Ferrite Cores for Class-D Amplifier Output Filter

Powdered Iron		Gapped Ferrite	
Pros	**Cons**	**Pros**	**Cons**
Very simple, no bobbin	Thermal aging	Choice of ferrite not critical	Fringing field around gap
Symmetric field	Choice of core important	Inductance function of gap	Requires use of bobbin

What's the difference? A powdered iron core uses many tiny little gaps distributed evenly throughout the core – it is essentially a *continuous gap*. These voids are filled with a filler material that is part of the "special formula". A gapped ferrite core uses a big *single gap*. That's it. The real difference is a bunch of tiny gaps versus one big gap.

Fundamental Protection Mechanisms

Now you've got the amplifier working, but you also want it to keep working if somebody inadvertently shorts the output, or gets overzealous with the volume control! There are two fundamental protection mechanisms needed for a class-D amplifier: **overcurrent** and **overtemperature**. Many more types of protection may be included, however these two should be considered an *absolute minimum*.

Overcurrent Protection

*The **overcurrent/safe operating area protection** of a linear amplifier is equivalent to the **overcurrent protection** of a class-D amplifier.*

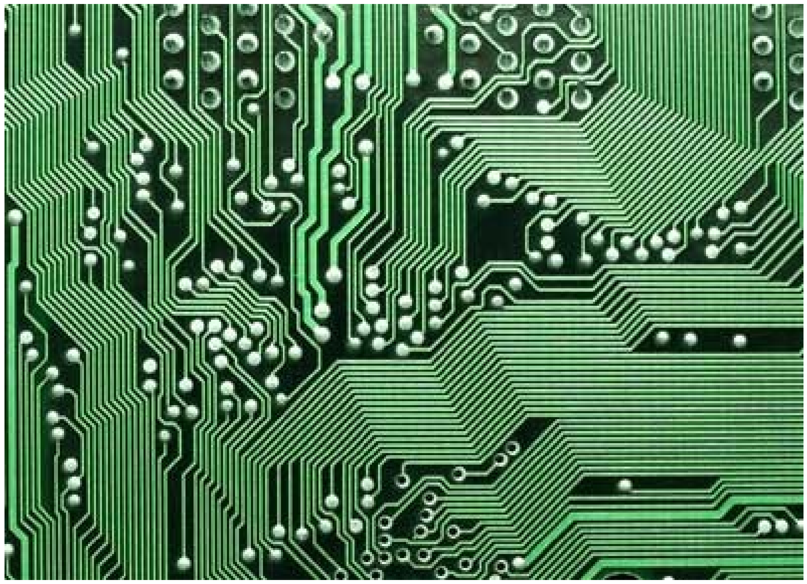
Safe operating area (SOA) protection is not needed in a class-D amplifier because the output devices are not operated in their linear region, but rather as switches. However, overcurrent protection is needed as the FETs used in a class-D amplifier are capable of conducting hundreds of amps for brief intervals. This is a welcome relief when compared to the sometimes complex SOA protection schemes of linear amplifiers.

Overtemperature Protection

*The **overtemperature protection** of a linear amplifier is equivalent to the **overtemperature protection** of a class-D amplifier.*

There is a specified maximum junction temperature for the FETs used in a class-D amplifier. However, the parameters of the FETs change undesirably even before this temperature is reached. Therefore it is important that the temperature of the output devices is measured and a mechanism is included to limit this temperature. The mechanism may be simply reducing the signal level or even turning off the oscillations completely.

PC Board Design Guidelines



*There is no real "equivalent" to the stringent **layout** requirements of a class-D amplifier in a linear amplifier. A classic "star ground" layout with reasonable routing of traces is perfectly adequate for a linear amplifier, but for a class-D amplifier such an approach is a perfect disaster!*

This is probably the least understood, and most neglected, element of class-D amplifier design. Here are some fundamental rules of thumb to get you started:

- Use a **ground plane**
  - Try to make it as continuous as possible under "critical areas"
- Keep the effective area of high di/dt loops small (big current transients)
  - Remember: all currents flow as **loops** – don't forget the return current!
- Keep the effective area of high dv/dt regions small (big voltage transients)
- Copper is your friend
  - Try to use **planes** instead of **traces** for high-speed/high-power
- Keep it short and sweet
  - Distance between the FETs and the FET driver
  - Distance between the FETs and any bypass capacitors
  - Anything that is high-speed and high-power

Class-D design is very challenging (1st prototypes usually don't work at all...sometimes 2nd and 3rd prototypes don't work either), but like most difficult pursuits it is fun and rewarding. I wish you the best of luck in your class-D design efforts!