An Introduction to Class D / Switching Audio Amplifiers

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Disclaimer!

A lot of info to compress into 1 hour. We will only touch on some highlights. More configurations and circuits than what is presented here.

What is a Switching Amp?

- An amplifier topology in which output power control devices are operated in discrete states to minimize losses.
- A.K.A→ Class D. Other marketing terms exist.
- Output devices are operated in 2 states, saturation and cutoff (on / off).
- Technology is very closely related to switching power supplies, except we are designing for AC outputs.
- Note: This technology can be very complex. Only a quick overview can be provided here.

Why Switching Technology?

- Amplifier efficiency (power to load with respect to power used by amplifier) is the preferred performance figure. 85%-95% can be achieved with a good design.
- First applications were variable frequency motor drives. 10KW motor drives could be made small and light.
- Advances is power control devices (i.e. transistors) and advanced switching techniques have improved metrics such as THD to a point where they are comparable to linear amps.

Why Switching Technology?

- As next generation switching devices become commercially available (Silicon Carbide → SiC), performance metrics will be almost always be better than ‘linear’ amplifier topologies.

- Commercially attractive to many markets. High power amps can be very small, less costly and require less mechanical systems to deal with waste heat.

Why NOT Switching Technology?

- Circuitry is generally more complex and more difficult to design.
- Sources of non-linearity are more difficult to identify and compensate for (especially for the novice).
- Debugging designs is more difficult as circuit designs can resemble RF circuits. ‘3-D’ prototypes are much harder to get working reliably. Elements such as ground planes, controlled power supply paths can be extremely critical.

Quick Review of Linear Amps…..

- **Class A** – Output power control device is biased to operate is most linear region of device throughout the full conduction cycle. Best performance at the expense of extremely poor efficiency → 25% best case.
- **Class AB (push pull).** Paired control devices (one for each half of the conduction cycle). Less power dissipation in control devices at the expense of additional sources of non-linearity and noise. Very common amp design. Provides the best trade-off of fidelity and efficiency of linear amps. 40-50% efficiency is easily achievable.

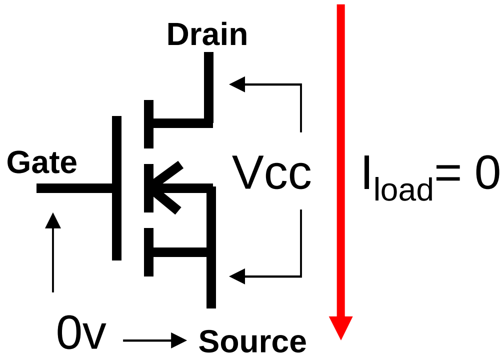
Quick Review of Linear Amps…..

- **Class B,C**,….   Not for Audio, Highly non-linear, often involving clipped outputs and tuned RF tanks……

- Even if one could operate a transistor) to power supply rails will perfect linearity, a theoretical maximum efficiency of 70.7% (assuming no quiescent current) is possible.

Why Switch?

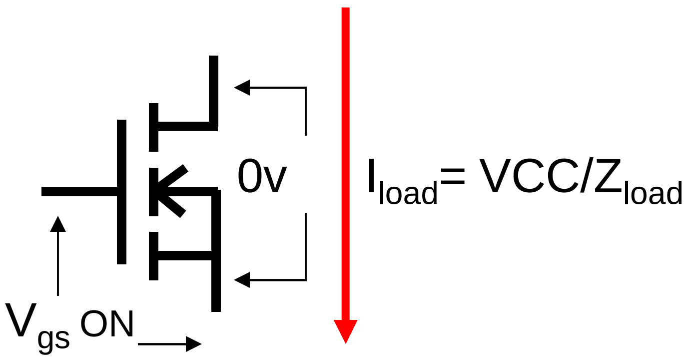
Ideal MOSFET



With no potential between Gate and Source, FET is off.

Zero current flows to load and supply potential is dropped across device. Power (V*I) dissipated by device is zero.

Ideal MOSFET



With the proper potential between Gate and Source, FET is saturated (on).

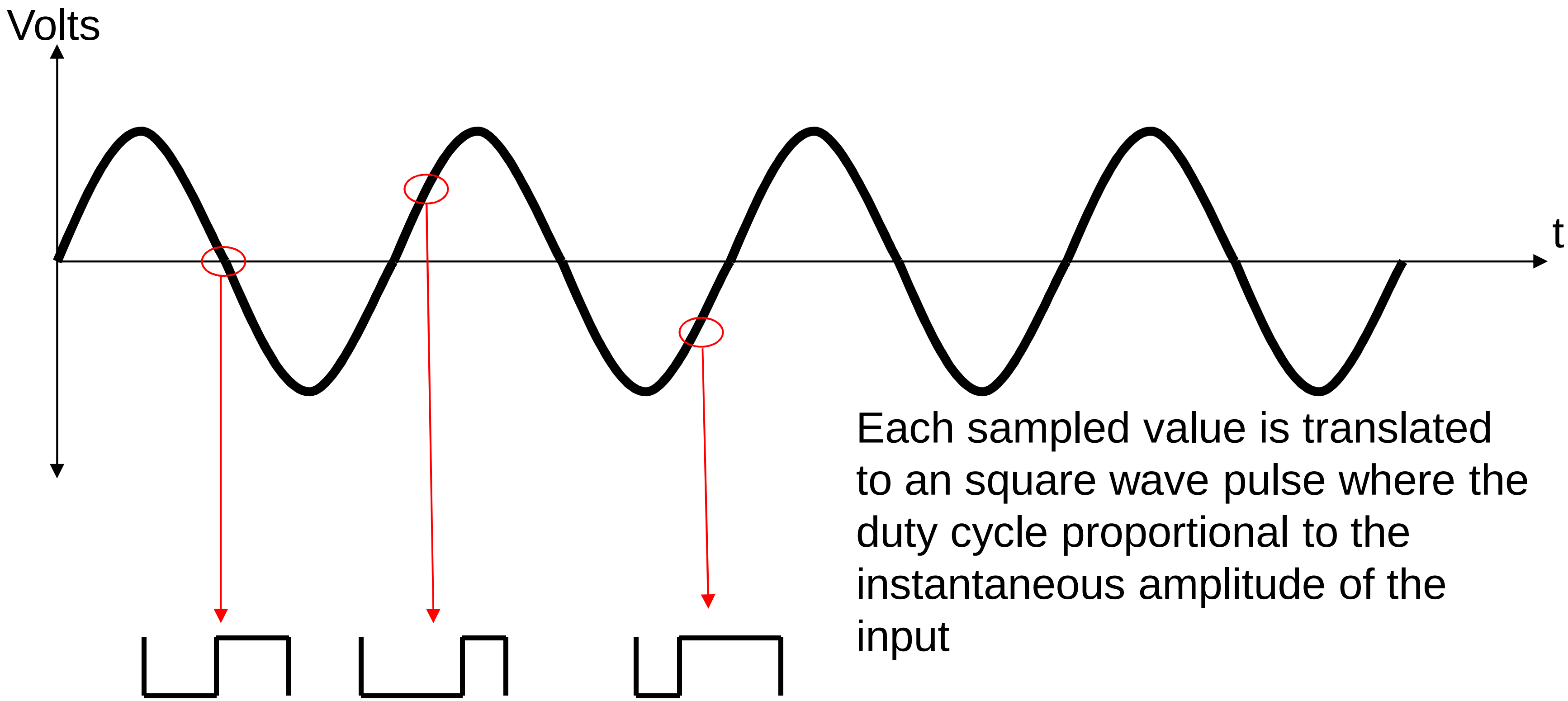
Current flows to load and zero potential is dropped across device. Power (V*I) Dissipated by device is zero.

Ideal Efficiency is 100% ….. But…..

But how can I use a power stage with only 2 states?

- With a 2 state output stage, we can create a pulse train, not a nice continuous waveform.
- Need a way to encode a continuous waveform into a “pulse train” in such a way that we can recover original signal at the speaker.
- Answer #1. Pulse Width Modulation.
  (0 Order Modulation)

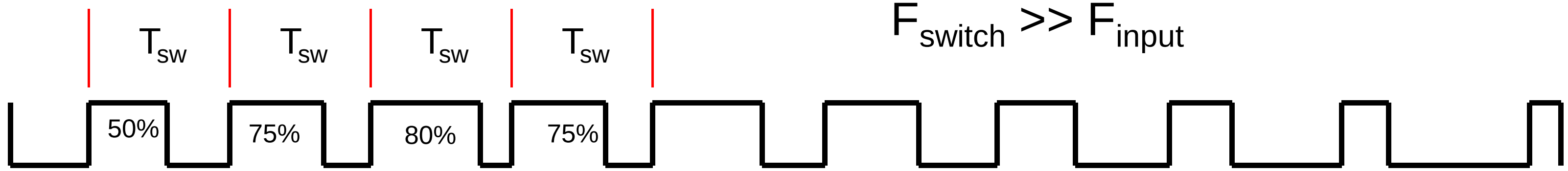
Pulse Width Modulation



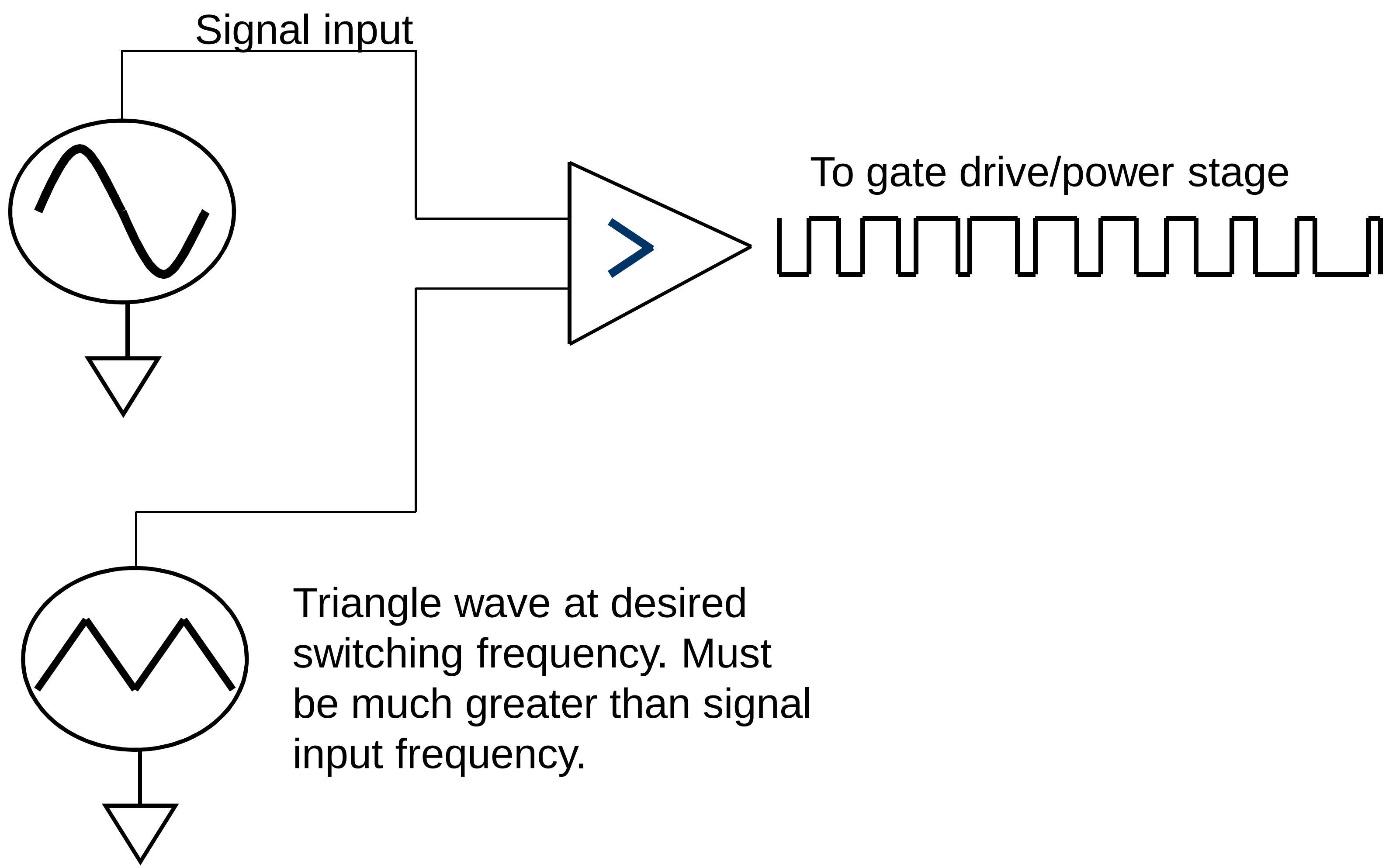
Each sampled value is translated to an square wave pulse where the duty cycle proportional to the instantaneous amplitude of the input

Frequency of output pulse train is constant, but the duty cycle of the pulse is continuously changing.

$F_{switch} >> F_{input}$

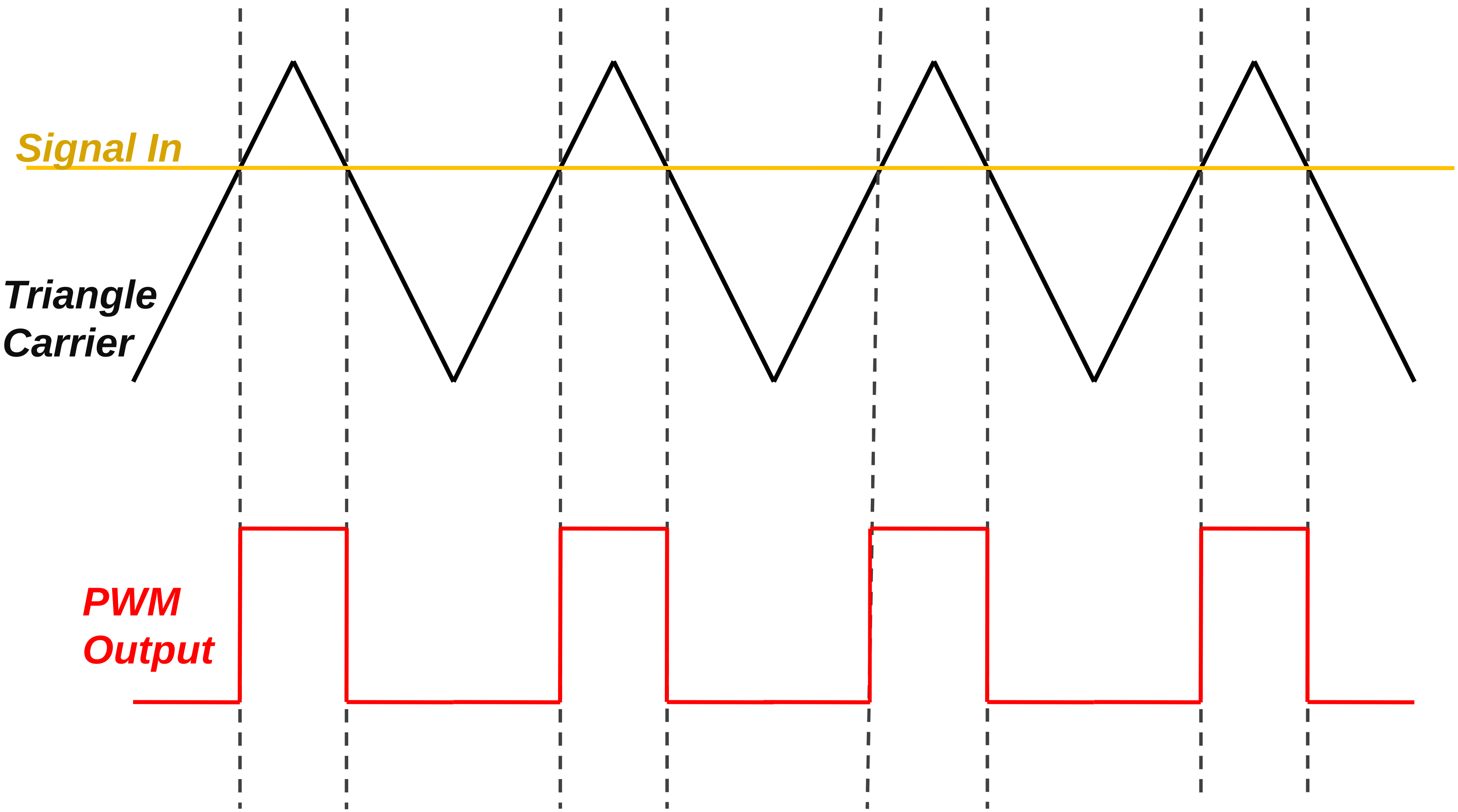


Analog PWM

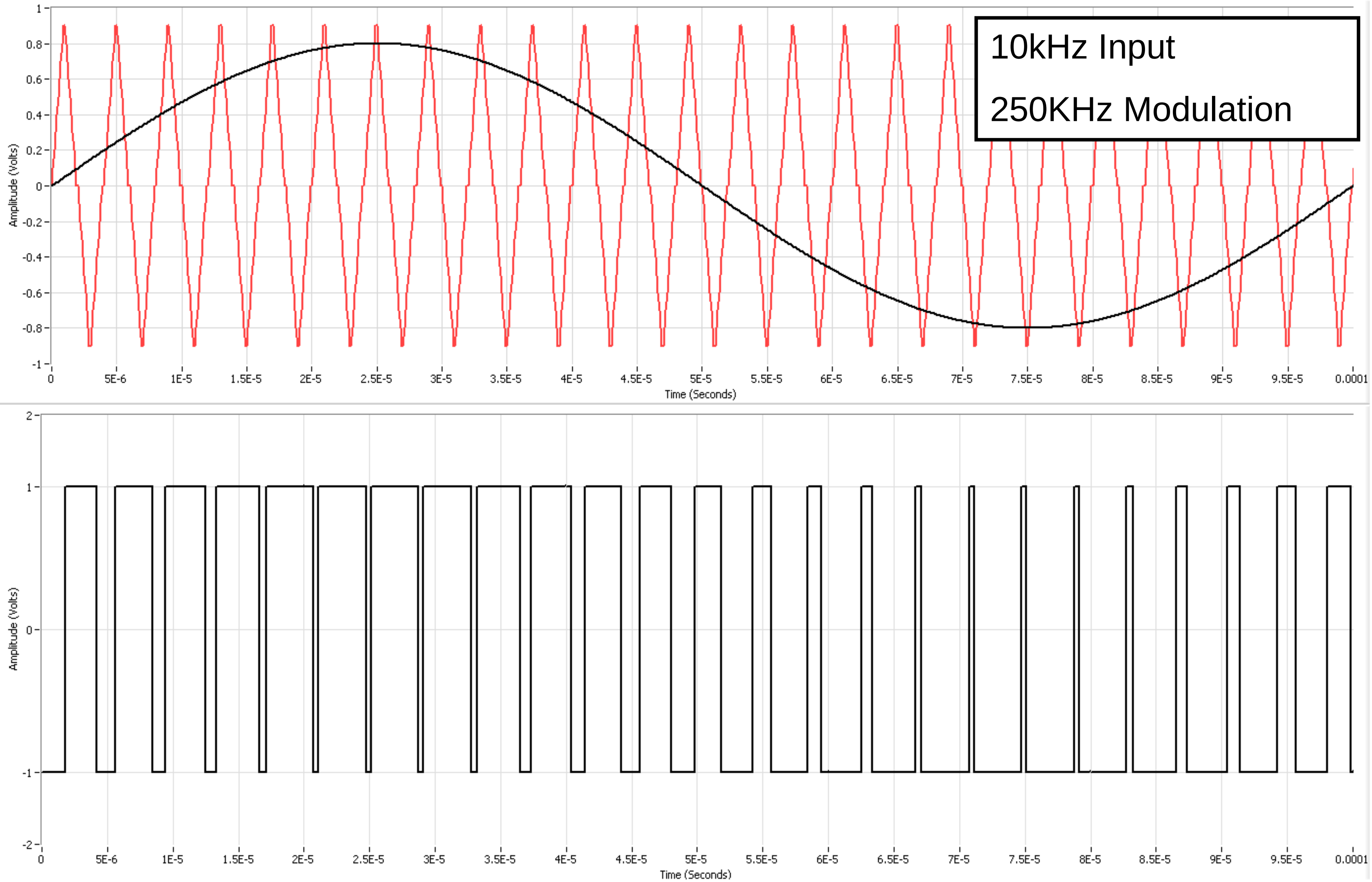


Signal input
To gate drive/power stage
Triangle wave at desired switching frequency. Must be much greater than signal input frequency.

Analog PWM



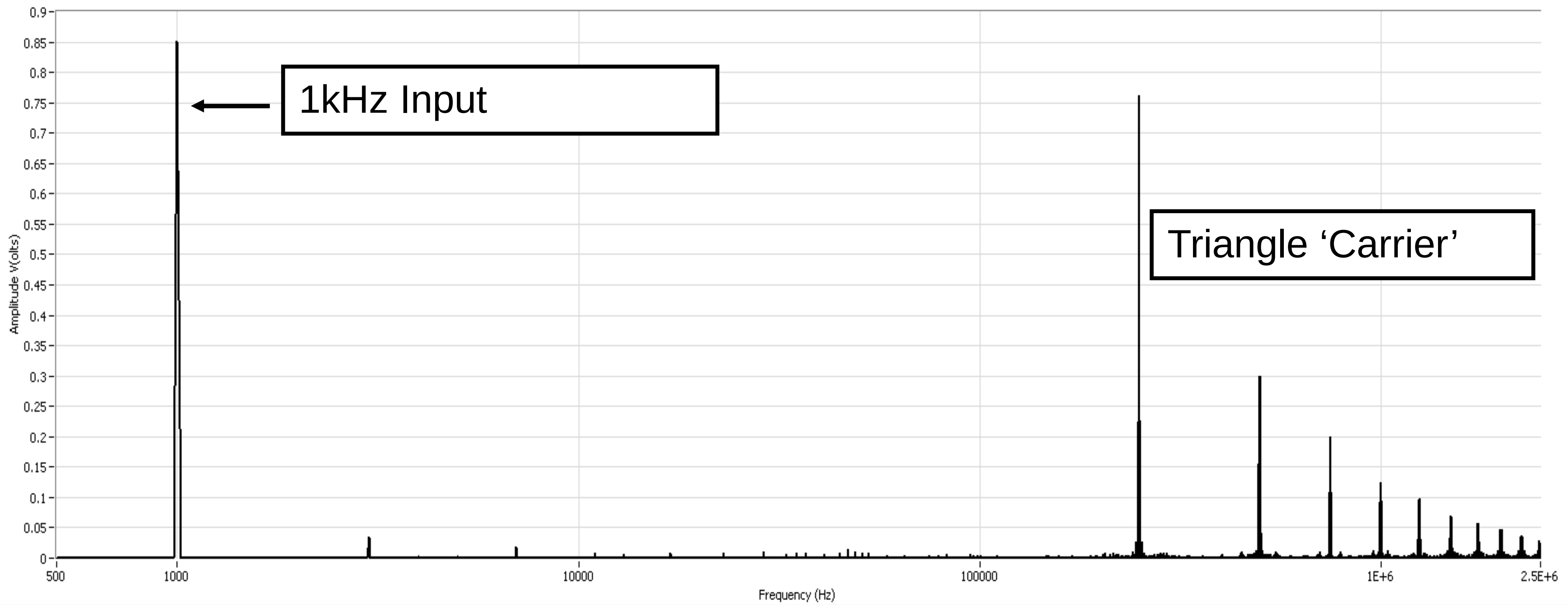
PWM – Time Domain



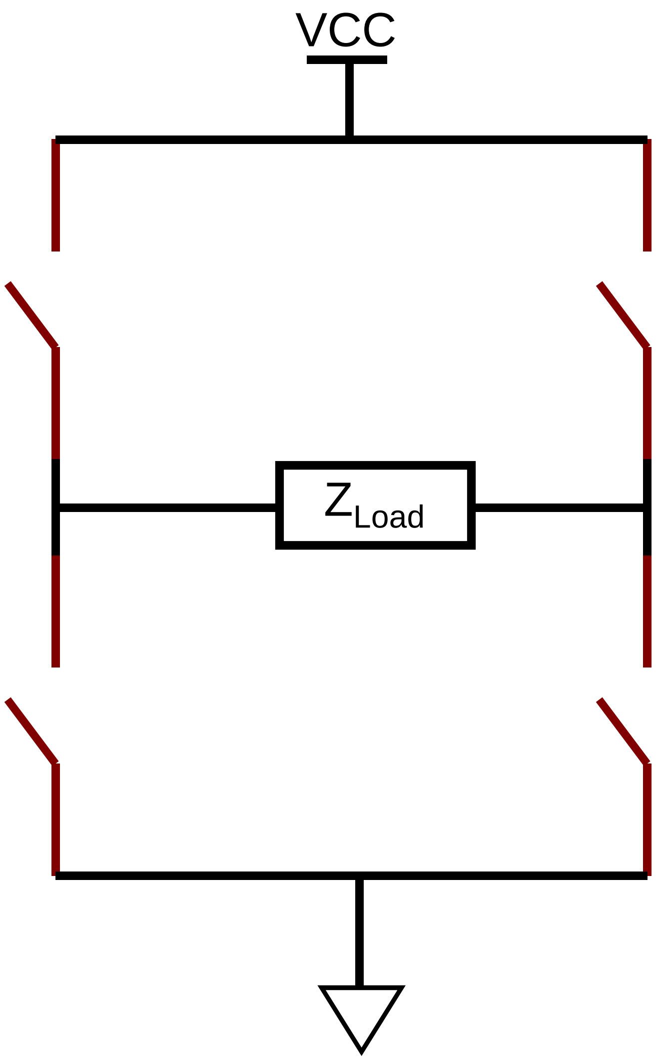
Spectrum of a PWM Signal

1kHz Input

250KHz Modulation

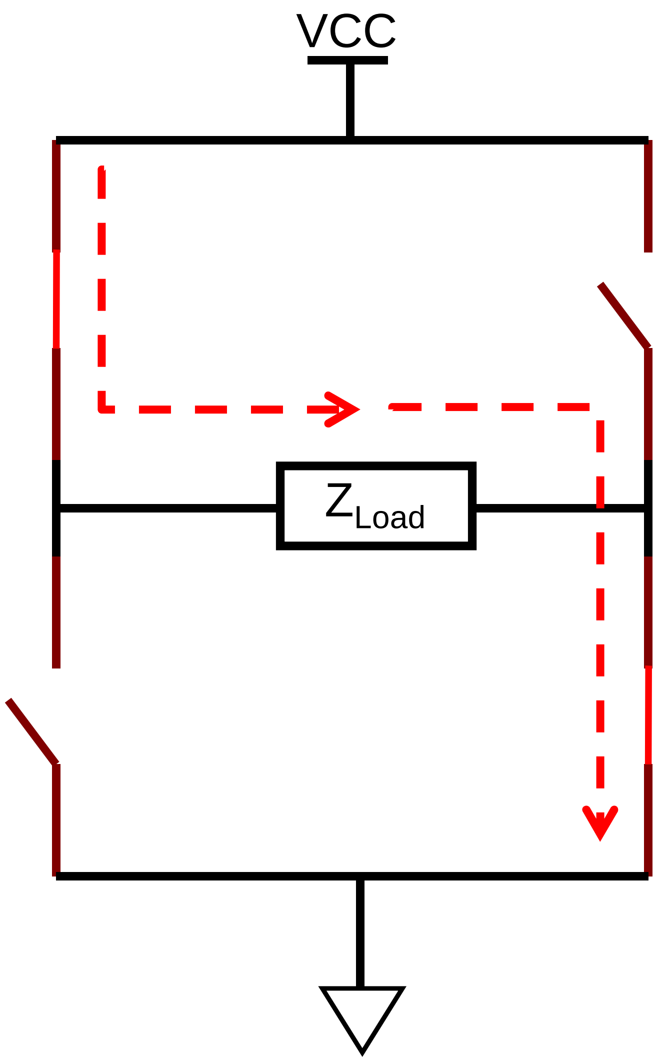


H-Bridge

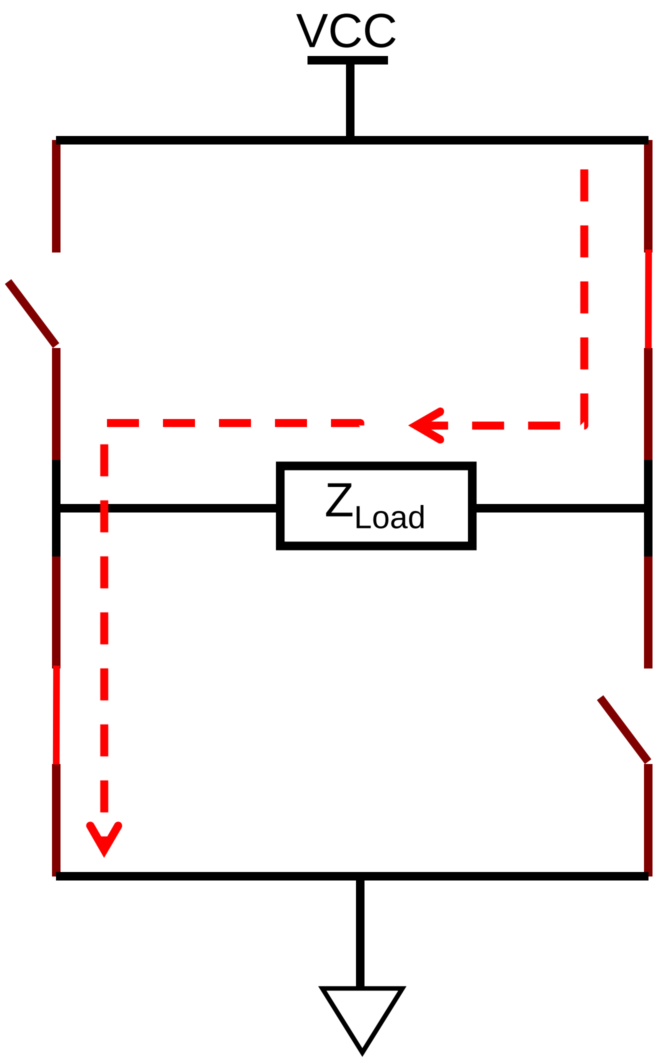


- Full H-Bridge is most popular. (Half bridge is also used)
- Can achieve bi-directional currents through load
- Possible to implement advanced switching noise cancellation techniques
- *Load is NOT ground referred!*

The Pieces → H-Bridge



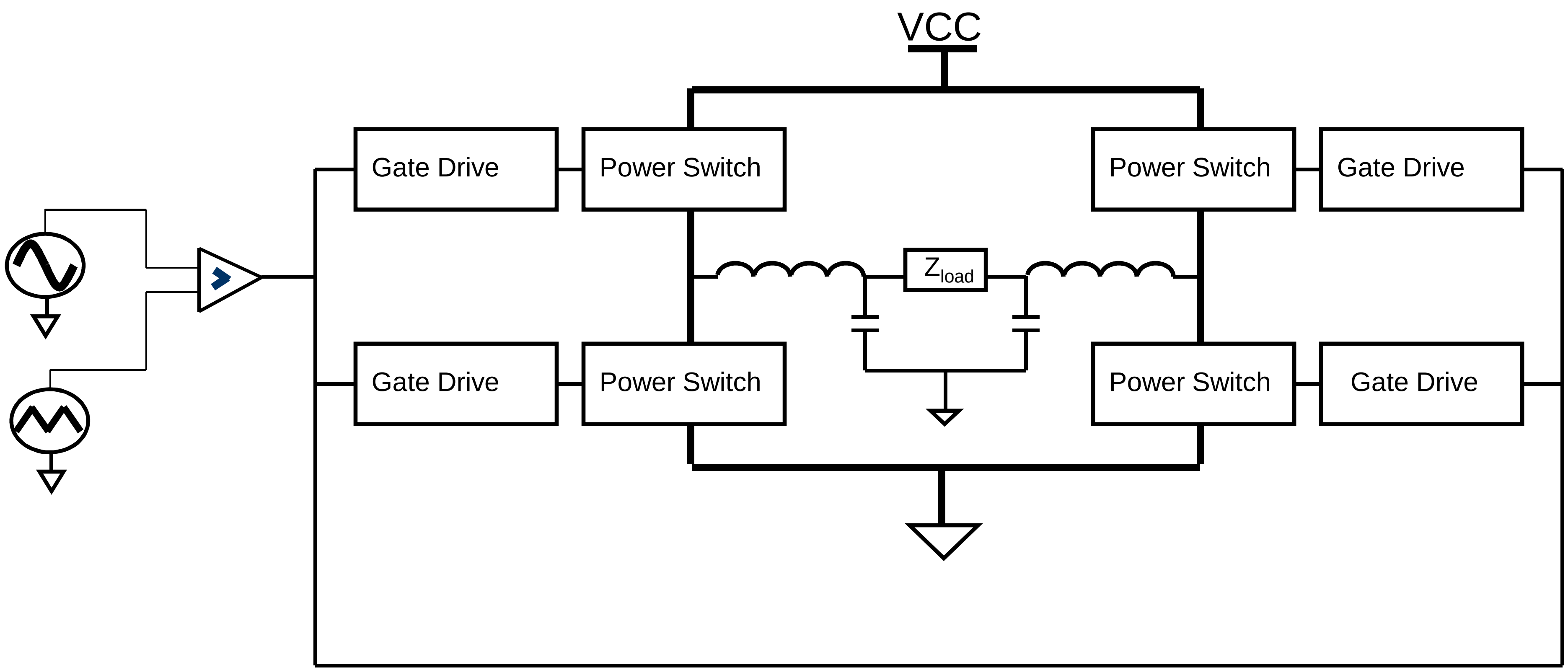
The Pieces → H-Bridge



Output Filter

- Need to reconstruct original signal.
- Most common method is to use an LC Low pass filter. Additional poles can be added to improve noise removal.
- Q of output filter is kept under control by load.
- Higher switching frequency means less filter but more loss (we will see this later).

Put the Pieces Together.



Sources of Inefficiency

- If one has perfect switches, one could achieve a perfectly linear amp (it only needs to re-create 2 states!) with no loss. This does not imply perfect THD+N. We just move noise to a band we can't hear!
- 3 primary sources of loss in MOSFET based switchers
  - Conduction Losses
  - Switching Losses
  - Gate Drive Losses

Conduction Loss

- All transistors have a certain amount of equivalent resistance through their channel when fully saturated.
- There is inevitably some amount of voltage dropped across the switch elements. For MOSFETs, (most common switch for Class D) this is referred to as $R_{ds(on)}$

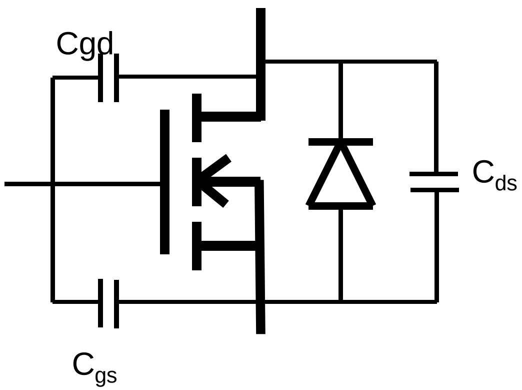
$$P_{cond} = \frac{R_{DS(on)}}{R_L} P_o$$

Switching Loss

- **There is loss that occurs during the finite time during a switch transition MOSFET AC switching models can be quite complex but the switching losses can be approximated by:**

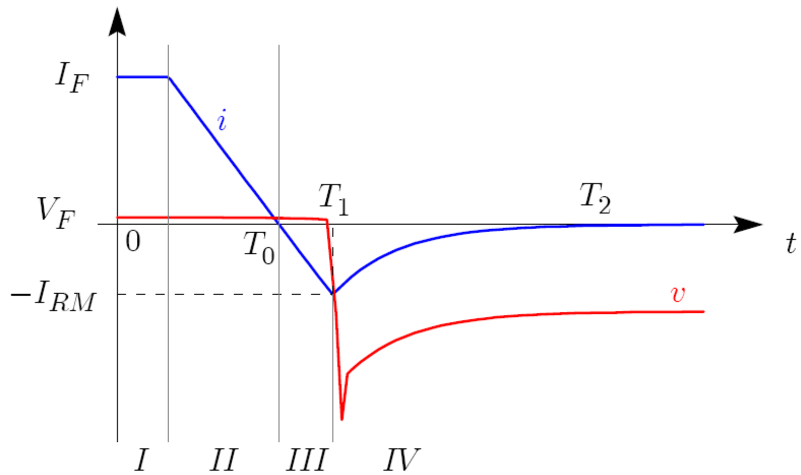
$$P_{switch} = \frac{f_{pwm}}{2}\left[V_{bus}{}^{2}C_{oss} + I_D V_{bus} t_{rise+fall} + K \cdot Q_{rr} \cdot V_{bus}\right]$$

Note, there are a couple of terms here that will be the major source of trade-offs in the design of a switching amp…..



$$C_{oss} = C_{ds} + C_{gd}$$

MOSFET AC MODEL



Body Diode Reverse Recovery

Gate Drive Loss

- The input to a MOSFET can be approximately modeled (**to 1st order!)** as a capacitance**.** There is a certain amount of charge required to turn a device on. This results in another loss mechanism.

$$P_{gatedrive} = 2 \cdot Q_g \cdot V_{gs} \cdot f_{pwm}$$

MOSFET Loss….

$$P_{cond} = \frac{R_{DS(on)}}{R_L} \cdot P_o$$

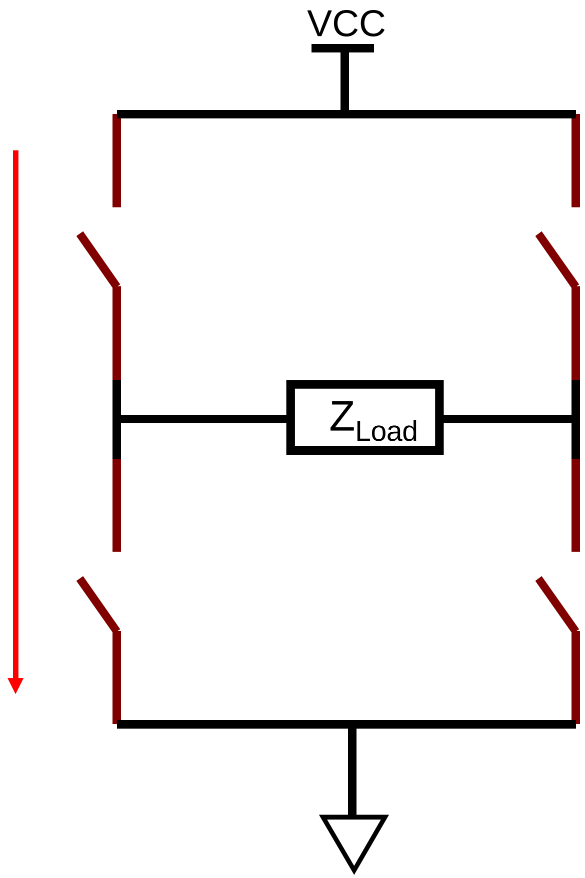
$$P_{switch} = \frac{f_{pwm}}{2} \left[V_{bus}{}^2 C_{oss} + I_D V_{bus} t_{rise+fall} + K \cdot Q_{rr} \cdot V_{bus} \right]$$

$$P_{gatedrive} = 2 \cdot Q_g \cdot V_{gs} \cdot f_{pwm}$$

Because a lot these terms are frequency dependent, there are design choices to be made. Running at high frequency makes filter smaller but increases loss! Lower frequency operation increases inductor size (square relationship) and makes design larger.

Shoot Through Current
A Loss / Linearity Tradeoff.

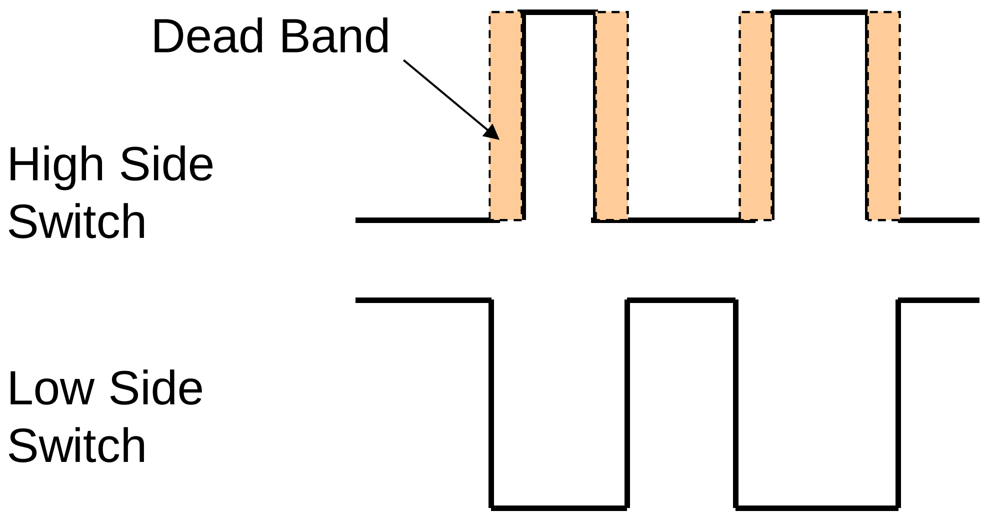
Because MOSFETs have a finite period in which they switch, the H-Bridge presents a problem…….



The left and right hand sides of the of bridge is short circuit Vcc to ground for a short period of time.

Solution: Dead Band

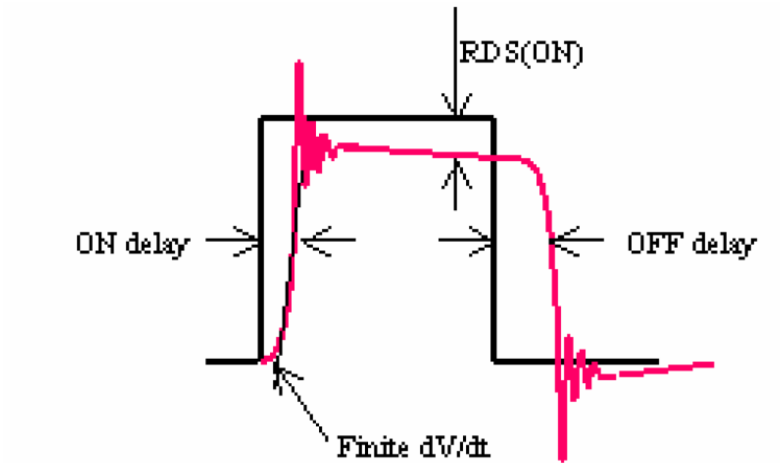
Add a short time delay between high-side and low side switches such that they never conduct at the same time.



This parameter is tweaked to minimize shoot-through current BUT non-linearity will be added. Excessive dead band will introduce noise into the audible spectrum.

Additional Sources of Problems

- Filter Inductor core saturation
- Non-Ideal PWM Synthesis.
- Poor gate drive circuit



Other Modulation Options?

- Is there something other than PWM that can encode a signal in a pulse train?

?

Advanced Modulation
Higher Orders

- Standard PWM modulation can be difficult to filter as a lot of the noise power exists at the fundamental switching frequency.

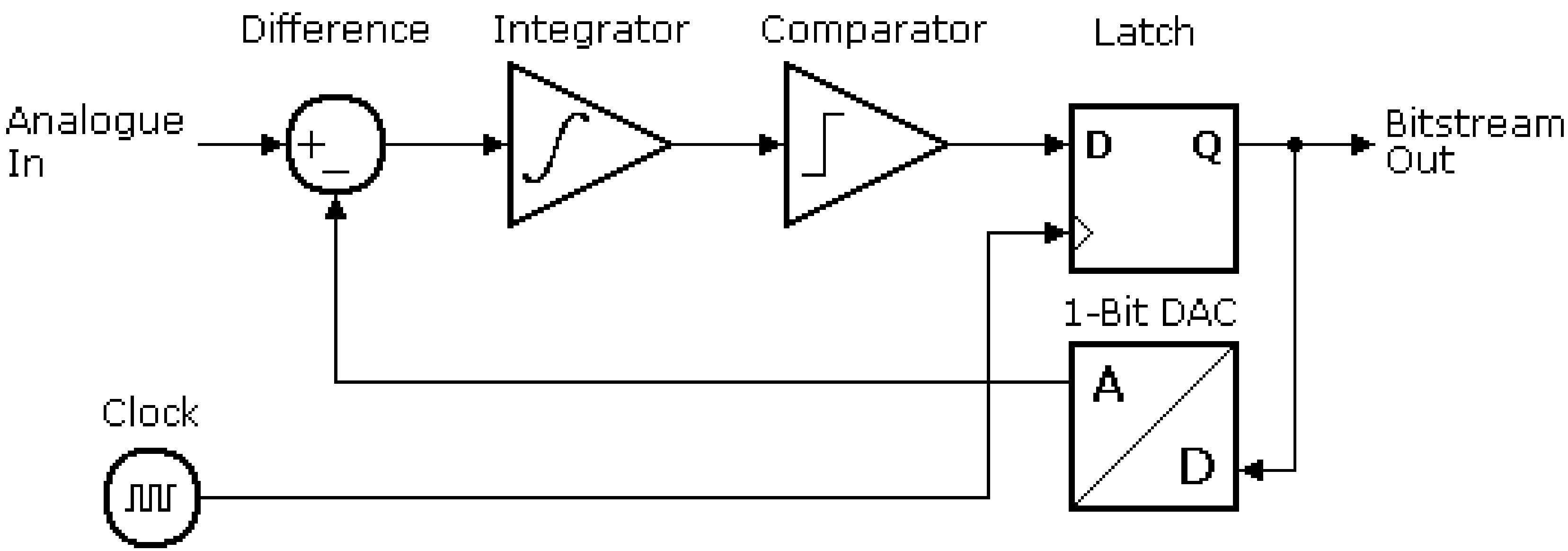
- Increasing the PWM switching frequency can be problematic as the losses are directly related to switching frequency!

Advanced Modulation Higher Orders.

- Answer: Find a method that changes switching *frequency* and duty cycle as the input changes.

- I.E. Spread spectrum switching

Advanced Modulation
Higher Orders

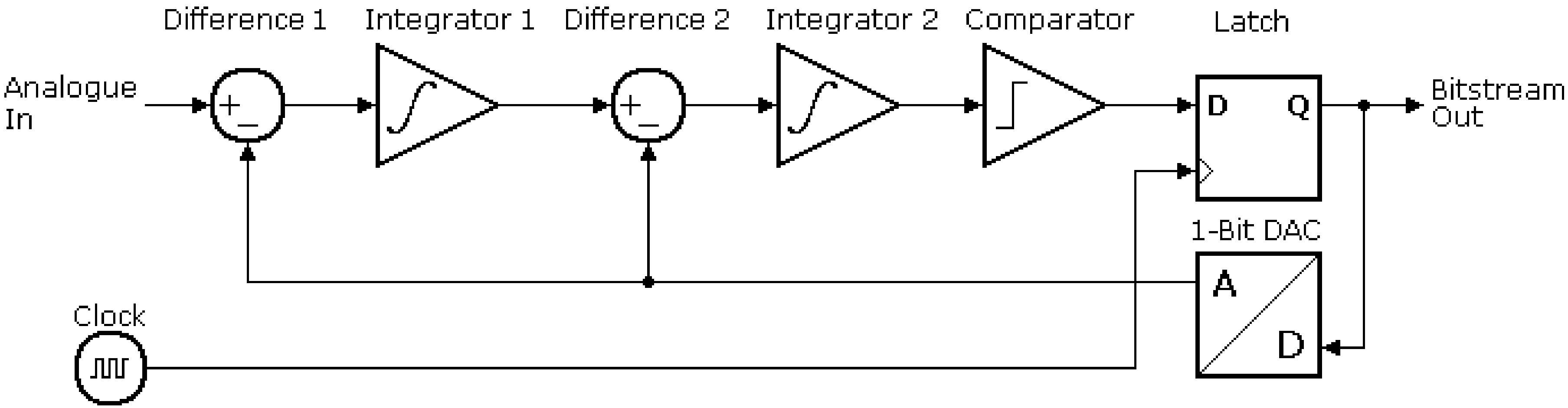


1st Order ΣΔ

http://www.beis.de/Elektronik/DeltaSigma/DeltaSigma.html

Diagrams Courtesy of Uwe Beis

Advanced Modulation
Higher Orders



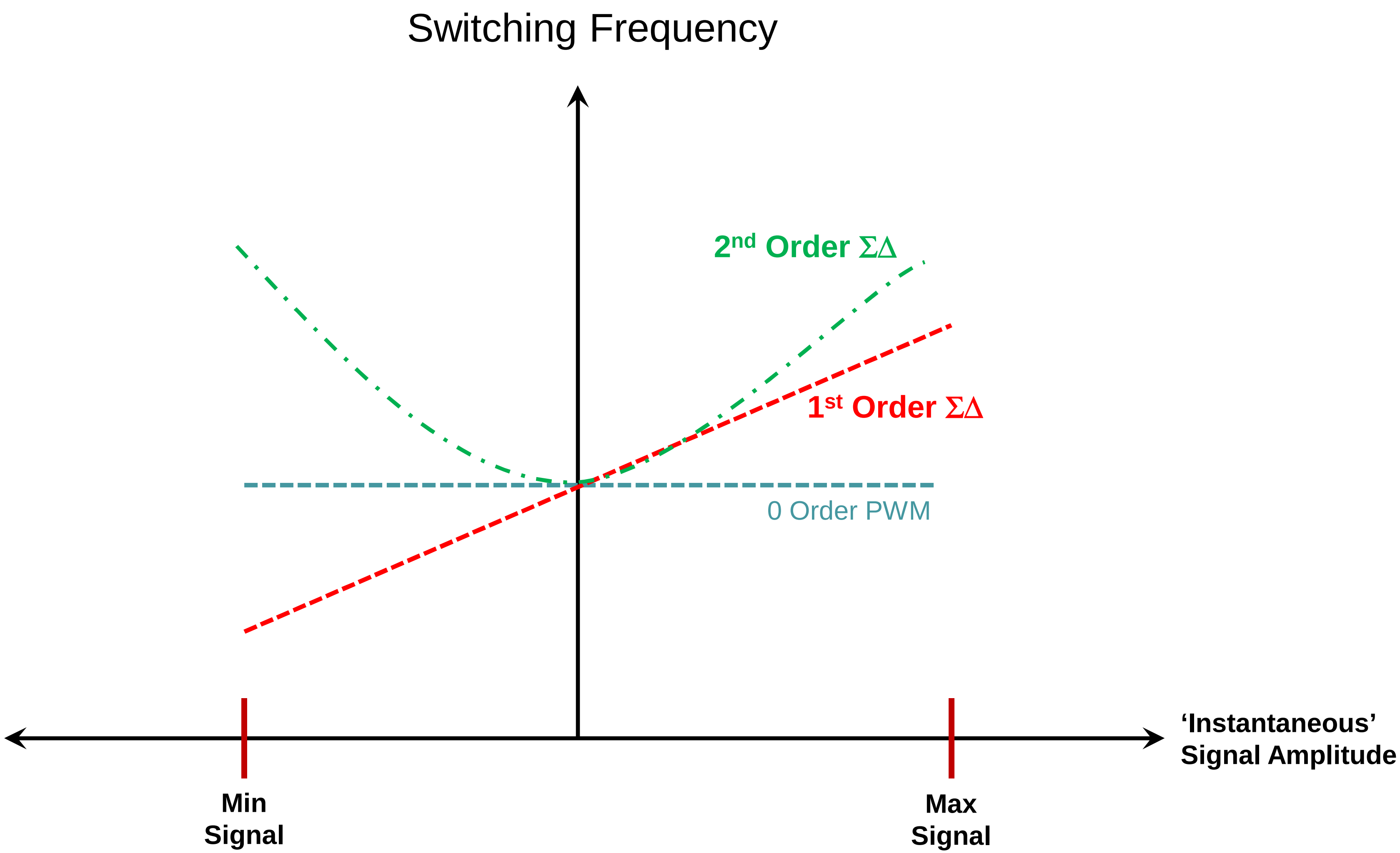
2^{nd} Order $\Sigma\Delta$

http://www.beis.de/Elektronik/DeltaSigma/DeltaSigma.html

Diagrams Courtesy of Uwe Beis

Advanced Modulation

Why does Eli call PWM 0 order modulation?



Advanced Modulation – Why Not?

- Fast, high order modulators can produce pulses very high in frequency (ΣΔ clock rate).
- Gate drive circuit becomes difficult
- Losses go up as switching frequency goes increase

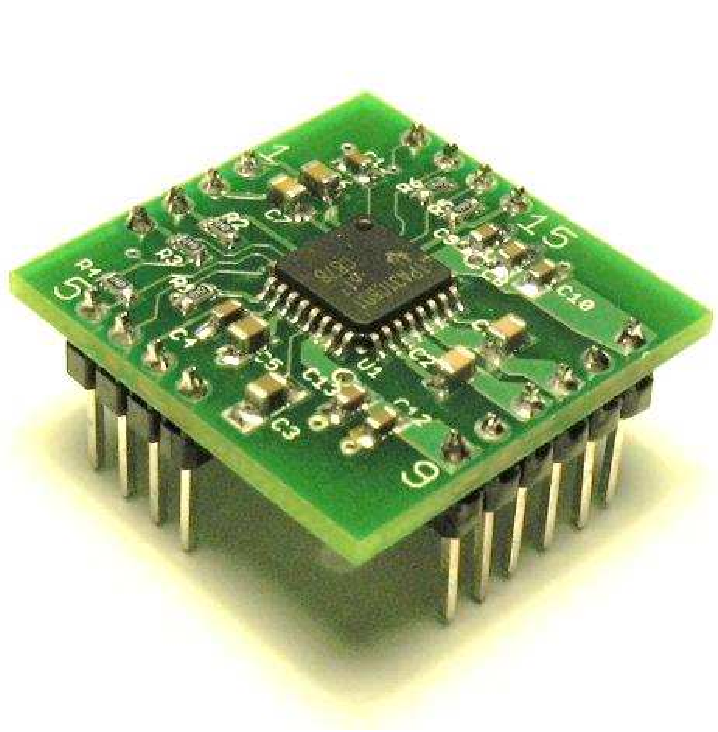
Who Makes Chipsets?

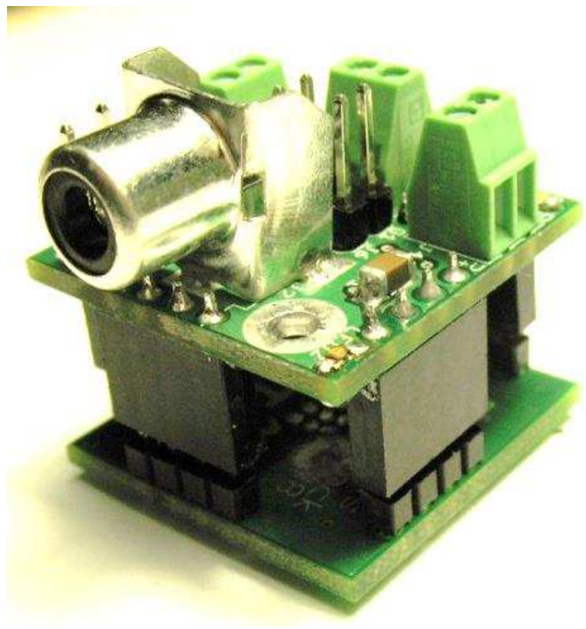
- Texas Instruments
- Analog Devices
- ST Micro
- Zetex

- Or….. Build from scratch!

Example

TPA3106 Chip





The Bottom Line

•Switching amps can provide a very nice solution to the loss problems associated with linear amps.

•Sound quality can be as good a linear amp, regardless of what an audiophile tells you. ΣΔ data converters are used in almost every high end digital audio application and very few are displeased with the sound.

•As switch technology improves (SiC), the sound quality will only get better as noise can be reduced. (not that it is bad now!)

The Bottom Line

- Several companies are starting to make switchers that integrate all of the logic and output devices on a single chip. No heatsink required. Only need minimal filter components required.

- Just about all high power audio companies (Crown, etc) offer at least one model of a switching topology. 1 KW amps get much smaller and lighter without the large heatsinks!

- You will only see more of this technology, it is important as an engineer to understand how they work and when to use them

Questions?

Great application notes at:

irf.com

advancedpower.com

Zetex.com