

Life on the Edge

A Universal Grammar of Class D Amplification

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Definition

A class D amplifier is a power amplifier where all active devices in the power stage are operating in on/off mode.

- On=current, but no voltage
- Off=voltage, but no current

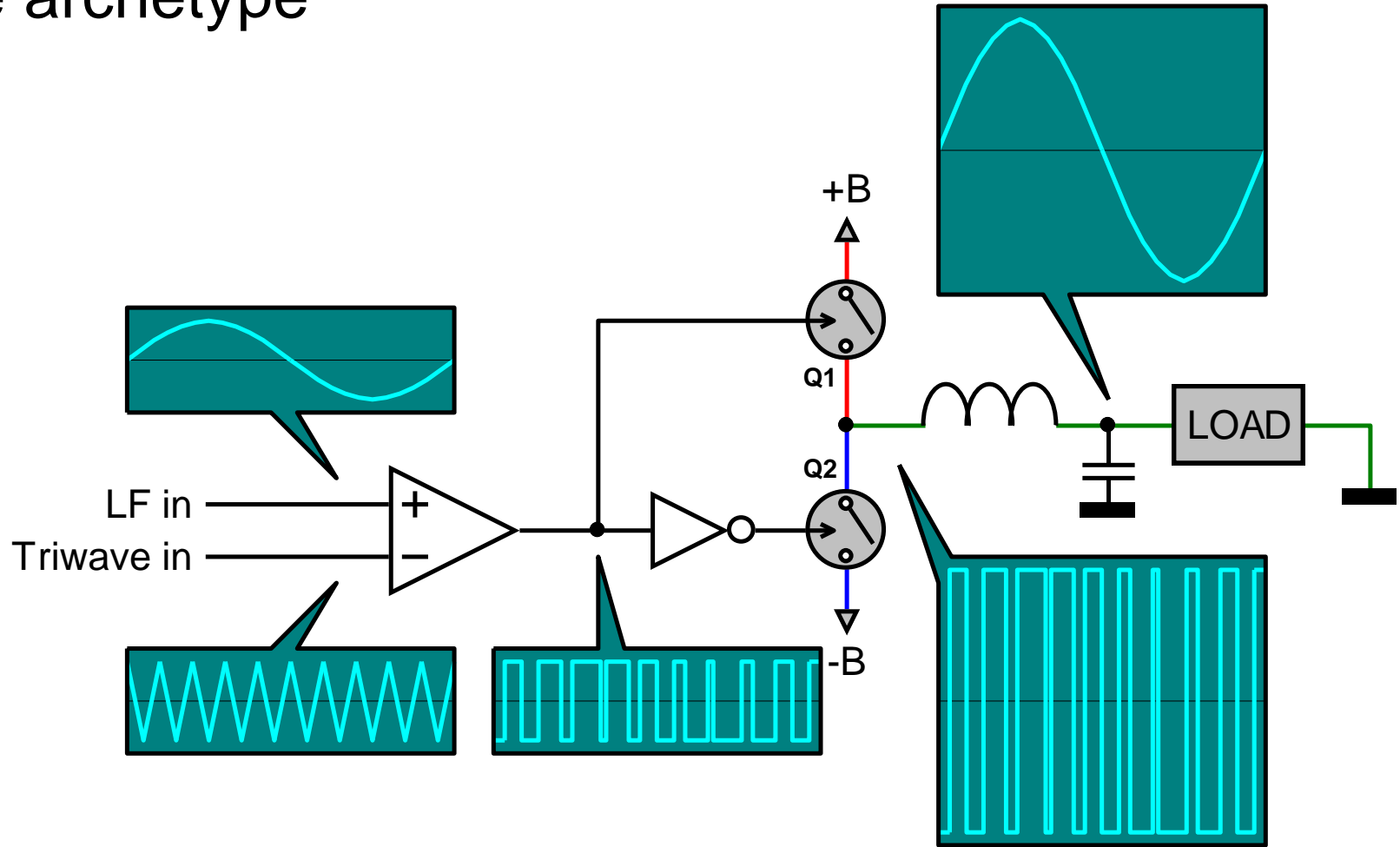
Definition

“Digital amplifier” is an oxymoron

- Voltage, current and time are physical quantities (analogue).
- Digital is strings of numbers.
- Speakers don't understand numbers.
- Class D requires analogue design skills to make work.
- DSP control may help solve or exacerbate analogue issues.

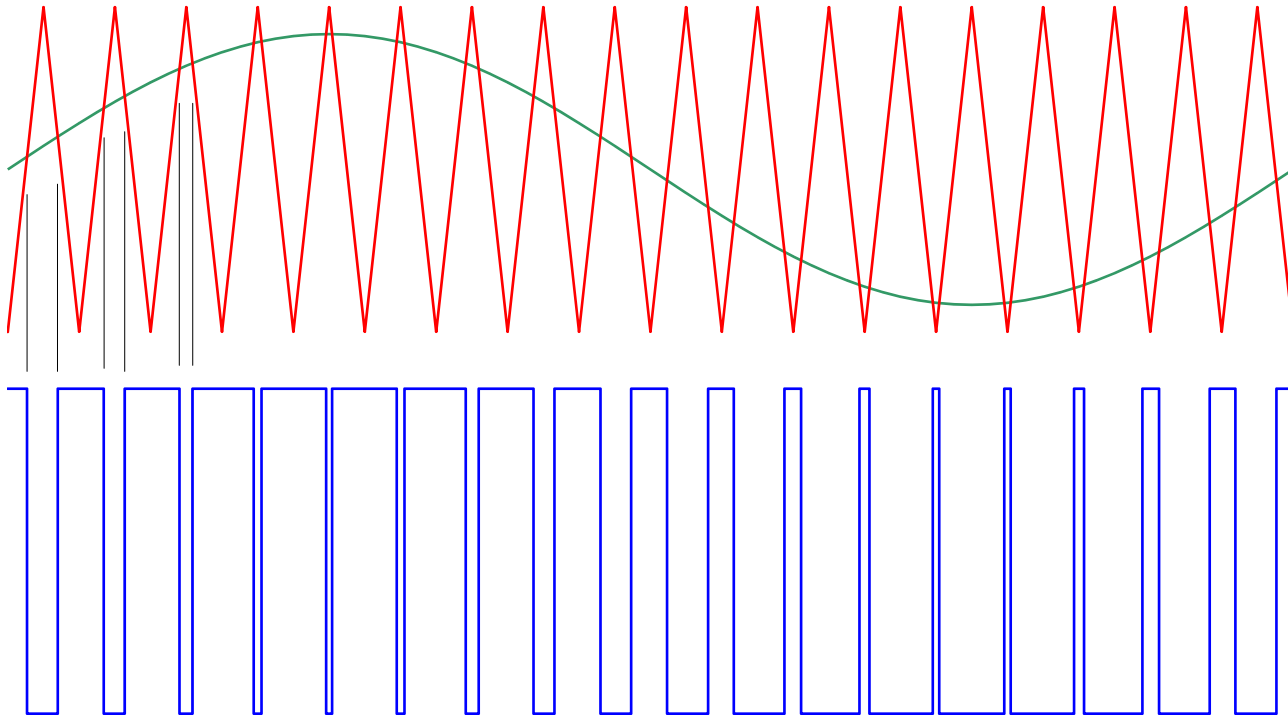
PWM basics

The archetype



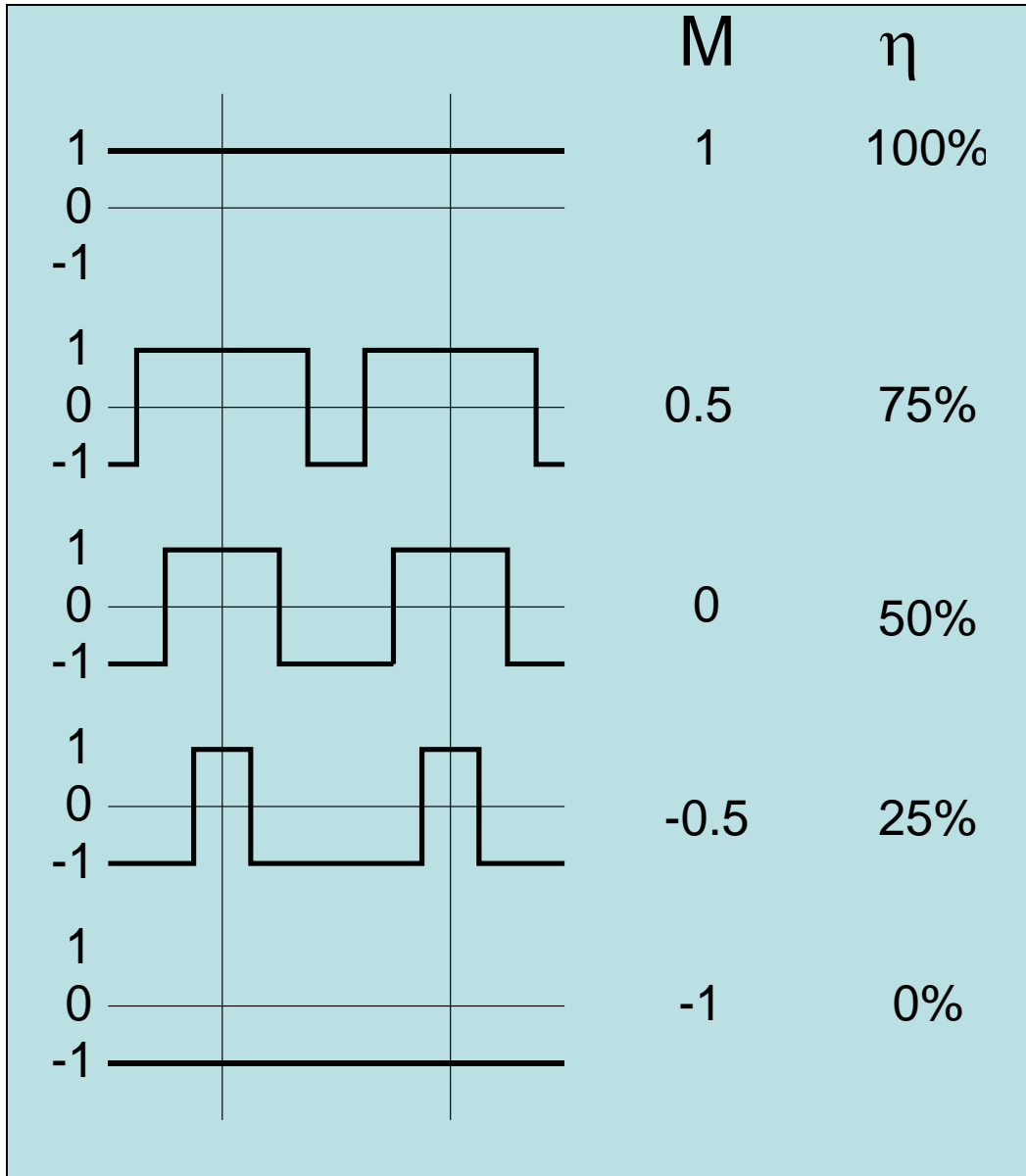
PWM basics

Two-state clocked PWM



$$A_v = \frac{V_{\text{PWM,pp}}}{V_{\text{tri,pp}}} = \frac{V_B - V_{-B}}{V_{\text{tri,pp}}}$$

Some conventions



$$t_{sw} = t_{on} + t_{off} = \frac{1}{f_s}$$

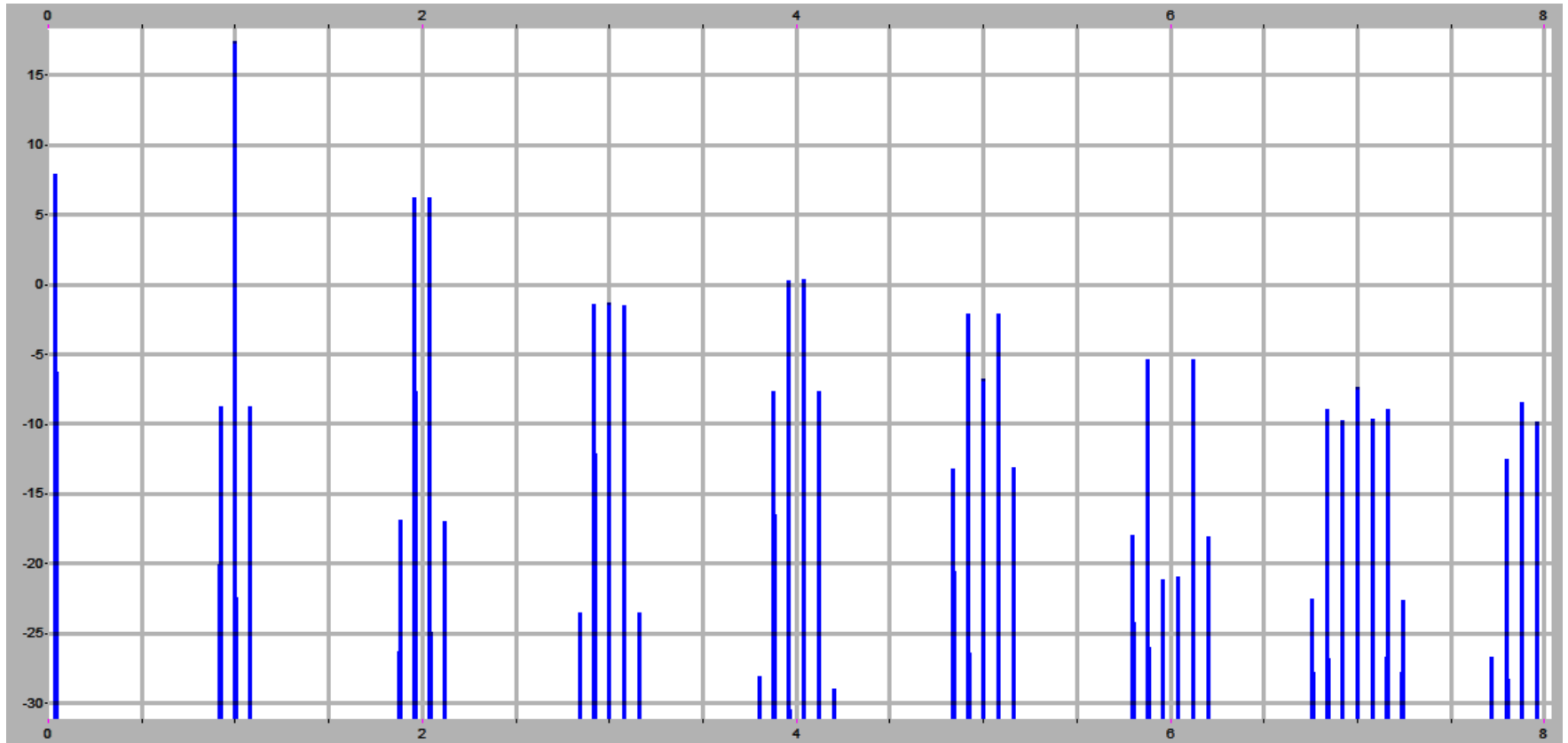
$$M = \frac{t_{on} - t_{off}}{t_{sw}}$$

$$\eta = \frac{t_{on}}{t_{sw}} \cdot 100\%$$

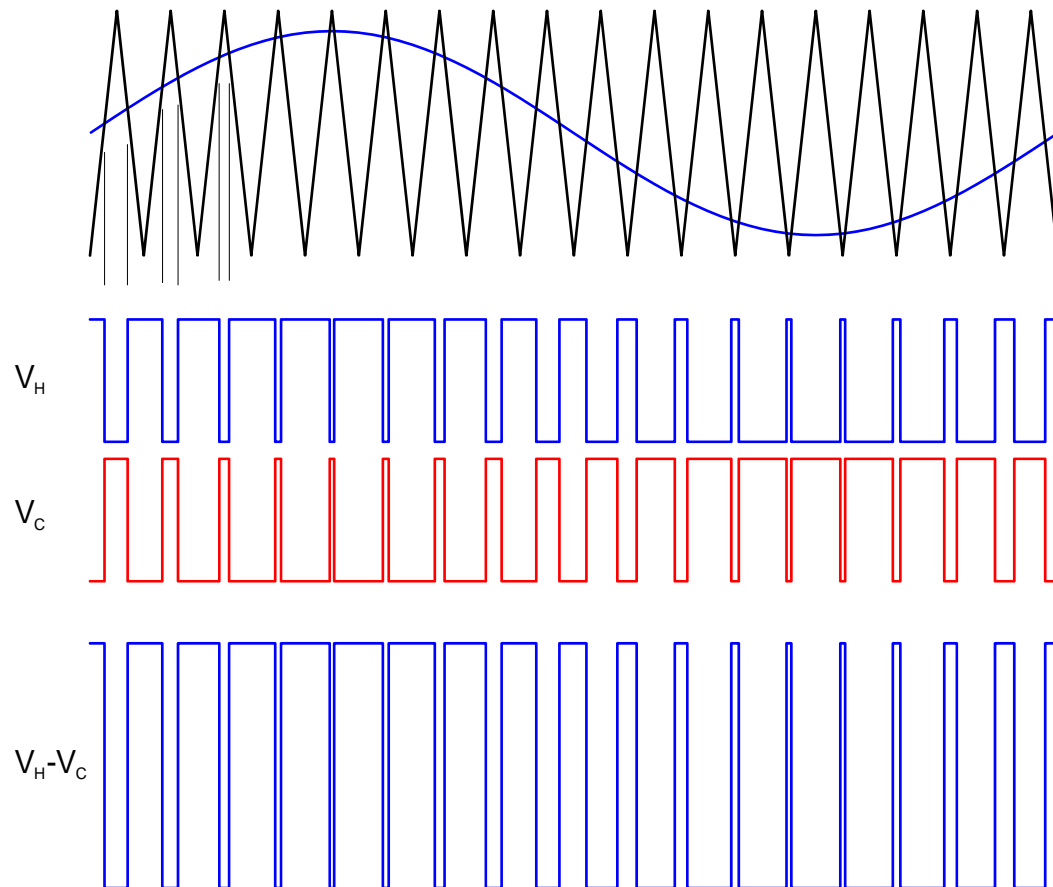
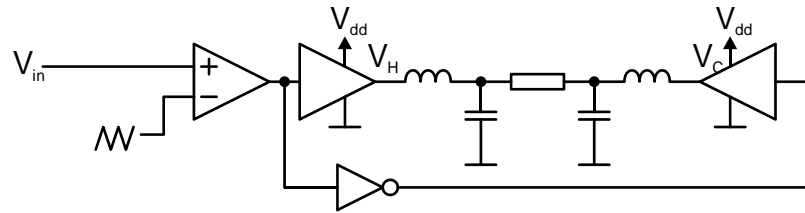
⇓

$$M = 2 \cdot \eta - 1$$

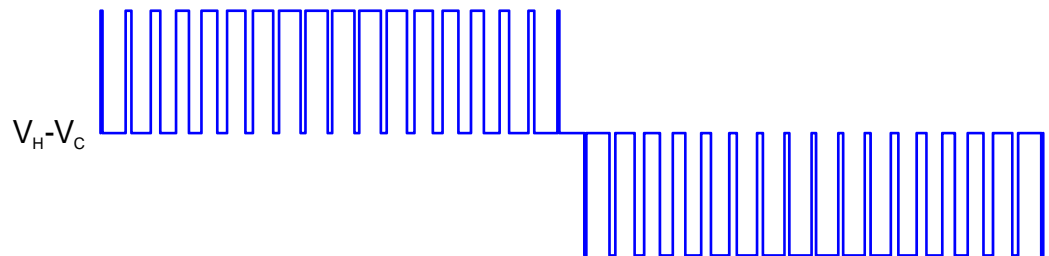
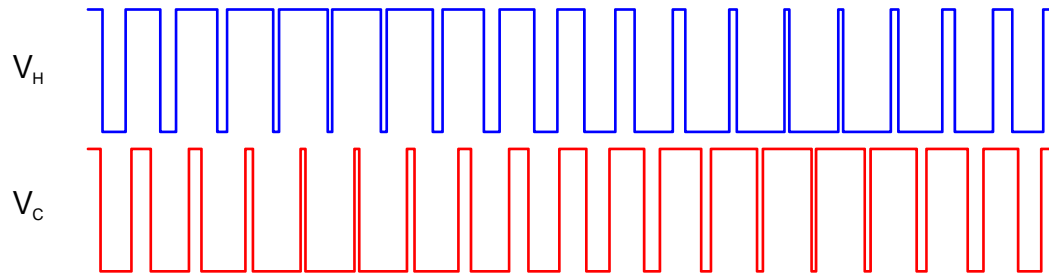
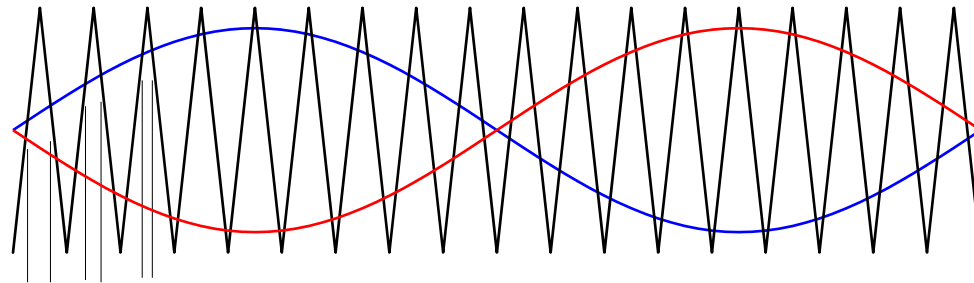
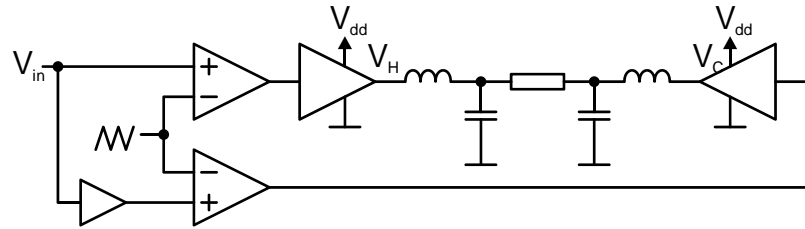
Spectrum of 2-state PWM



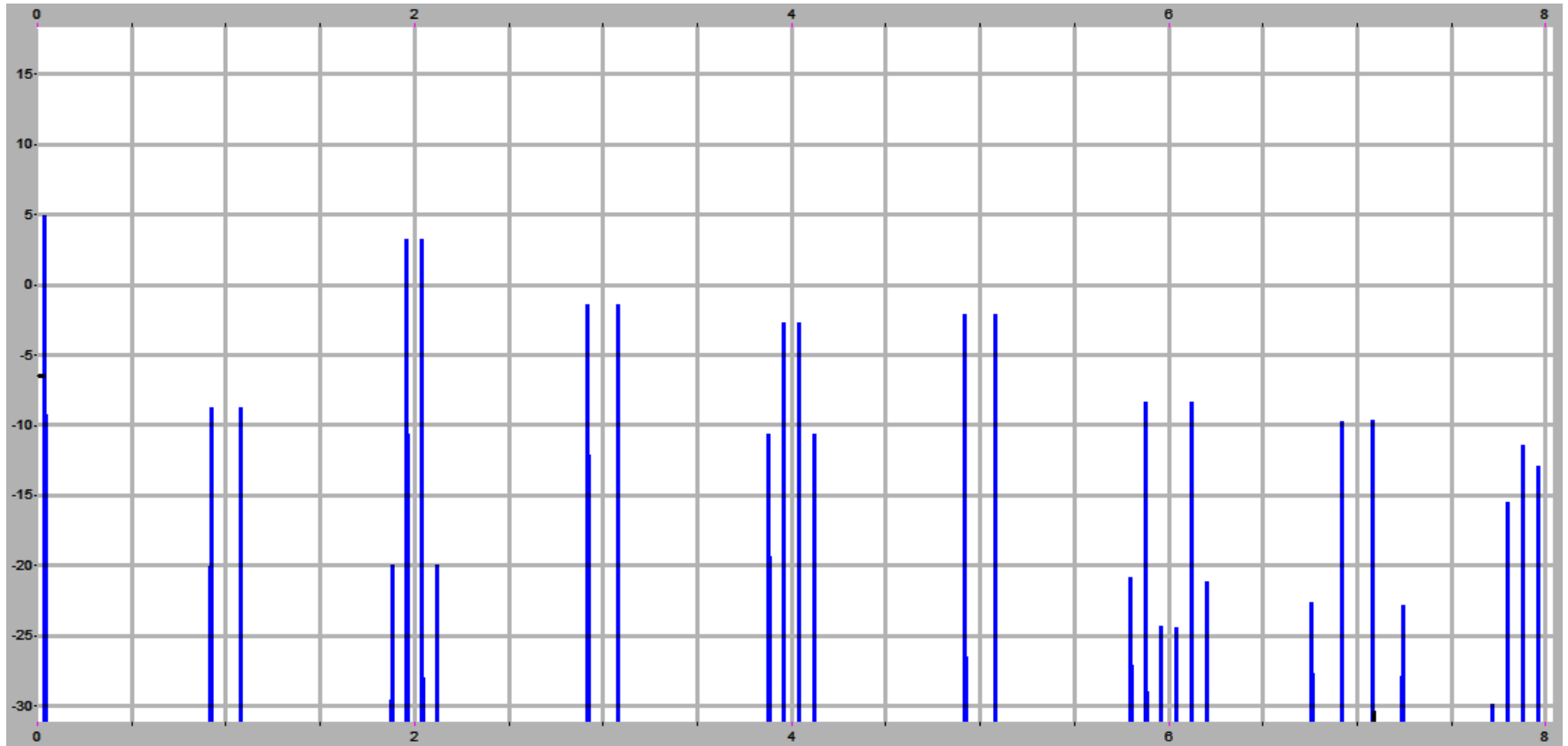
Full-Bridge amplifier in 2 state PWM



Three-state PWM (class BD)



Spectrum of 3-state PWM



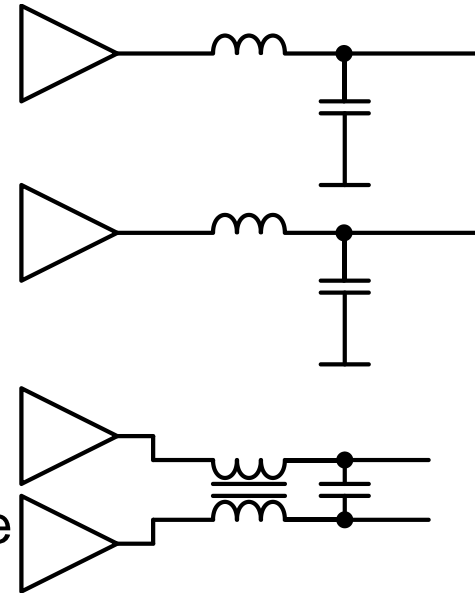
2-State vs 3-State

Three-state...

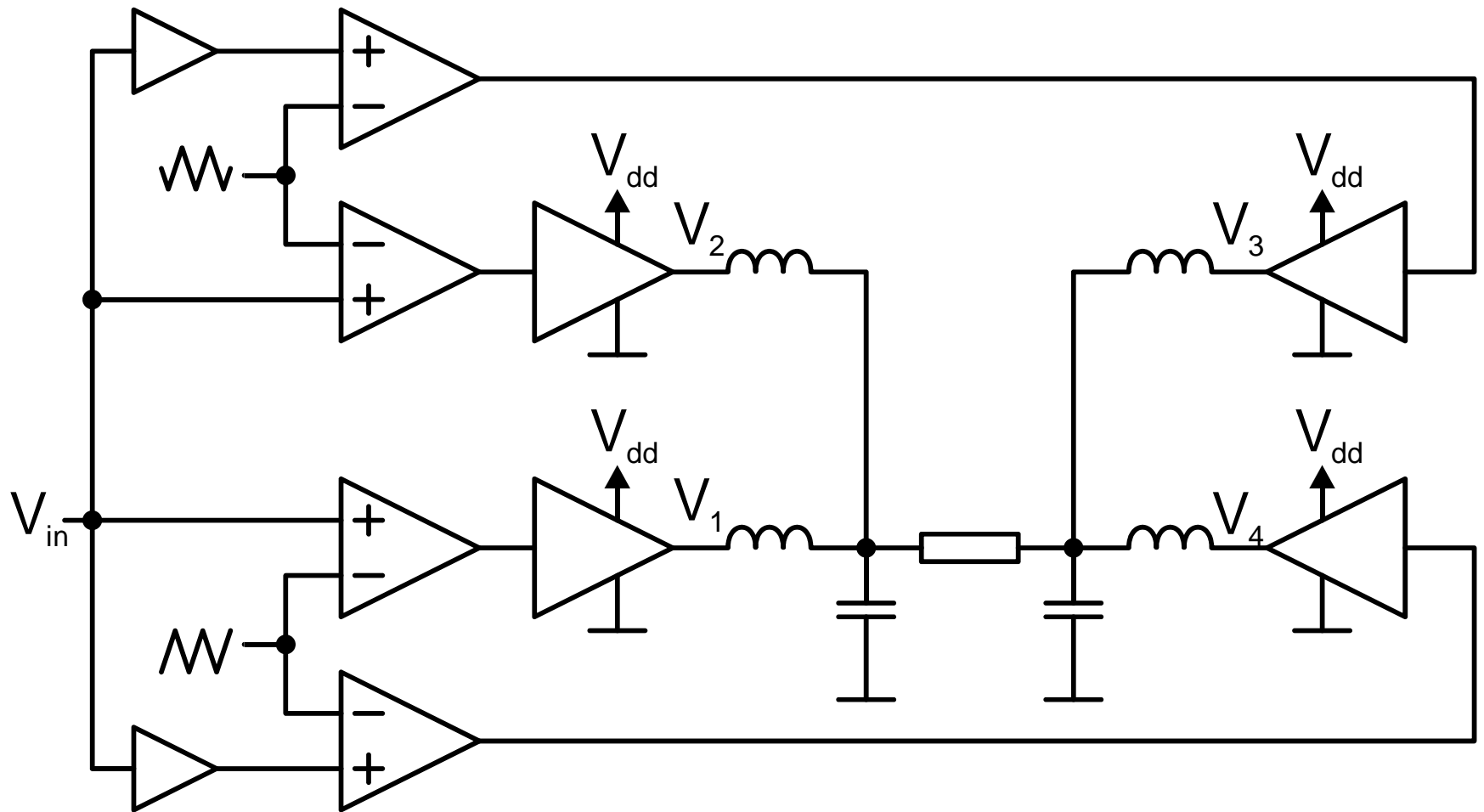
- doubles sampling rate
 - Better efficiency vs bandwidth
- halves open-loop error

Output filter?

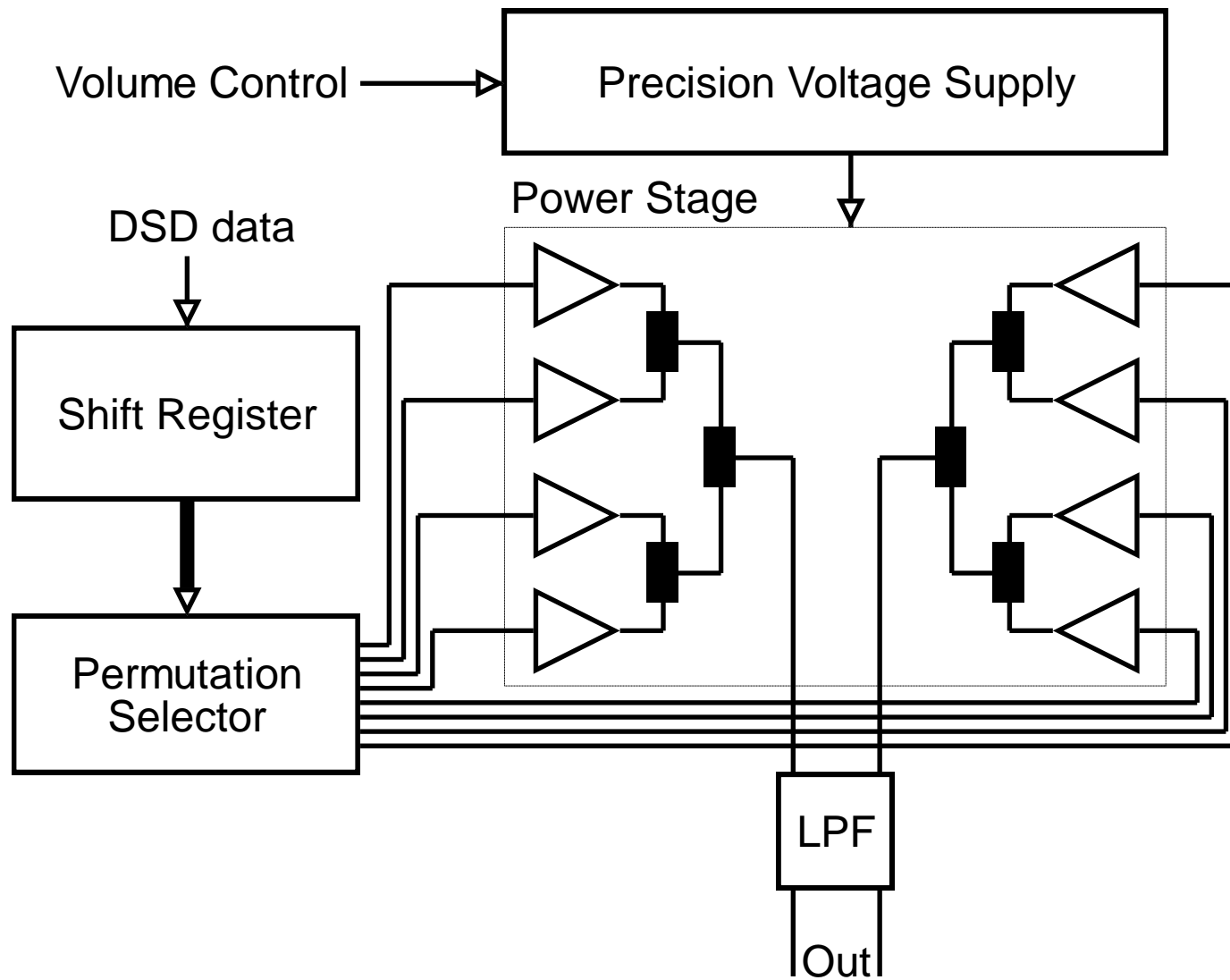
- Single-core
 - no excitation current
 - crossover distortion results
- Two-core
 - excitation current doubles for constant sampling rate



Yet More Phases

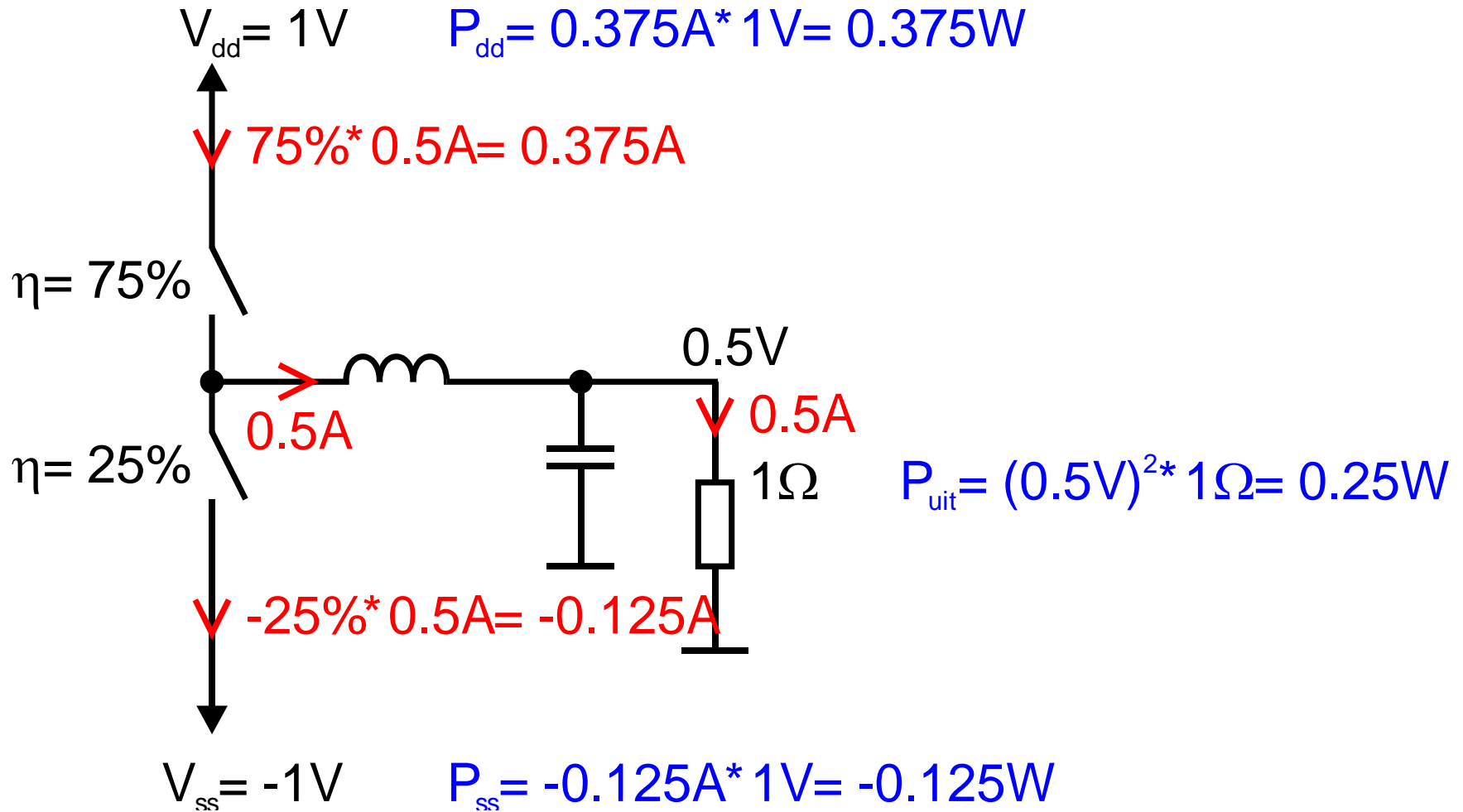


It can get worse...



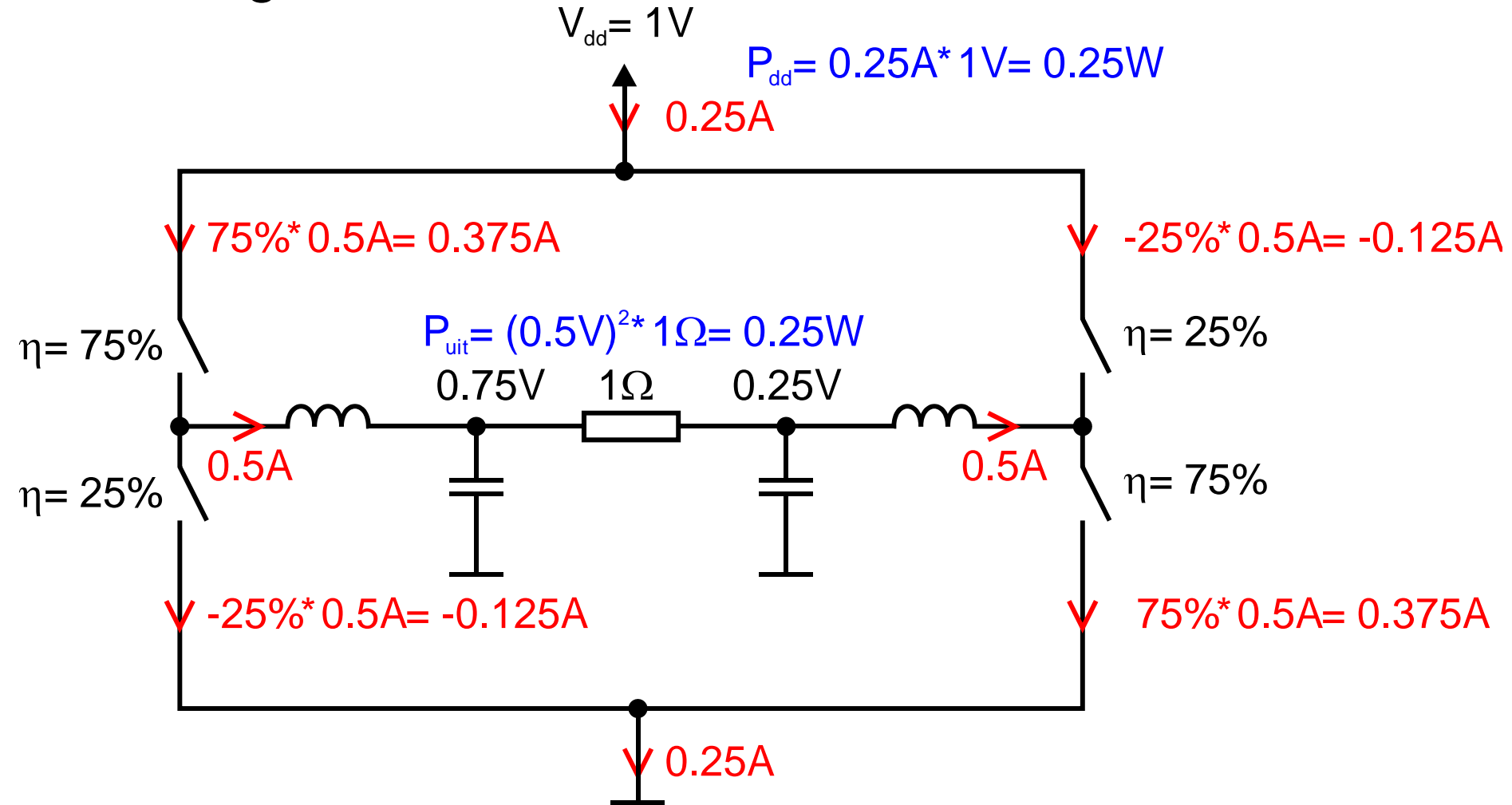
Class D as Power Converter

Half bridge



Class D as Power Converter

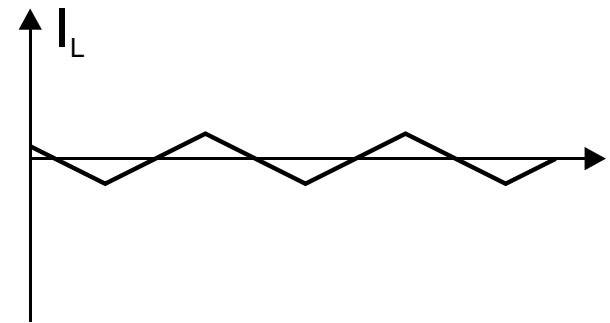
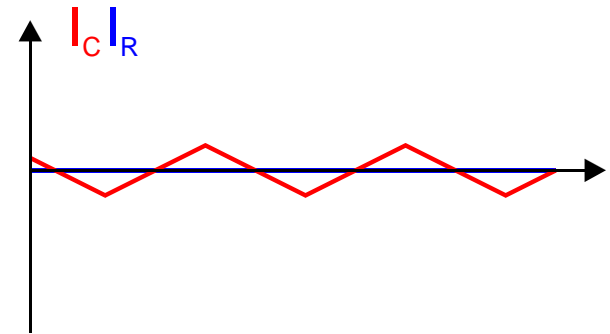
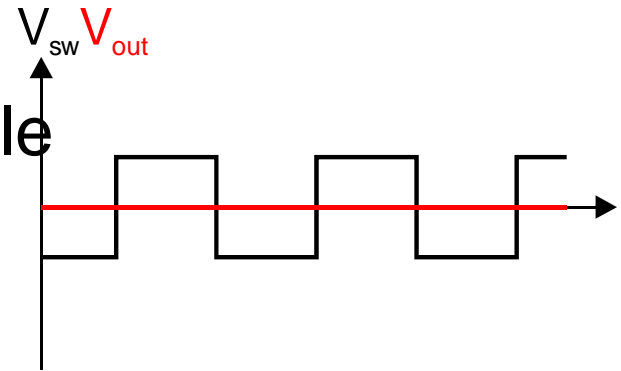
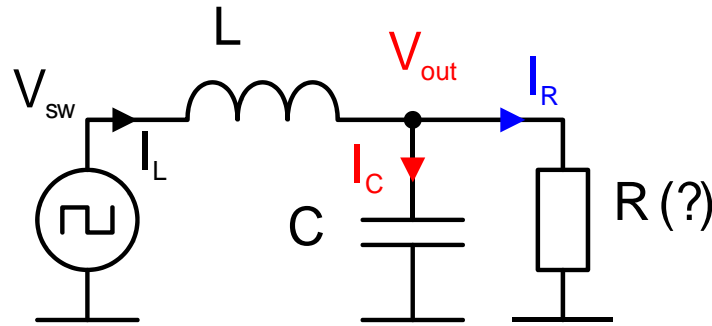
Full bridge



Inductor current

Small modulation index

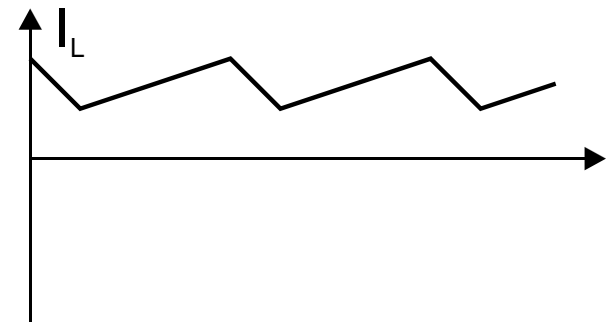
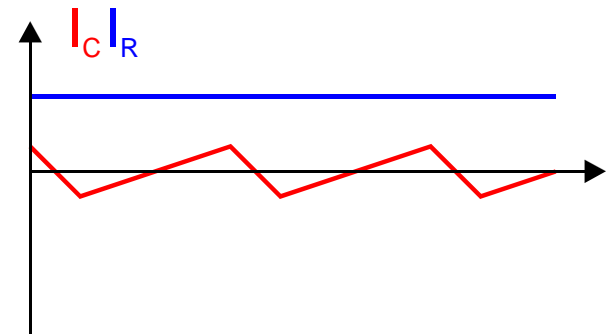
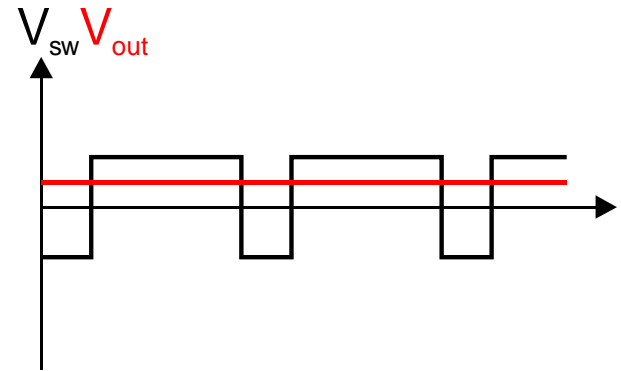
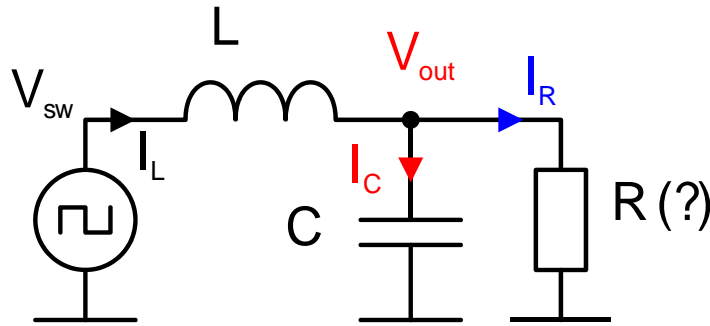
- Current changes sense every cycle



Inductor current

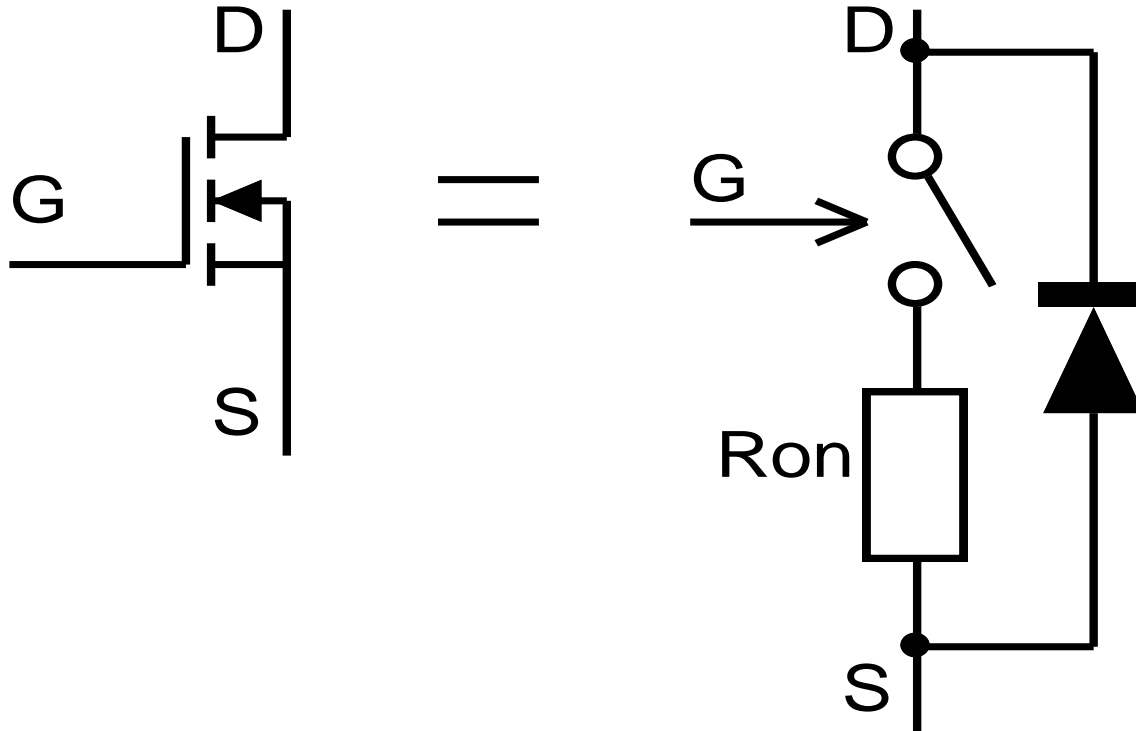
Large modulation index

- Current sense does not change



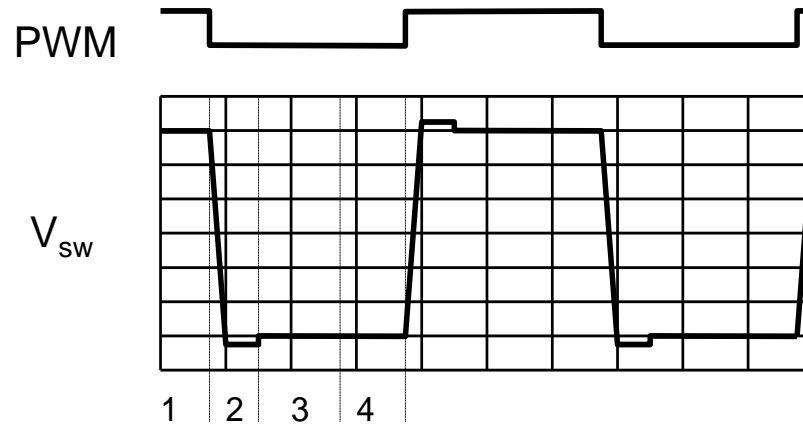
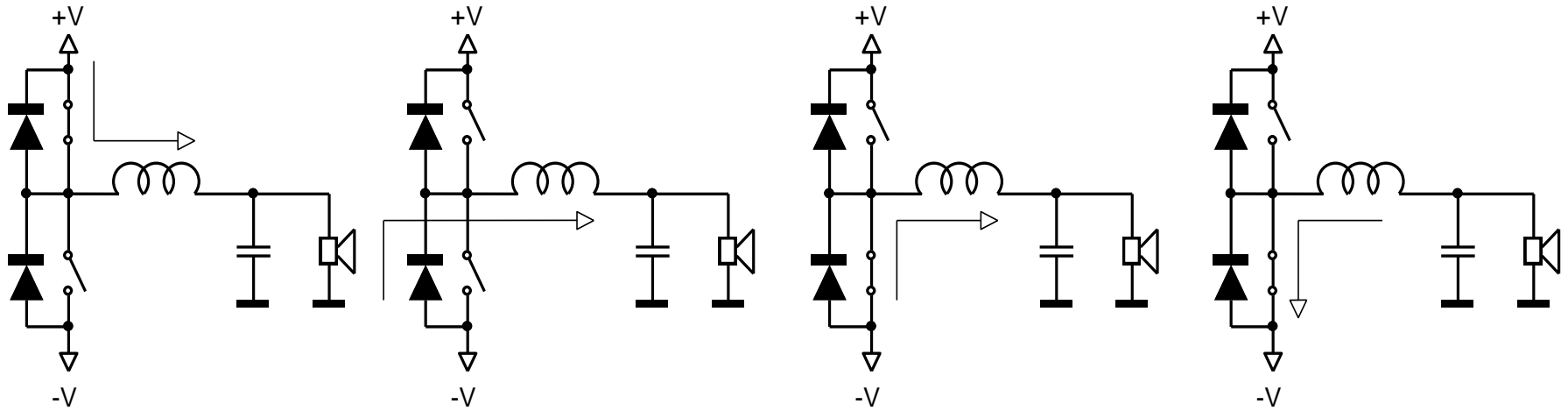
Dead time effects

Simplified MOSFET model



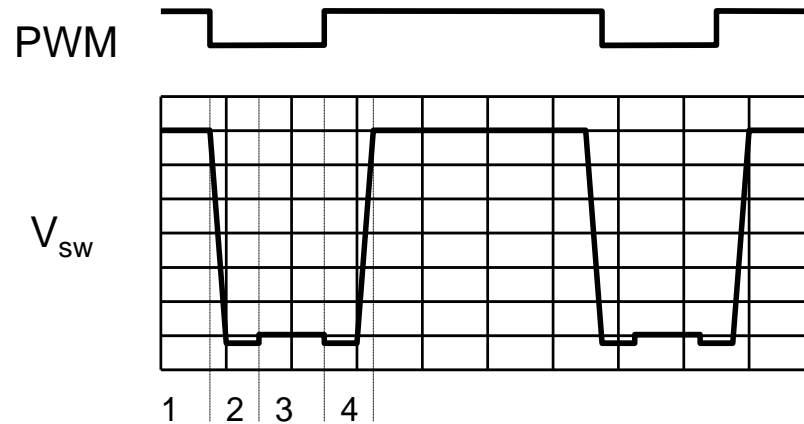
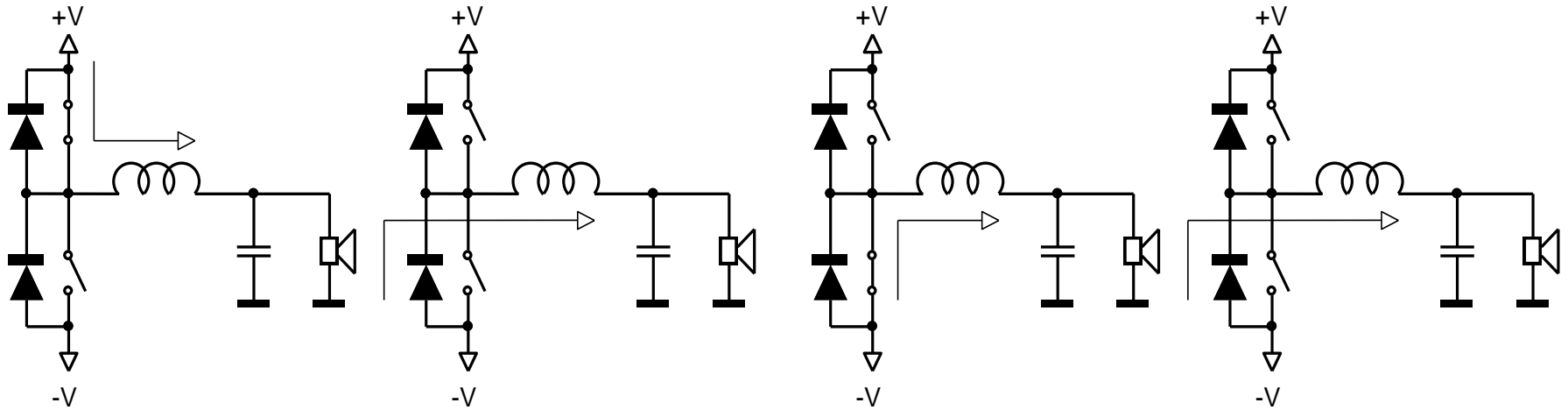
Dead time effects

Small modulation index

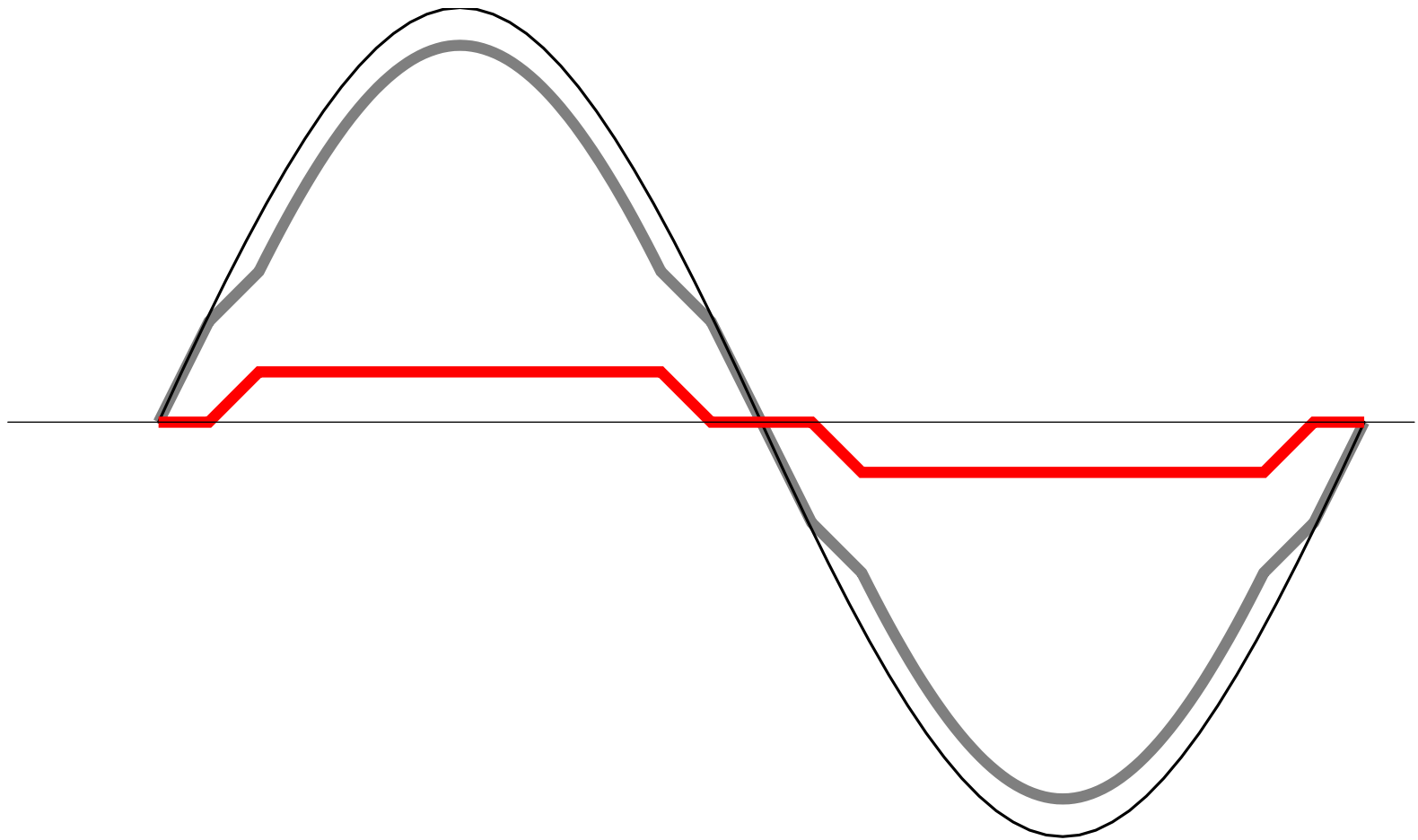


Dead time effects

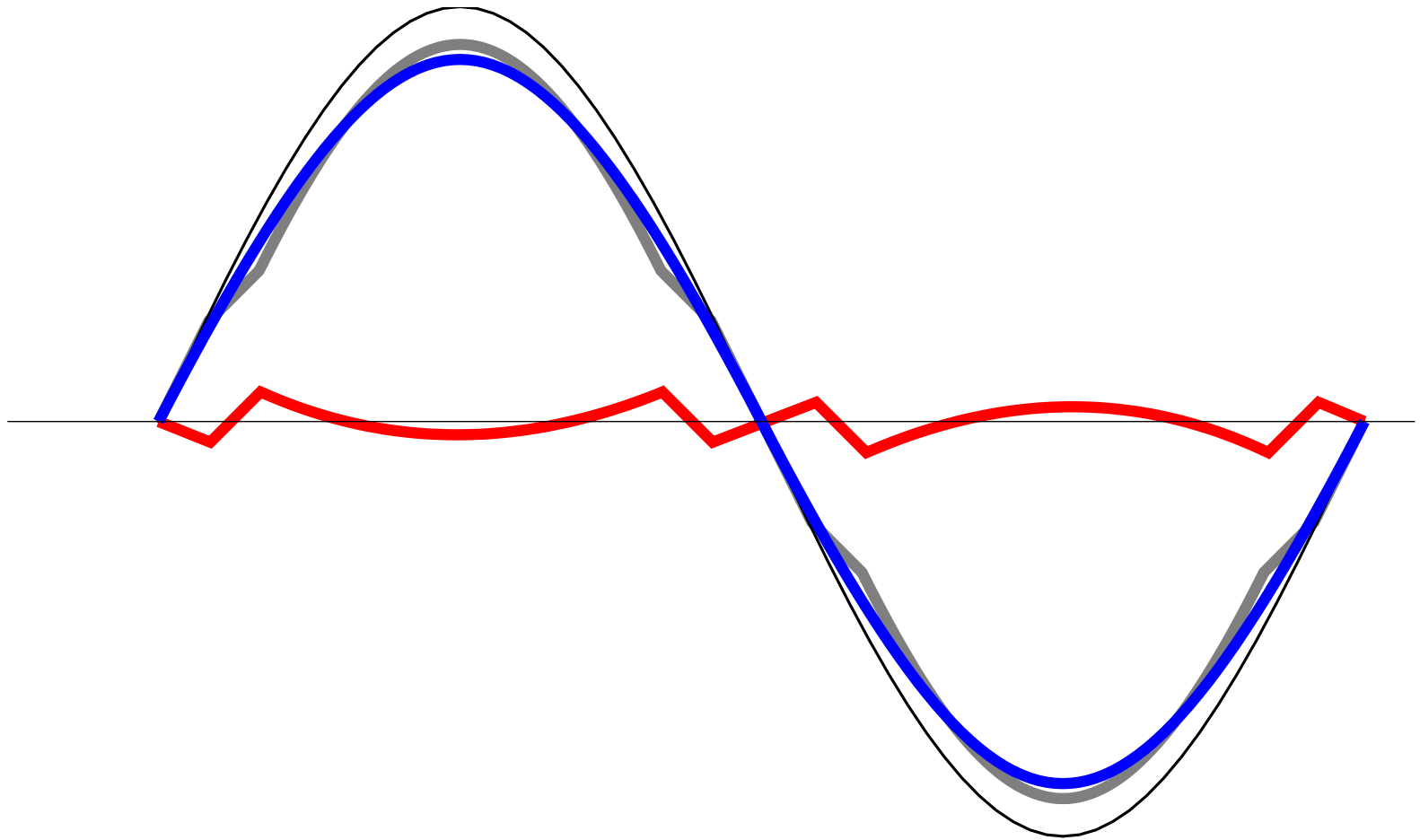
Large modulation index



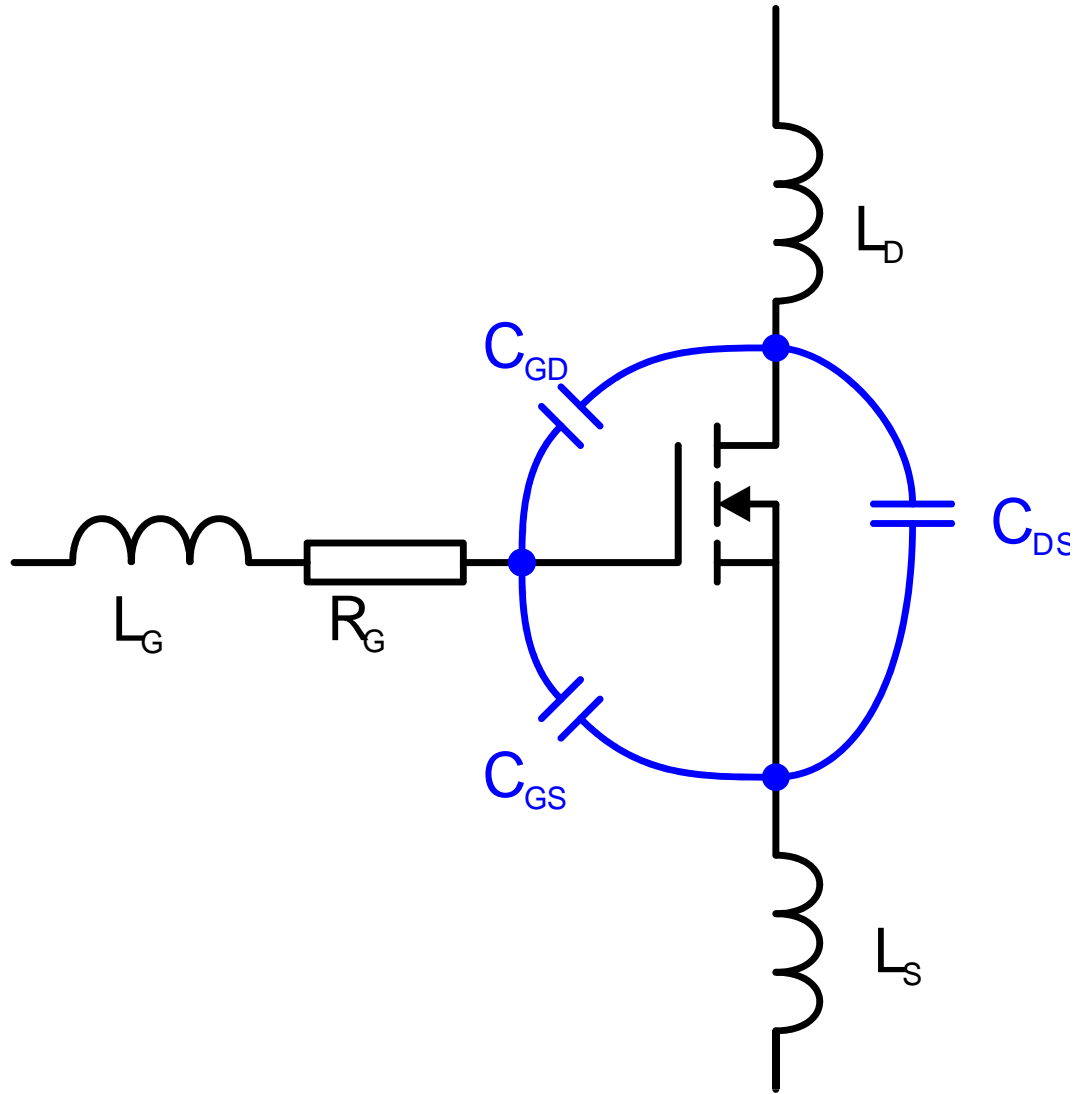
Open-Loop Distortion



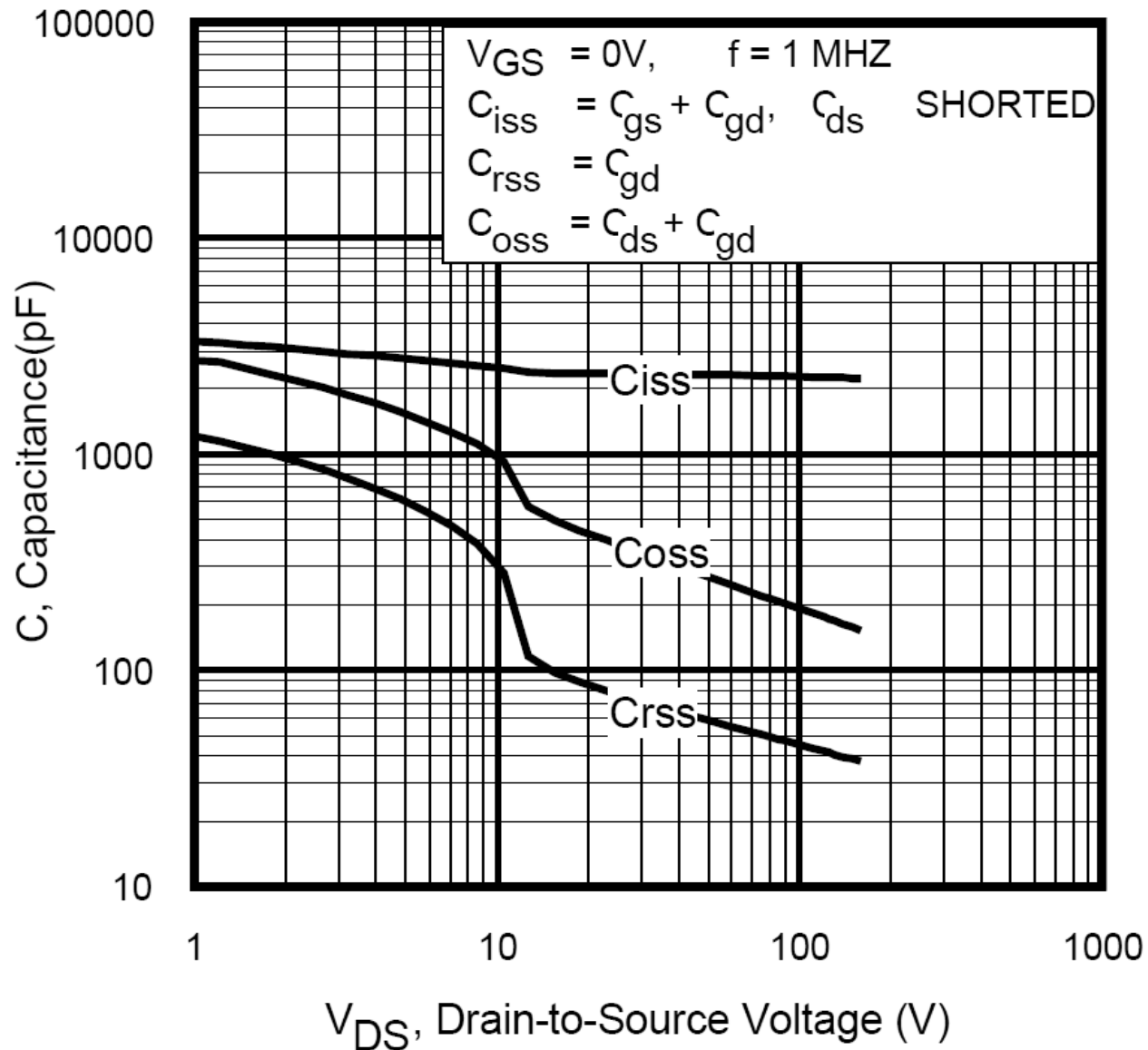
Analyser Reading



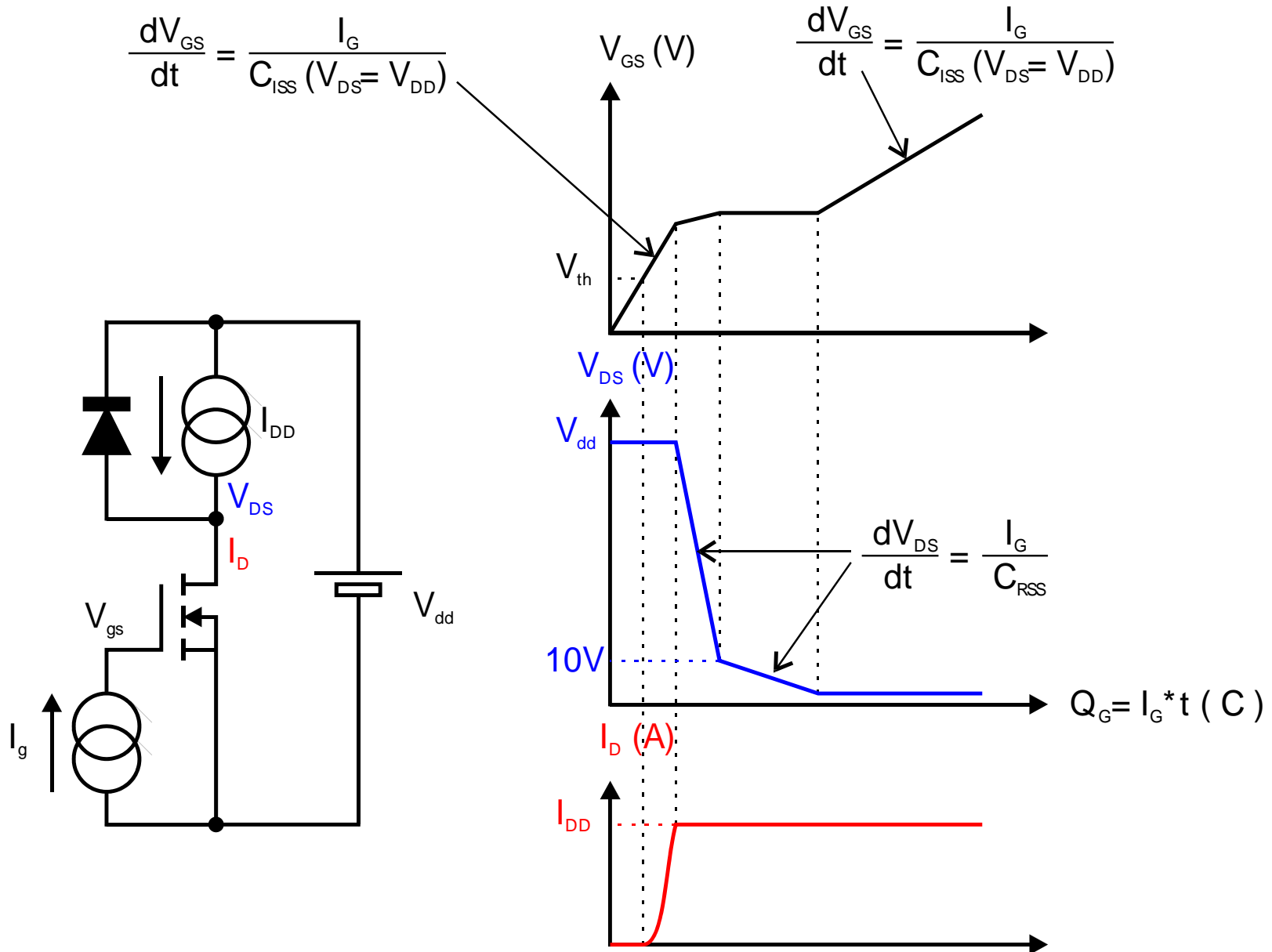
MOSFET parasitics



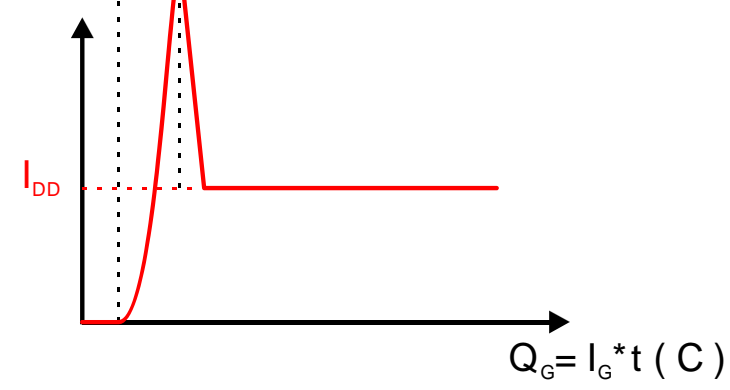
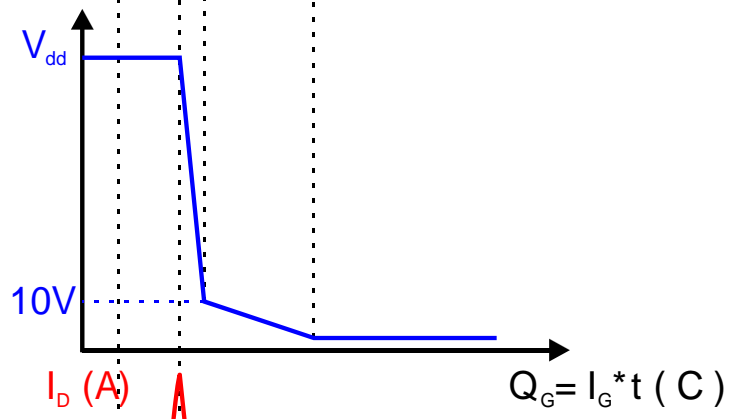
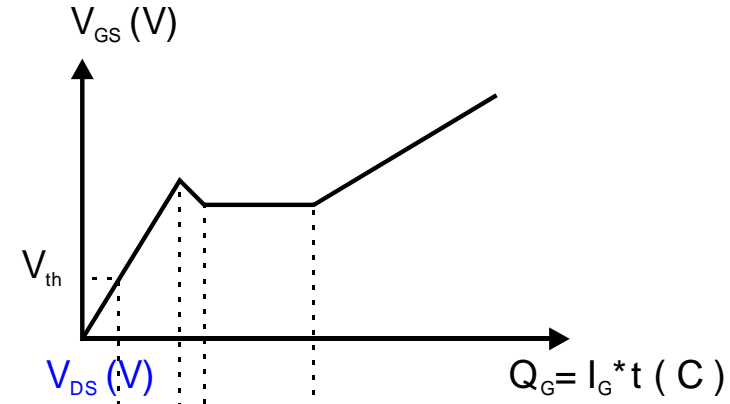
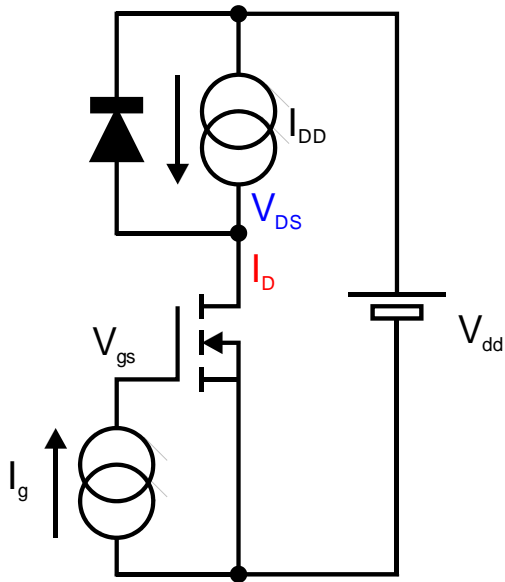
Parasitic capacitances



Gate Waveform (hard switching, ideal diode)



Gate Waveform (real diode)



Gate Gotchas

Until and during recovery

- Dissipated power = $V_{cc} \cdot Q_{rr}$
- $V_{ds} = V_{cc}$
- Gate capacitance is low
- But we'd like to go slow

After recovery

- $V_{ds} < V_{gs}$
- Gate capacitance is high
- Dissipated power = $V_{ds} \cdot I_d \cdot \text{time}$
- We'd like to finish quickly

Current limiting gate driver works the wrong way round.

Output filter

Desired function

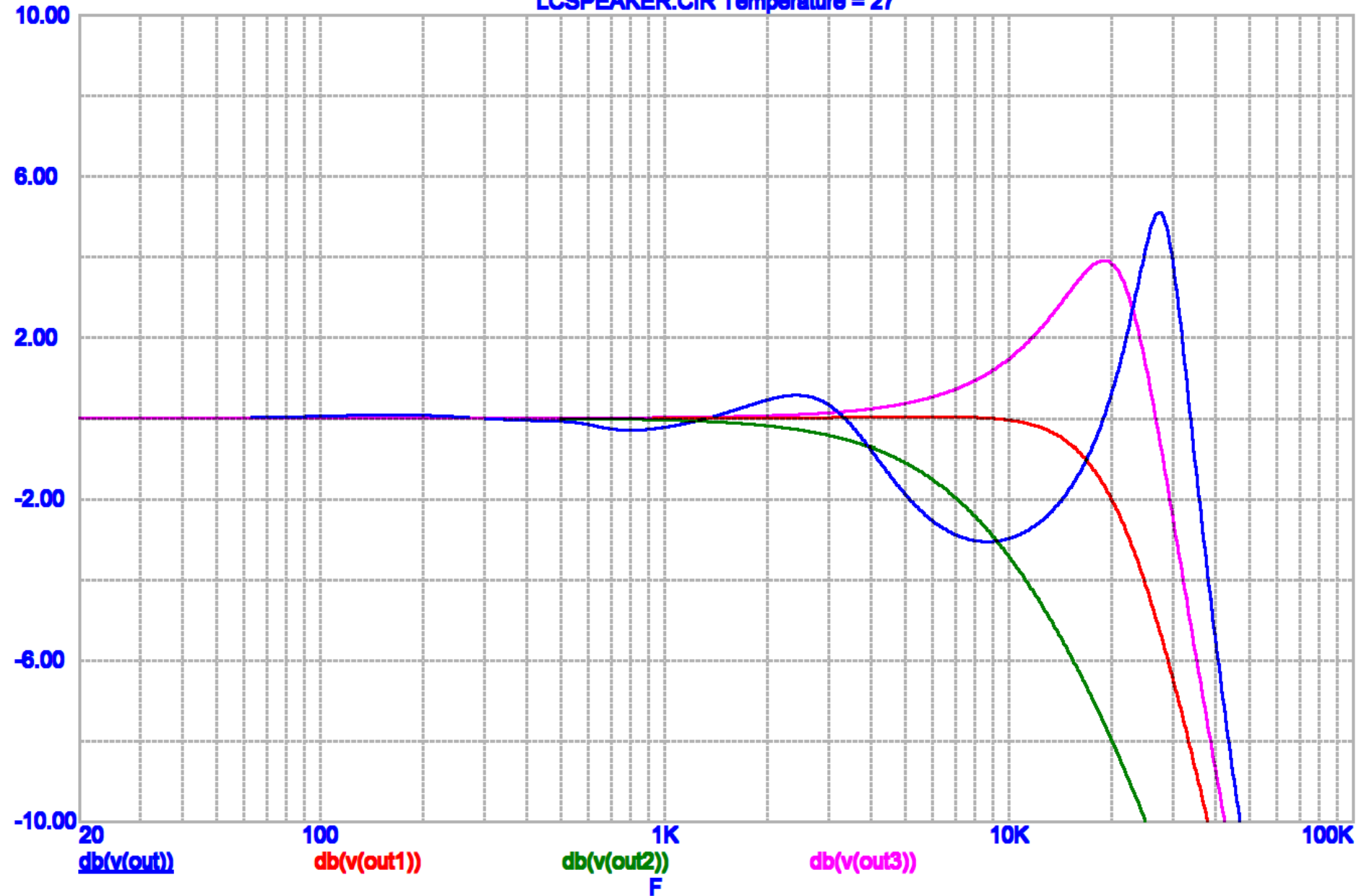
- Attenuate the carrier

Undesired functions

- Restrict bandwidth
- Increase output impedance
- Modify the frequency response
- Add distortion

Load response of 2nd order LPF

LCSPEAKER.CIR Temperature = 27



Output Filter

The optimisation problem

- Reduce Z_{out} \rightarrow Increase f_c \rightarrow Reduce attenuation
- Improve Bandwidth \rightarrow Increase f_c \rightarrow Reduce attenuation
- Improve Flatness \rightarrow Increase f_c \rightarrow Reduce attenuation
- Reduce distortion \rightarrow Reduce L \rightarrow Reduce attenuation

The root cause

- Controlled variable is an internal node
- Output voltage is uncontrolled

Summary of (analogue!) nonidealities

Power Supply Rejection

- PWM power stage is an AM modulator

Switch Timing

- Dead time causes distortion

Output Filter

- Output impedance is infinity at f_c
- Inductor is non-linear

Feedback

Solves many problems at once

- Output impedance (post LPF only)
- Distortion
- Frequency response (post LPF only)

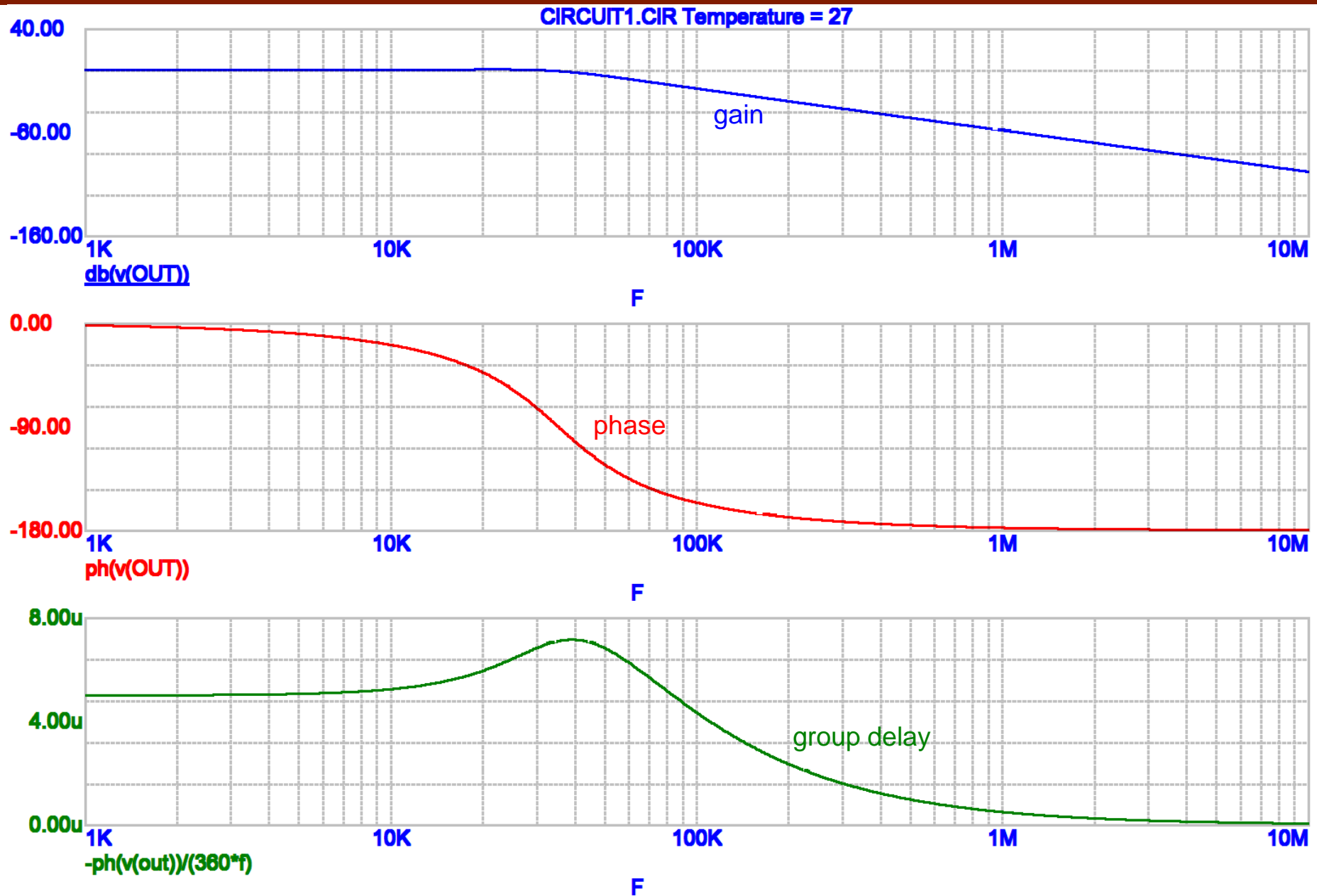
Why many don't use it

- Audio folk lore
 - “Feedback sounds bad”
 - “Class D is Digital”

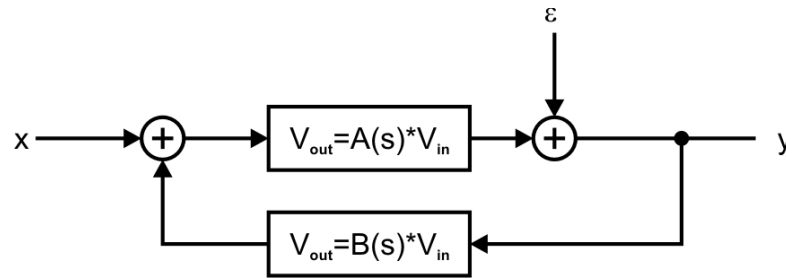
Why global feedback is even rarer

- LC phase shift considered “insurmountable”
- No “rules of thumb”

Delay in the LC filter?



Some control theory basics



$$y = \varepsilon + A(s) \cdot (x + B(s) \cdot y)$$

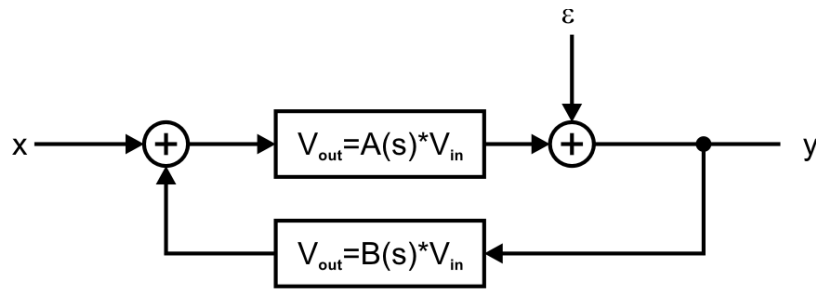
\Leftrightarrow

$$y - A(s) \cdot B(s) \cdot y = \varepsilon + A(s) \cdot x$$

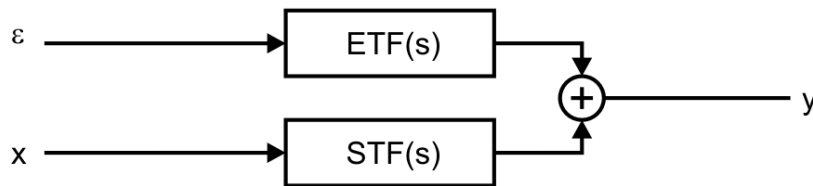
\Leftrightarrow

$$y = \frac{\varepsilon + A(s) \cdot x}{1 - A(s) \cdot B(s)} = \frac{\varepsilon}{1 - A(s) \cdot B(s)} + \frac{A(s) \cdot x}{1 - A(s) \cdot B(s)}$$

ETF & STF



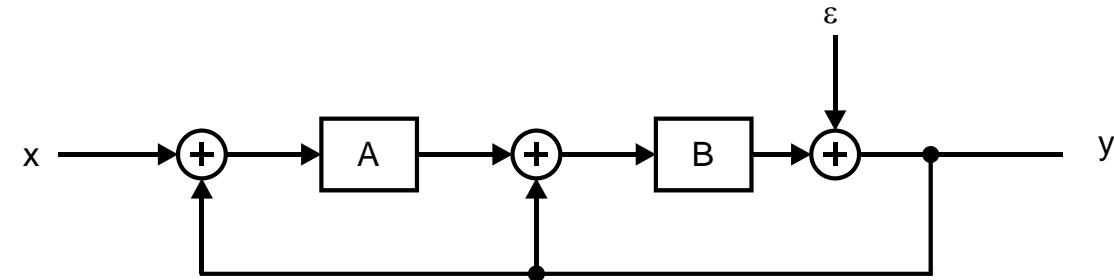
||



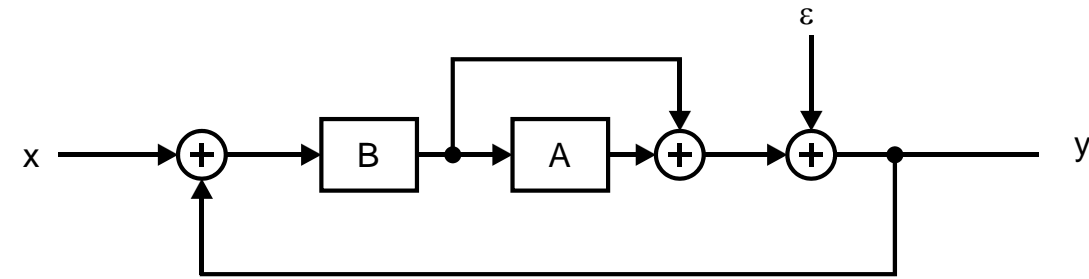
$$ETF(s) = \frac{1}{1 - A(s) \cdot B(s)}$$

$$STF(s) = \frac{A(s)}{1 - A(s) \cdot B(s)}$$

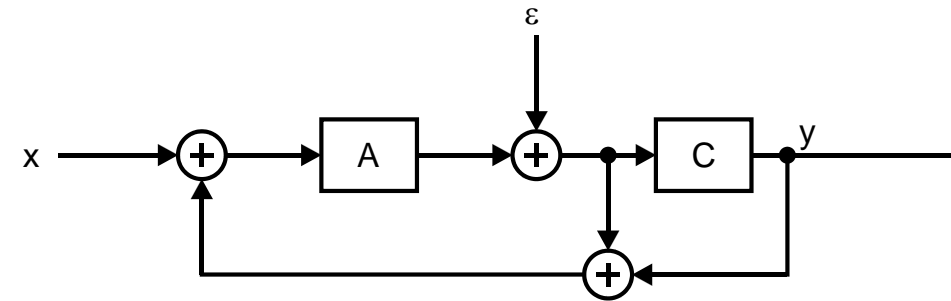
Various permutations



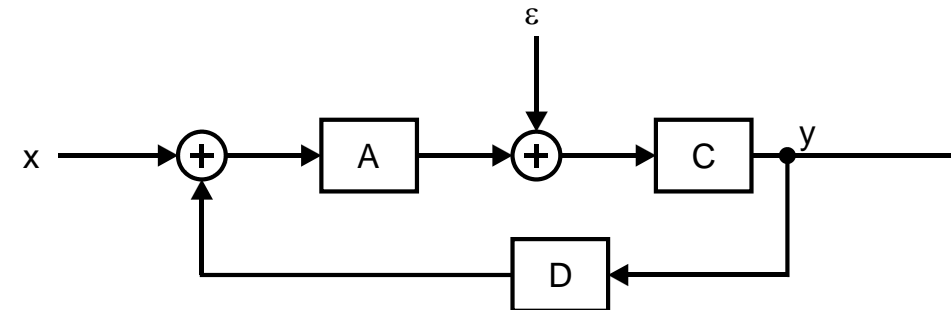
$$y = \frac{A \cdot B}{1 - B - A \cdot B} \cdot x + \frac{1}{1 - B - A \cdot B} \cdot \varepsilon$$



$$y = \frac{B + A \cdot B}{1 - B - A \cdot B} \cdot x + \frac{1}{1 - B - A \cdot B} \cdot \varepsilon$$

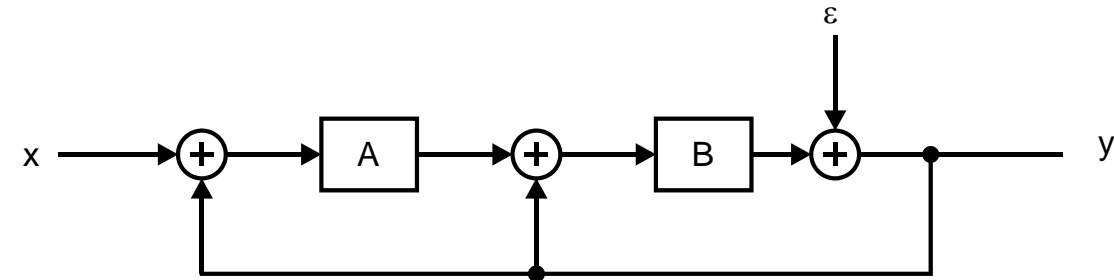


$$y = \frac{A \cdot C}{1 - A - A \cdot C} \cdot x + C \cdot \frac{1}{1 - A - A \cdot C} \cdot \varepsilon$$



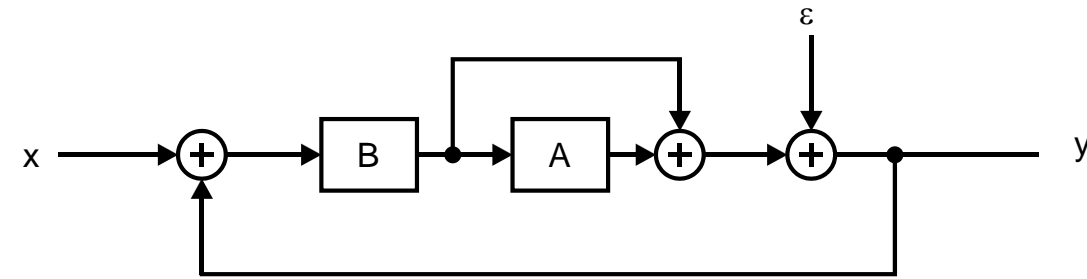
$$y = \frac{A \cdot C}{1 - A \cdot C \cdot D} \cdot x + C \cdot \frac{1}{1 - A \cdot C \cdot D} \cdot \varepsilon$$

Various permutations



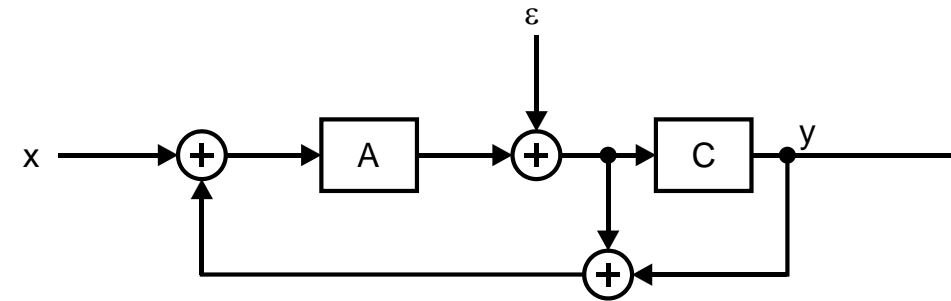
$$A_L = B + A \cdot B$$

$$y = \frac{A \cdot B}{1 - A_L} \cdot x + \frac{1}{1 - A_L} \cdot \varepsilon$$



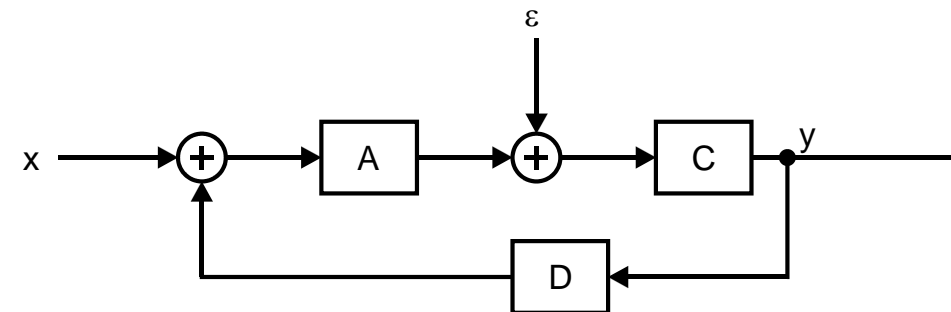
$$A_L = B + A \cdot B$$

$$y = \frac{A_L}{1 - A_L} \cdot x + \frac{1}{1 - A_L} \cdot \varepsilon$$



$$A_L = A + A \cdot C$$

$$y = \frac{A \cdot C}{1 - A_L} \cdot x + C \cdot \frac{1}{1 - A_L} \cdot \varepsilon$$



$$A_L = A \cdot C \cdot D$$

$$y = \frac{A \cdot C}{1 - A_L} \cdot x + C \cdot \frac{1}{1 - A_L} \cdot \varepsilon$$

Loop needs

ETF must be stable and not have excessive gain

- Poles well left of imaginary axis

ETF must have very low gain in audio band

- Zeros close to or on imaginary axis

Loop function A_L

- Loop poles=zeros of ETF
- Loop zeros must be freely settable

Universal loop control function

If A_L ...

- has n poles and $n-1$ zeros
- has independantly settable zeros

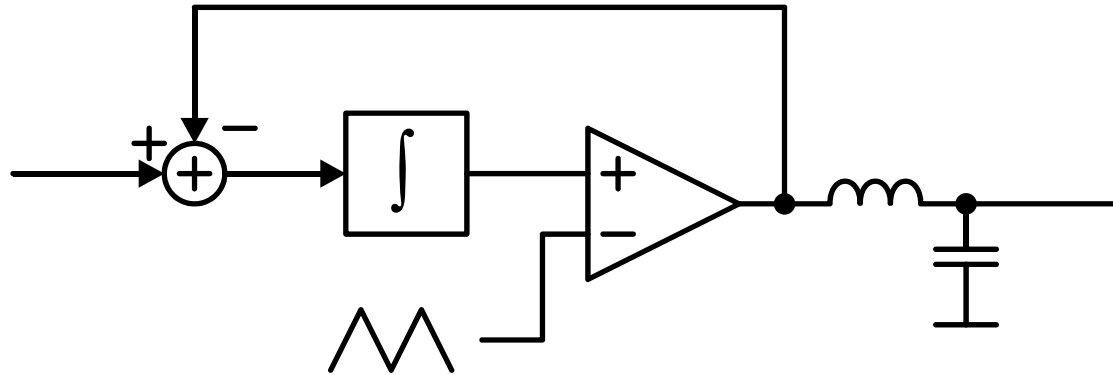
...then

- a stable loop is always possible

$$A_L(s) = k \cdot \frac{\prod_{i=1}^{n-1} (s - z_i)}{\prod_{i=1}^n (s - p_i)} = \frac{\sum_{i=0}^{n-1} a_i \cdot s^i}{\sum_{i=0}^n b_i \cdot s^i}$$

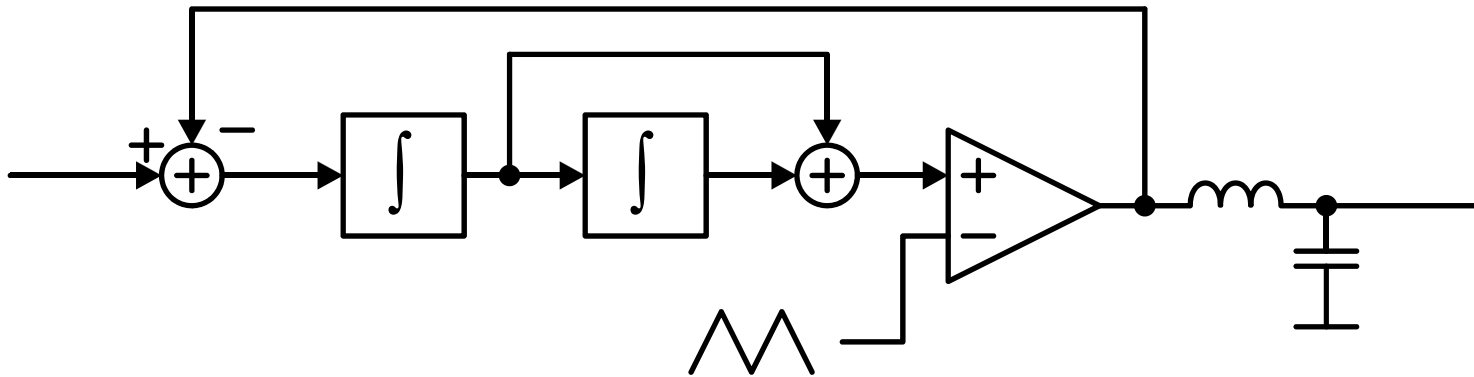
Typical loops

1 pole, no zeros, pre-filter f/b only



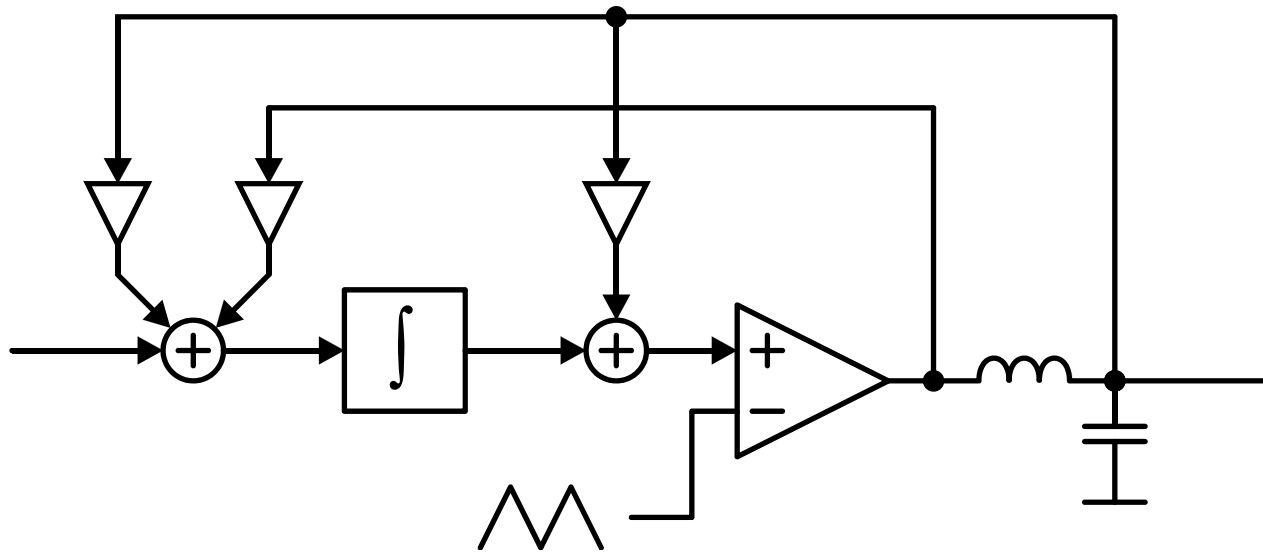
Typical loops

2 poles, 1 zero, pre-filter f/b only



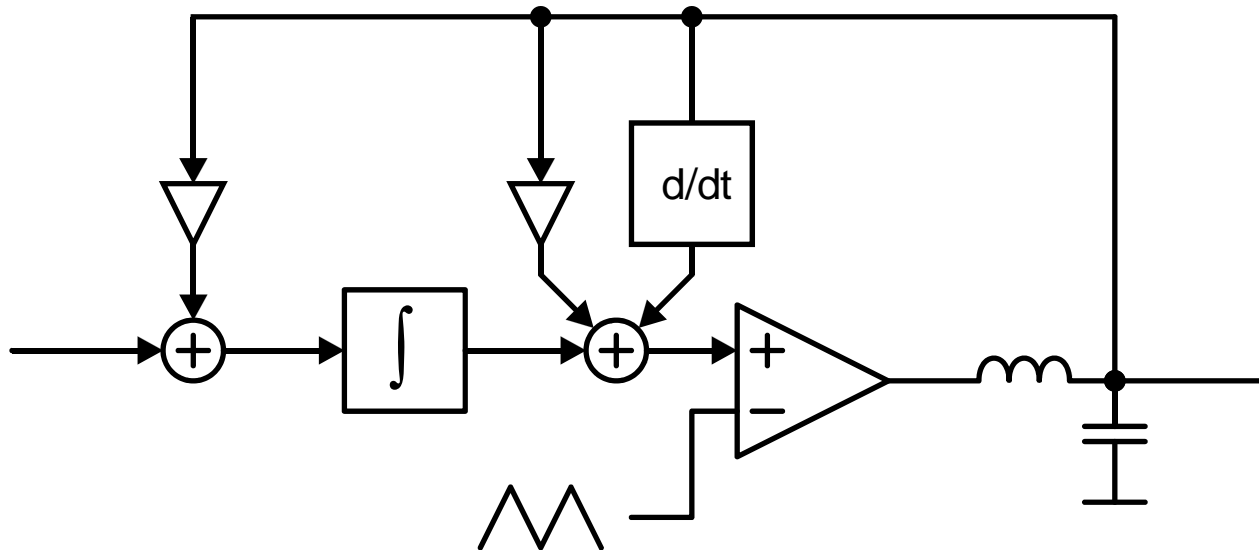
Typical loops

3 poles, 2 zeros, mixed feedback



Typical loops

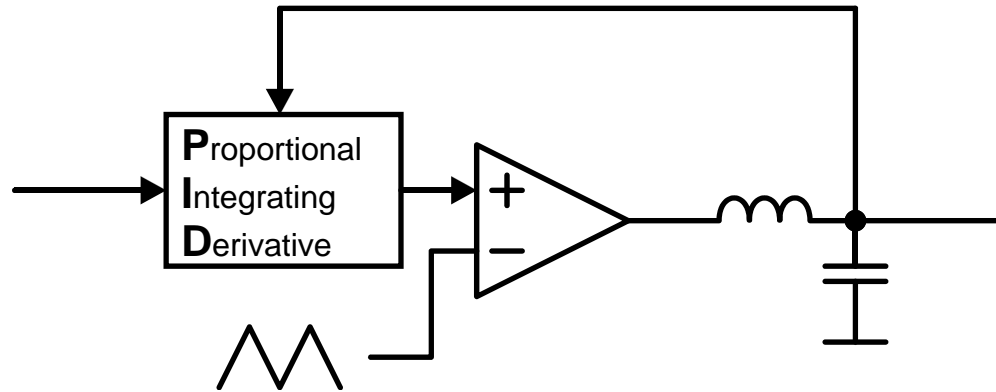
3 poles, 2 zeros, global feedback



...also known as...:

Typical loops

...PID!



PI(I...)D control for global loops

Pro

- Very low output impedance
- Minimum 3rd order loop
 - Large loop gain
- Nonlinear distortion from inductor is reduced
- Known art

Contra

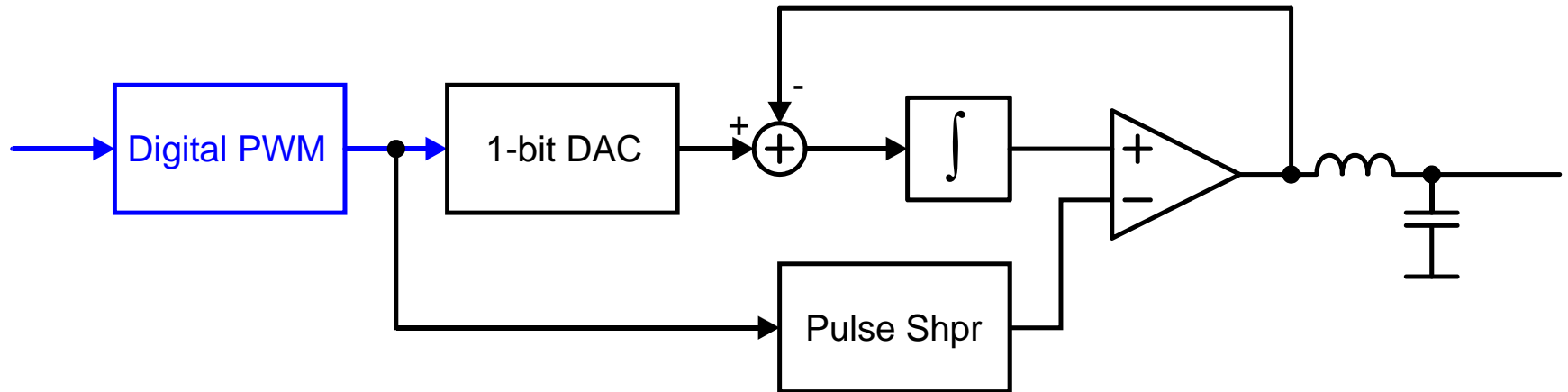
- Can't get away with bad PCB layout

No good excuses for not using global feedback

Pre-LC and mixed f/b are provably suboptimal

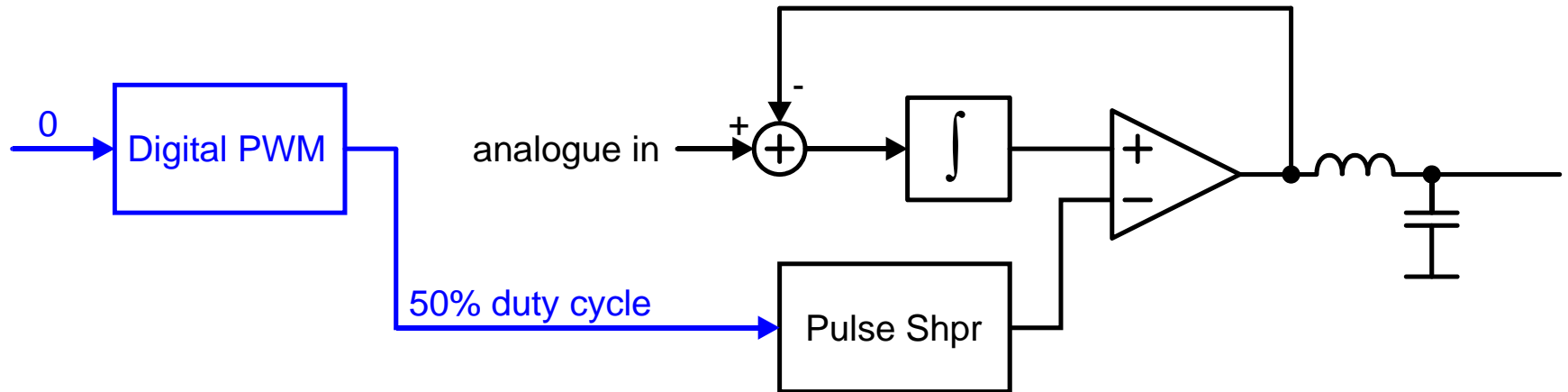
Rearranged loops

Digital PWM + local loop (“edge error correction”)



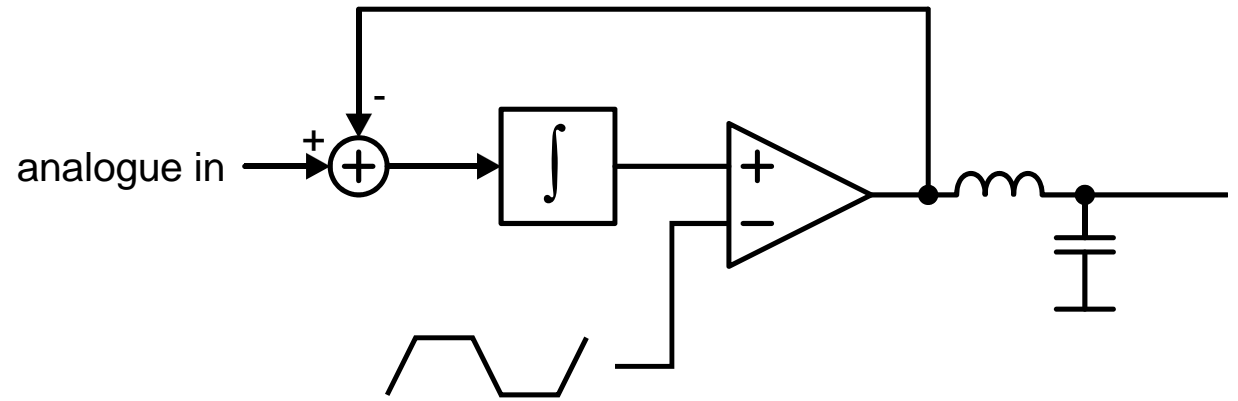
Rearranged loops

Hidden “analogue” amplifier:



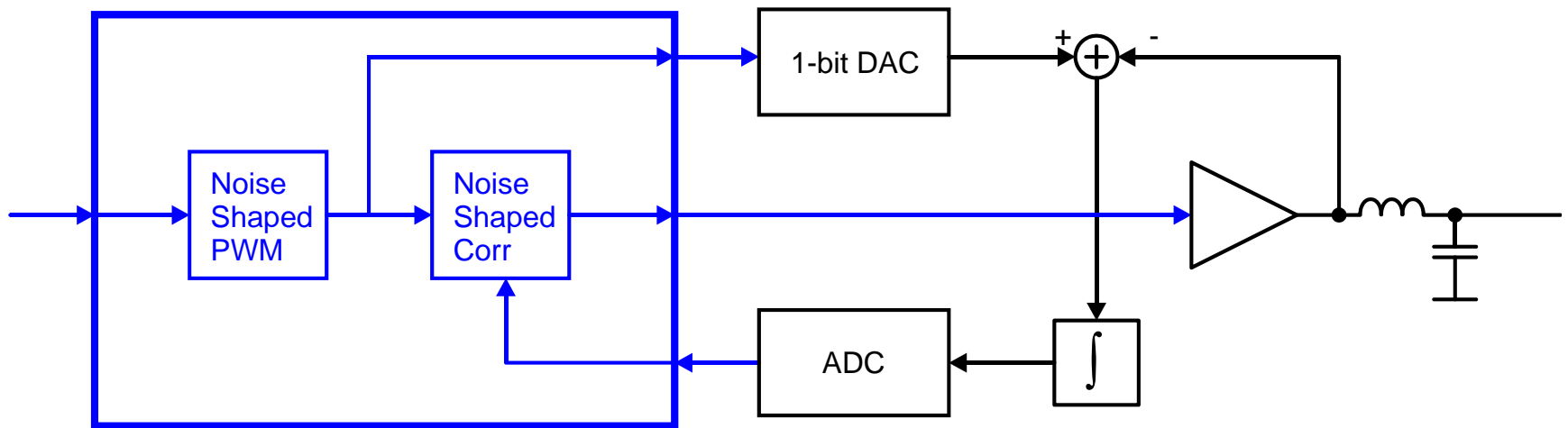
Rearranged loops

No news at all, really:



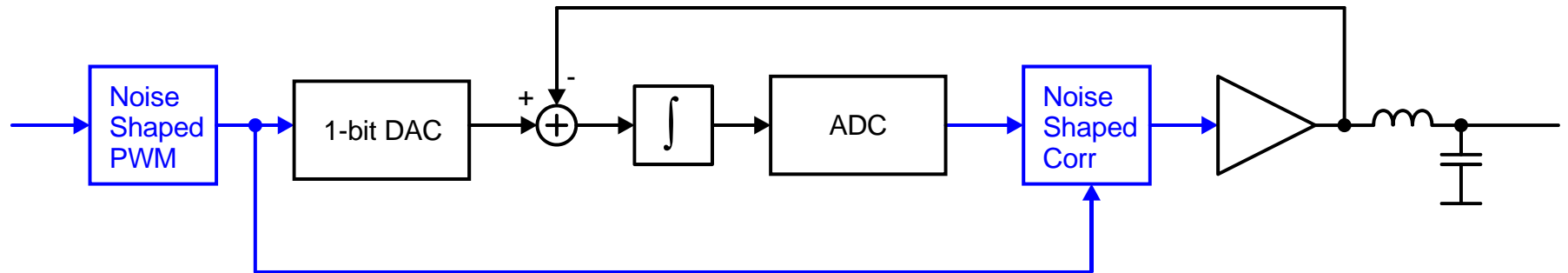
Rearranged loops

Indirect “digital feedback”

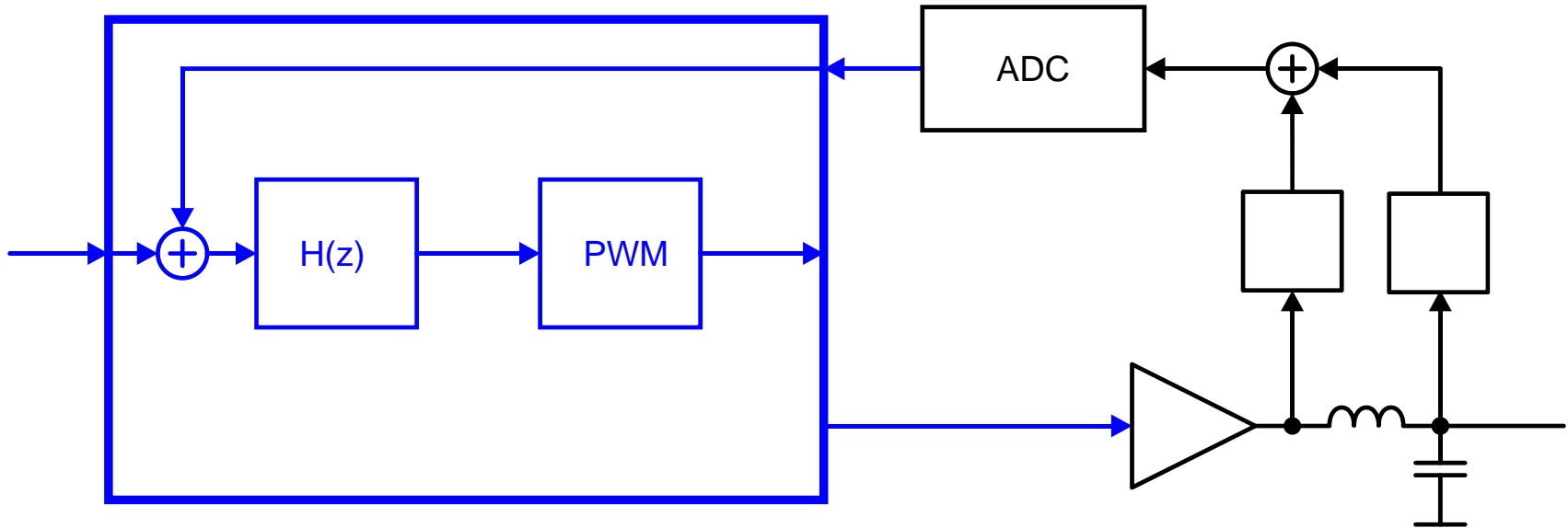


Rearranged loops

...a remarkable similarity...



Full ADC based feedback



Full ADC based feedback

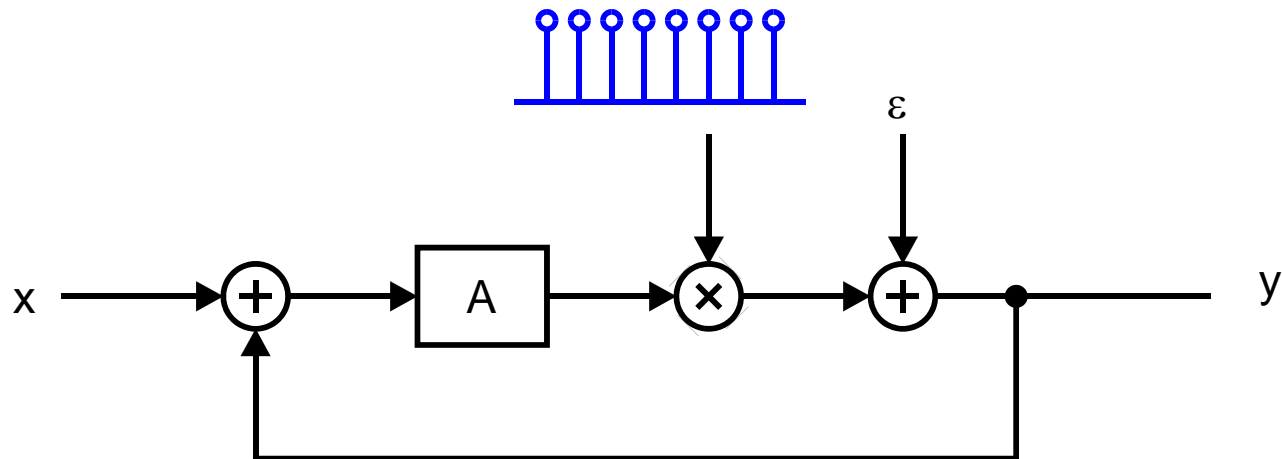
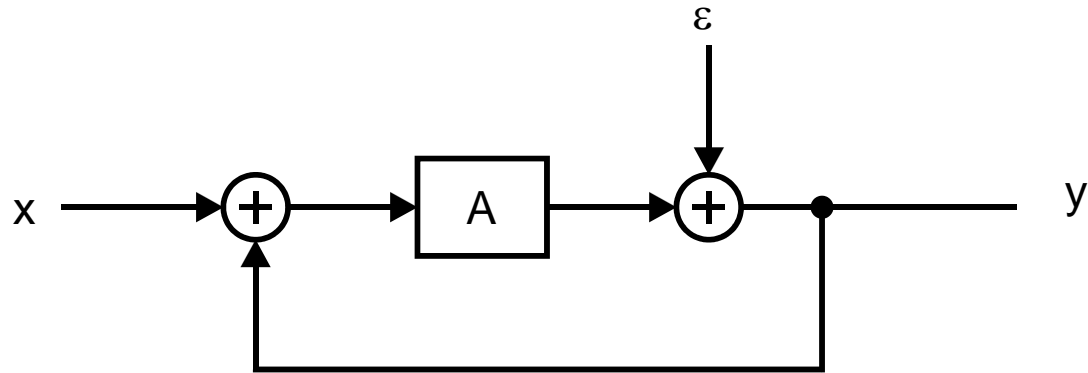
Reasons for use

- Silicon area of ADC + loop control < equivalent analogue loop.
- Complicated linearization circuits
- Start/stop/overload recovery

Not reasons for use

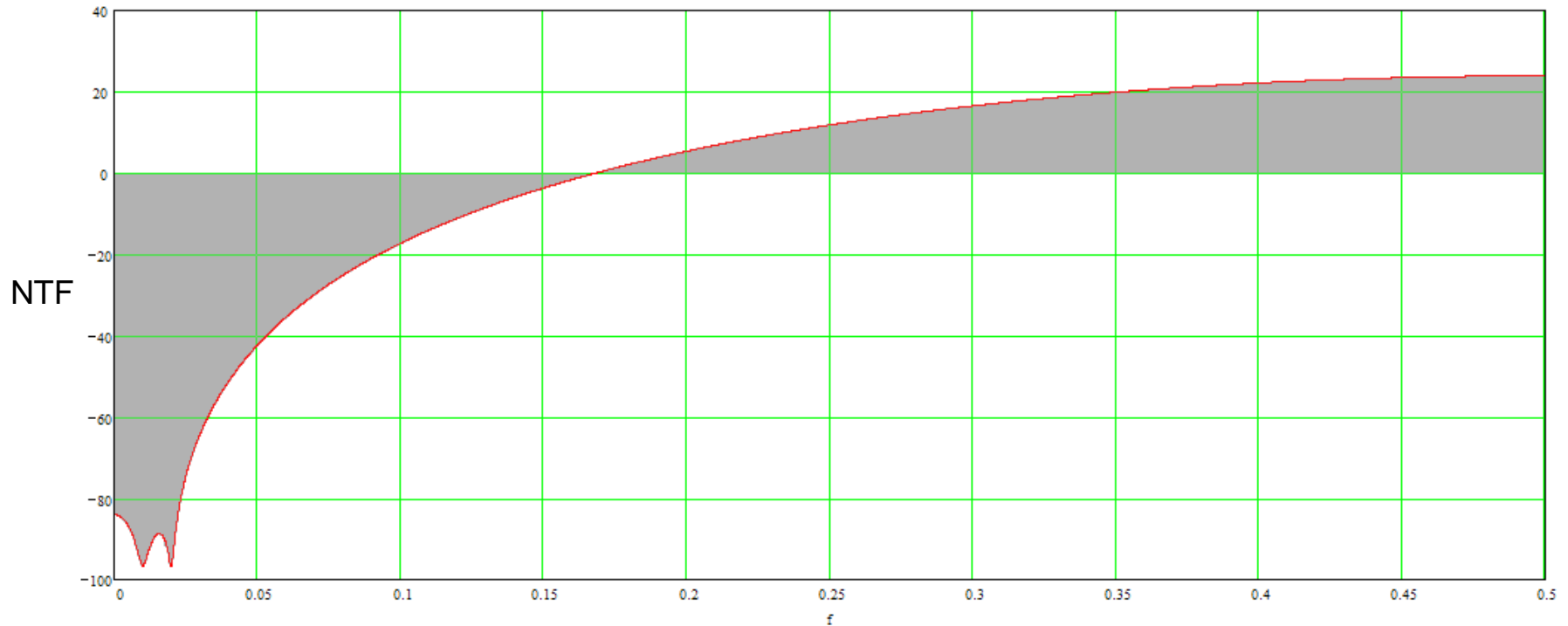
- Nearly anything else:
 - “digital, hence better”
 - investor retention

Effect of sampling on loop control



Effect of sampling on loop control

Noise Shaper Theorem holds

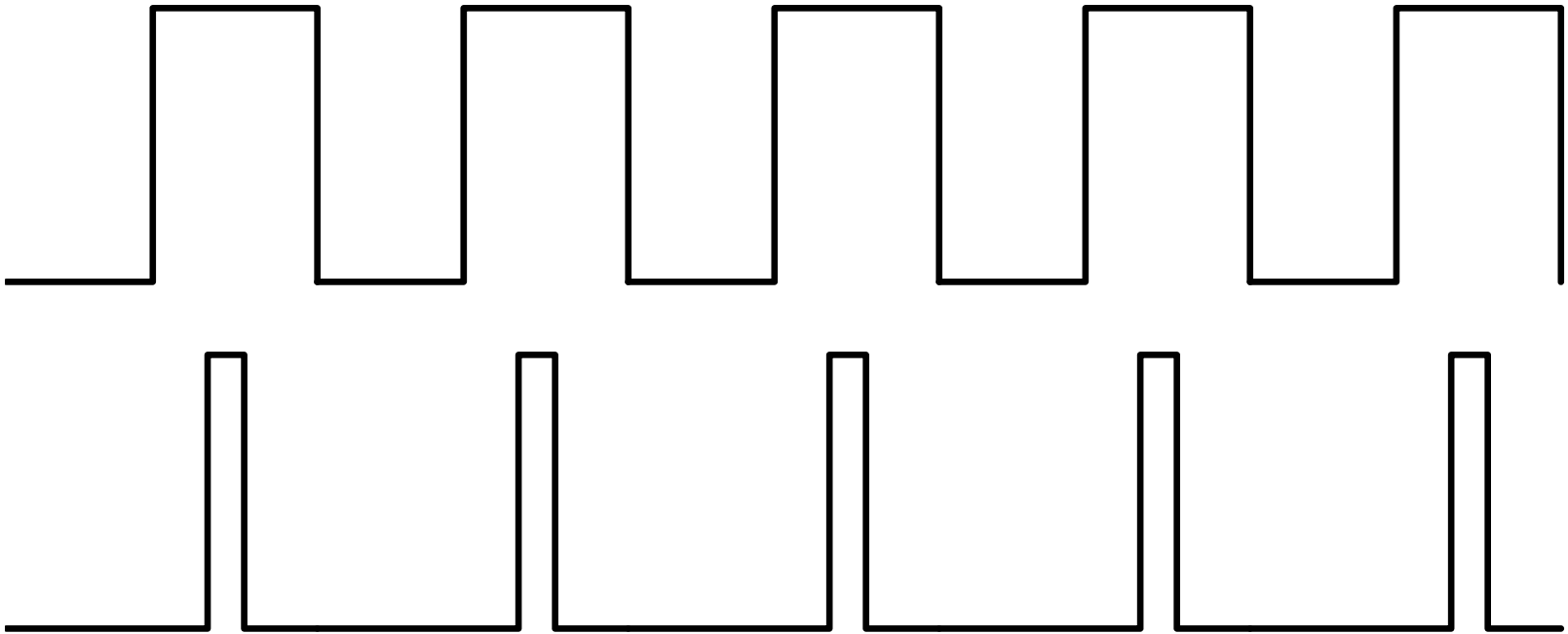


- Transform A_L to z domain
- Highly optimised A_L may seem unstable in linear analysis and be critically damped in sampled system!

Effect of sampling on loop control

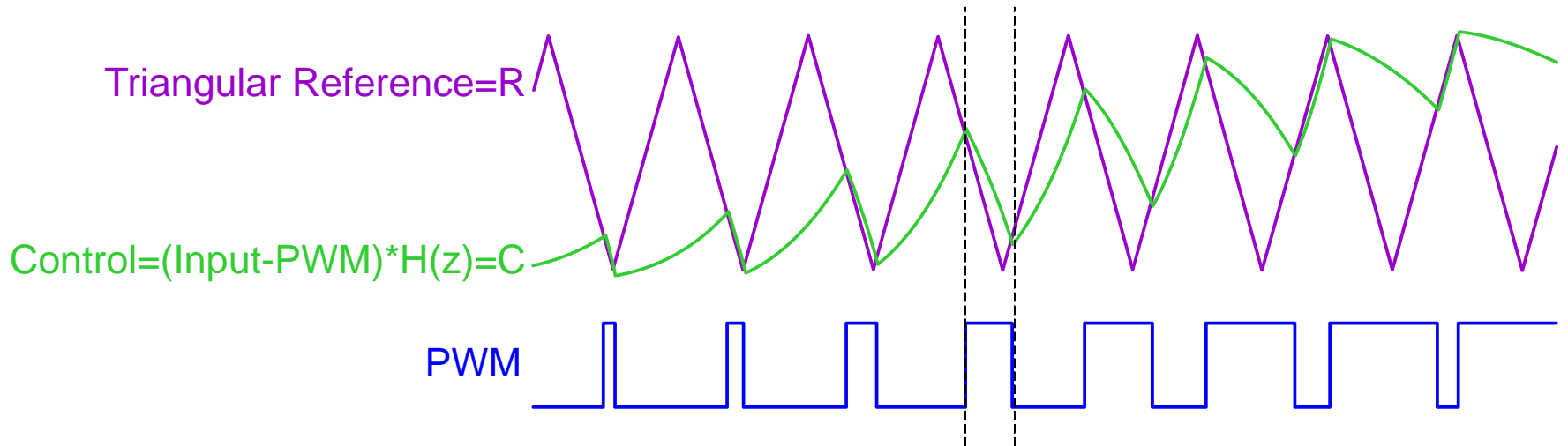
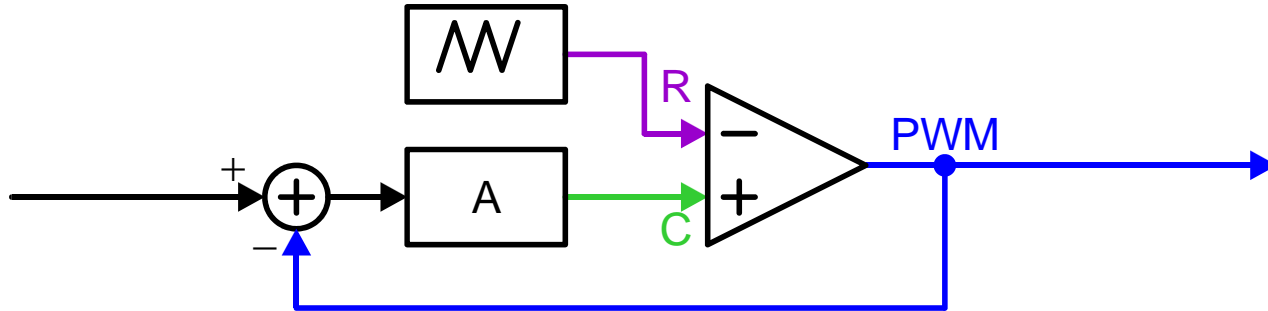
Most PWM is double-sided

- $f_s = f_{sw}$ (low modulation index)
- $f_s = 0.5 \cdot f_{sw}$ (clipping)



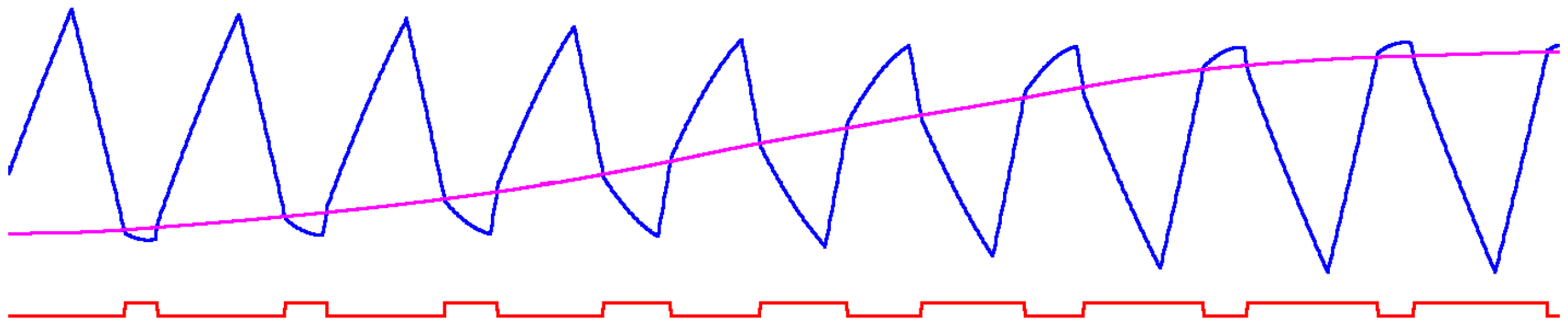
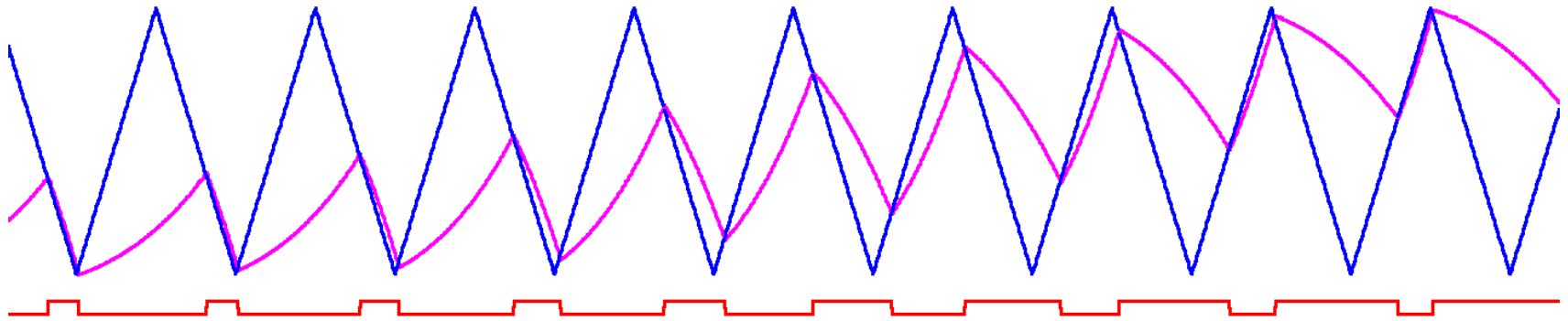
- ETF (NTF) becomes modulation dependent

Ripple aliasing



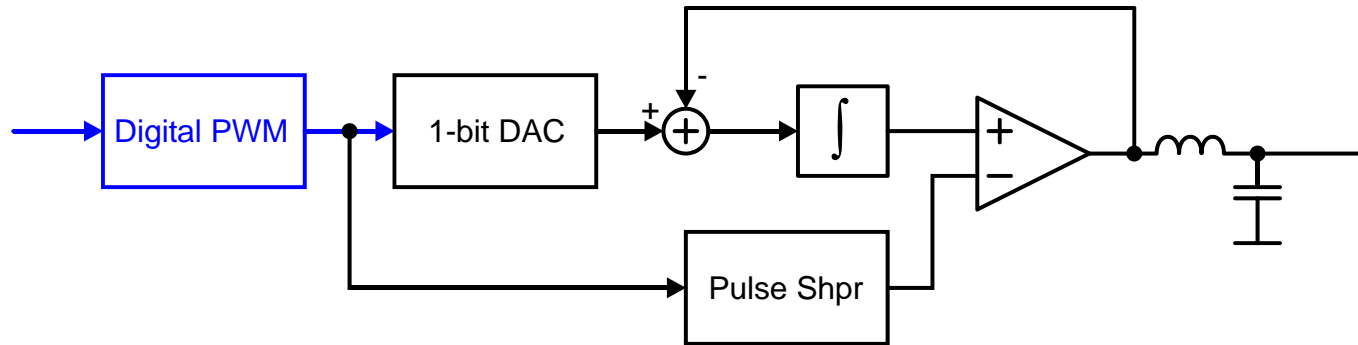
Ripple aliasing

Ripple distorts carrier



Dealing with Ripple Aliasing

Local Error Feedback (PEDEC etc)



- Operation

- Minimal ripple in feedback loop.

- Pro

- Theoretically perfect regardless of loop order

- Contra

- Gains must be matched: 1-bit DAC and PWM must scale with supply
- PWM generator is a problem in its own right
- Not compatible with post-filter feedback

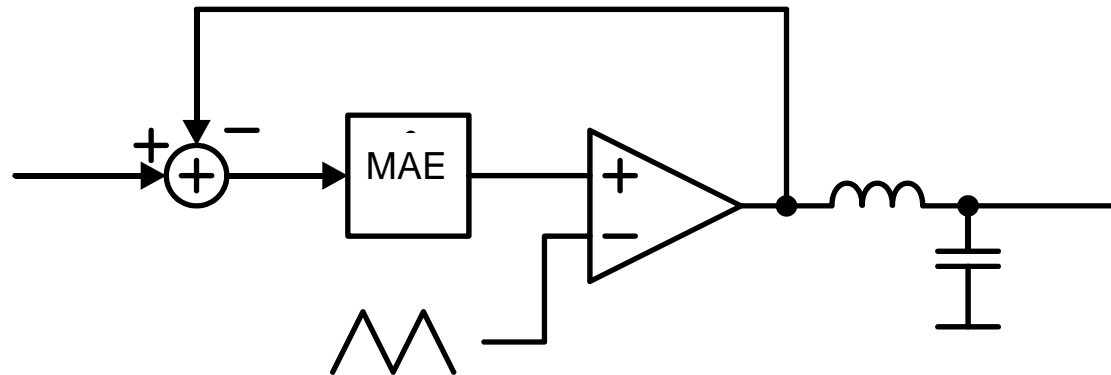
Dealing with Ripple Aliasing

Carrier slope correction (Candy)

- Operation
 - Dynamically modify triangle wave slopes
- Pro
 - Theoretically perfect for 1st order loop
 - Reasonably compatible with higher order including mixed post-filter f/b
- Contra
 - Complex triwave generation

Dealing with Ripple Aliasing

Minimum Aliasing Error filter (Risbo)



- Operation

- Ripple in feedback loop not reduced, phase shift optimised for minimum impact.

- Pro

- Grafts well onto “standard” control circuit.
- Compatible with post-filter feedback (perhaps not fully global)

Dealing with Ripple Aliasing

“Invariant PWM” (Yours Truly)

- Operation
 - Secret
- Pro
 - Perfectible for any loop (5th order with global f/b demonstrated)
 - Compatible with global f/b
 - Closed-form analysis and design
- Contra
 - Complex triwave generation
 - High sensitivity to parts tolerance

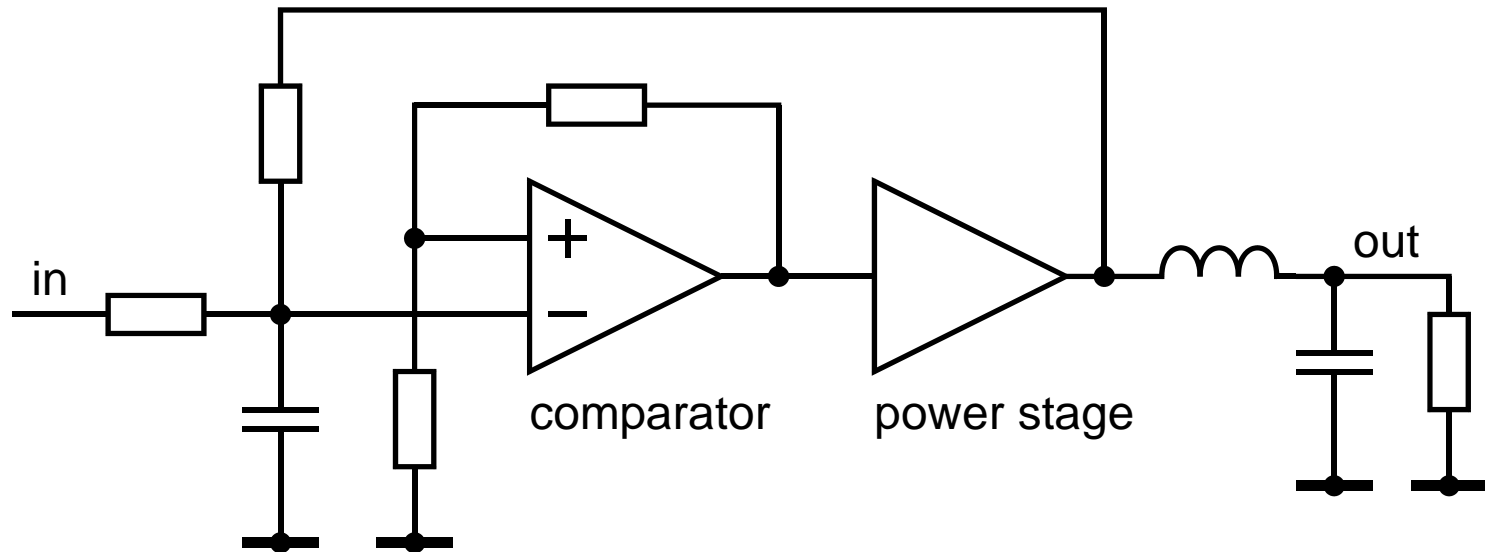
Self-Oscillating Loops

Aim

- Getting rid of the oscillator
- Improving maximum modulation index

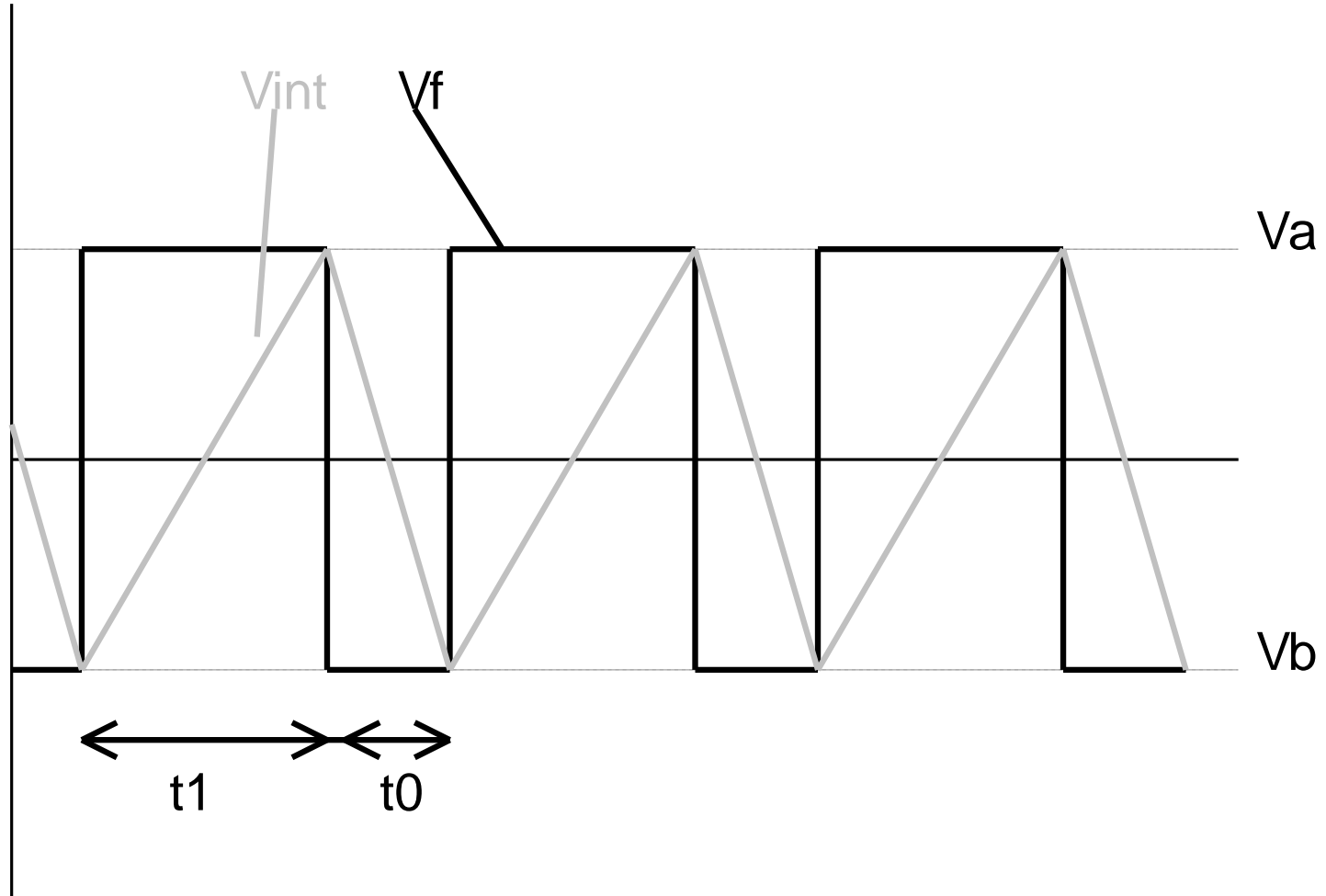
Self-Oscillating Loops

Hysteresis modulator



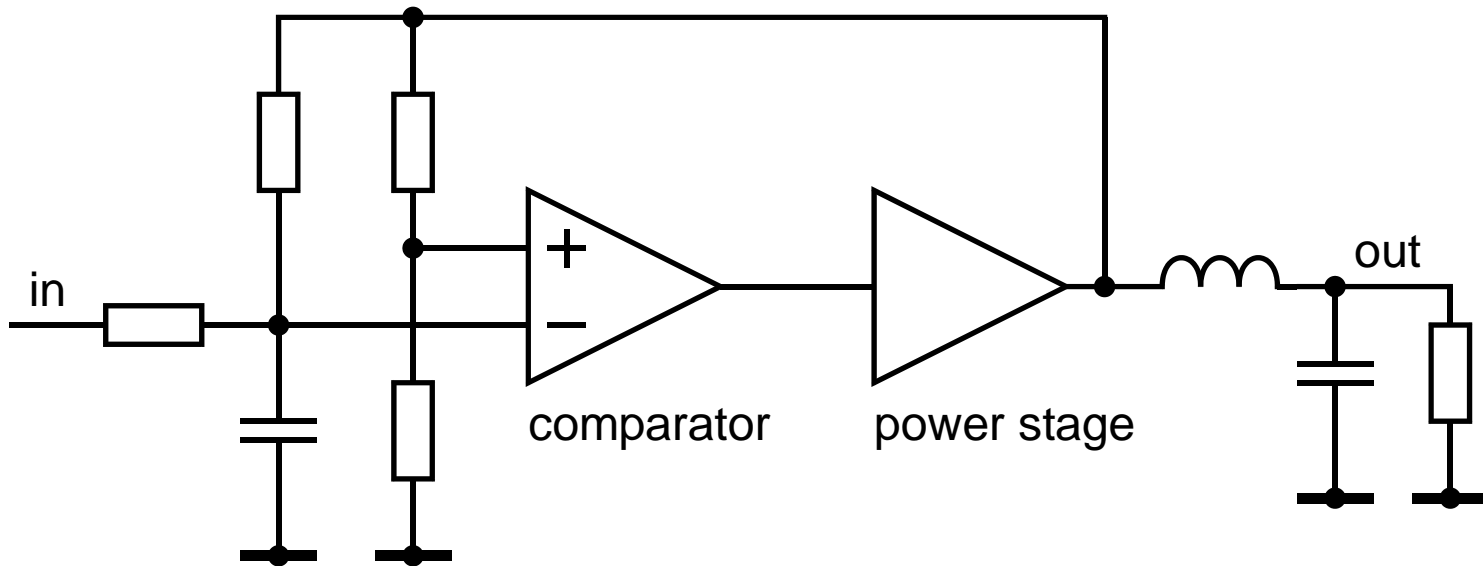
Hysteresis modulator

Operation



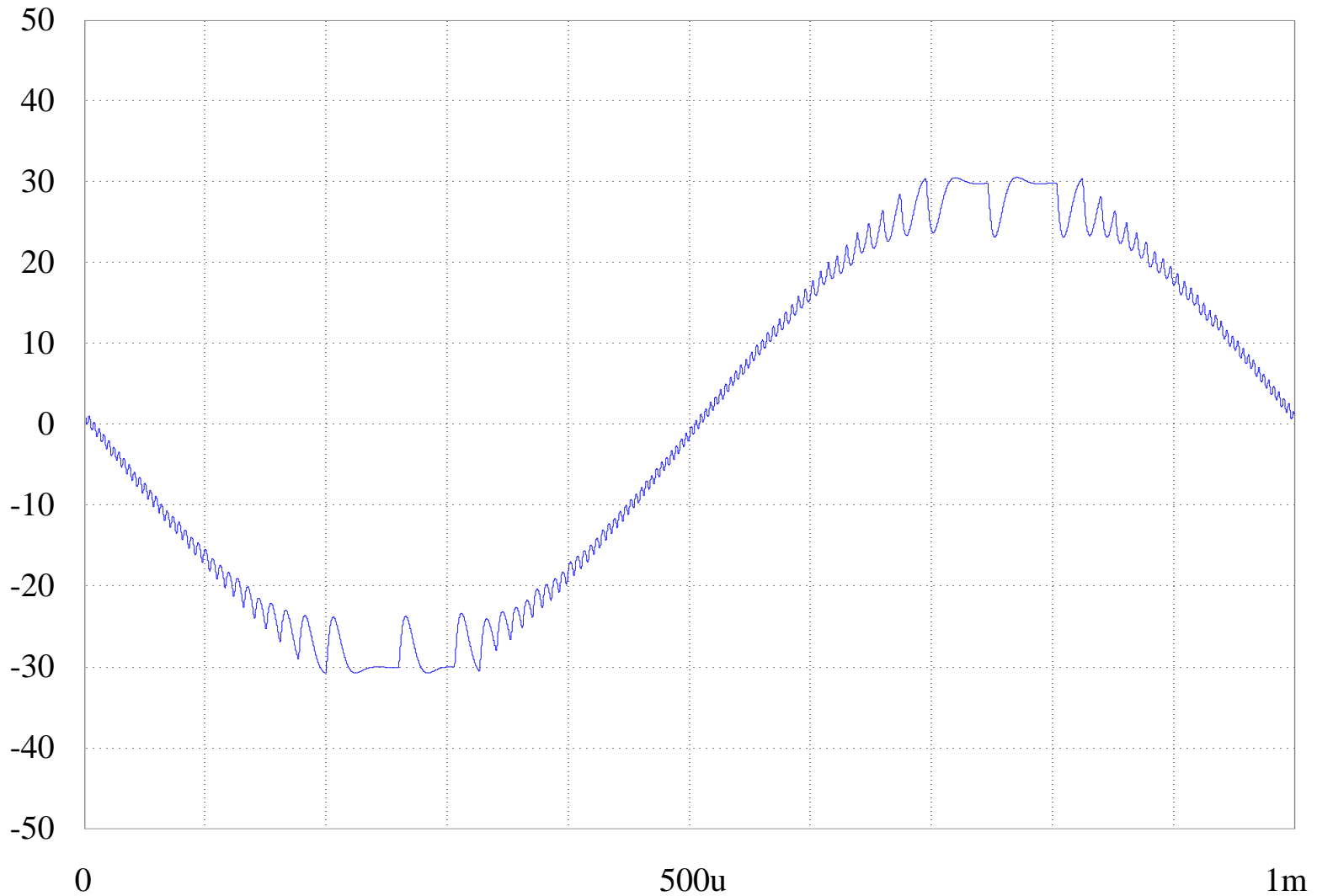
Hysteresis modulator

Improved version



Hysteresis modulator

Output Signal

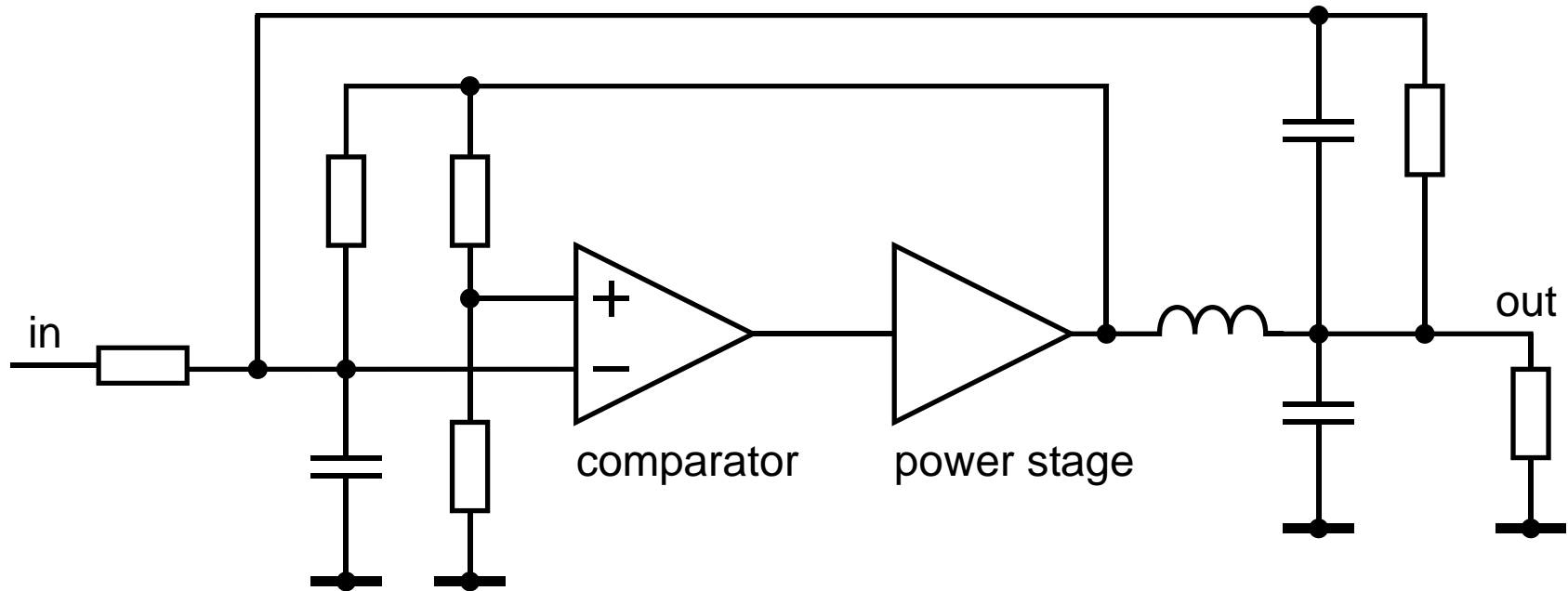


Hysteresis modulator

- Completely linear
- Switching frequency falls early
 - becomes audible near clip

Hysteresis modulator

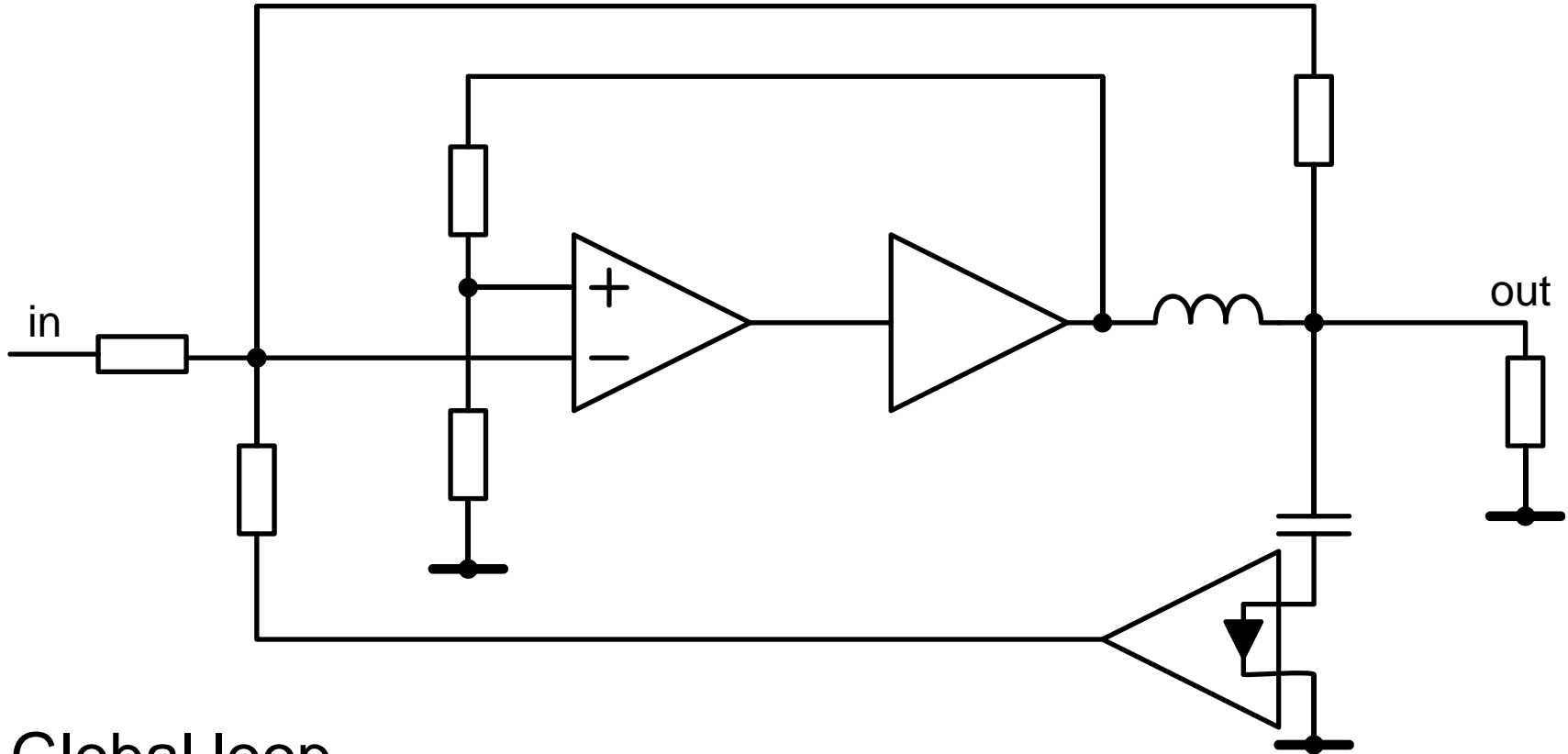
Post-LPF added



- Less linear
- No-load stability not guaranteed

Hysteresis modulator

Capacitor current feedback (Mueta)

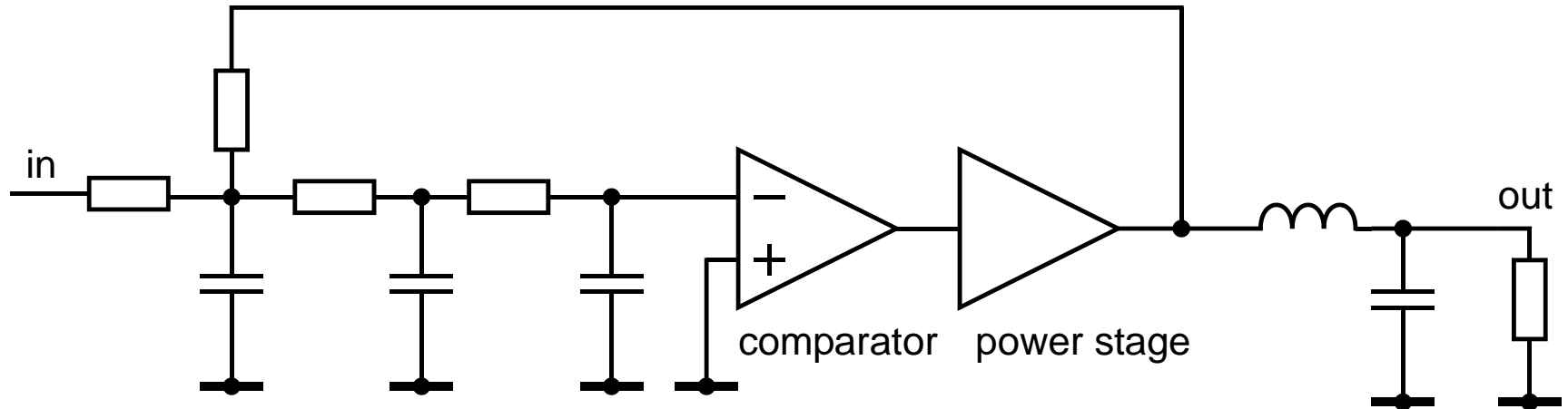


- Global loop
- Good linearity
- Current sense has low EMI sensitivity

Phase-shift controlled oscillation

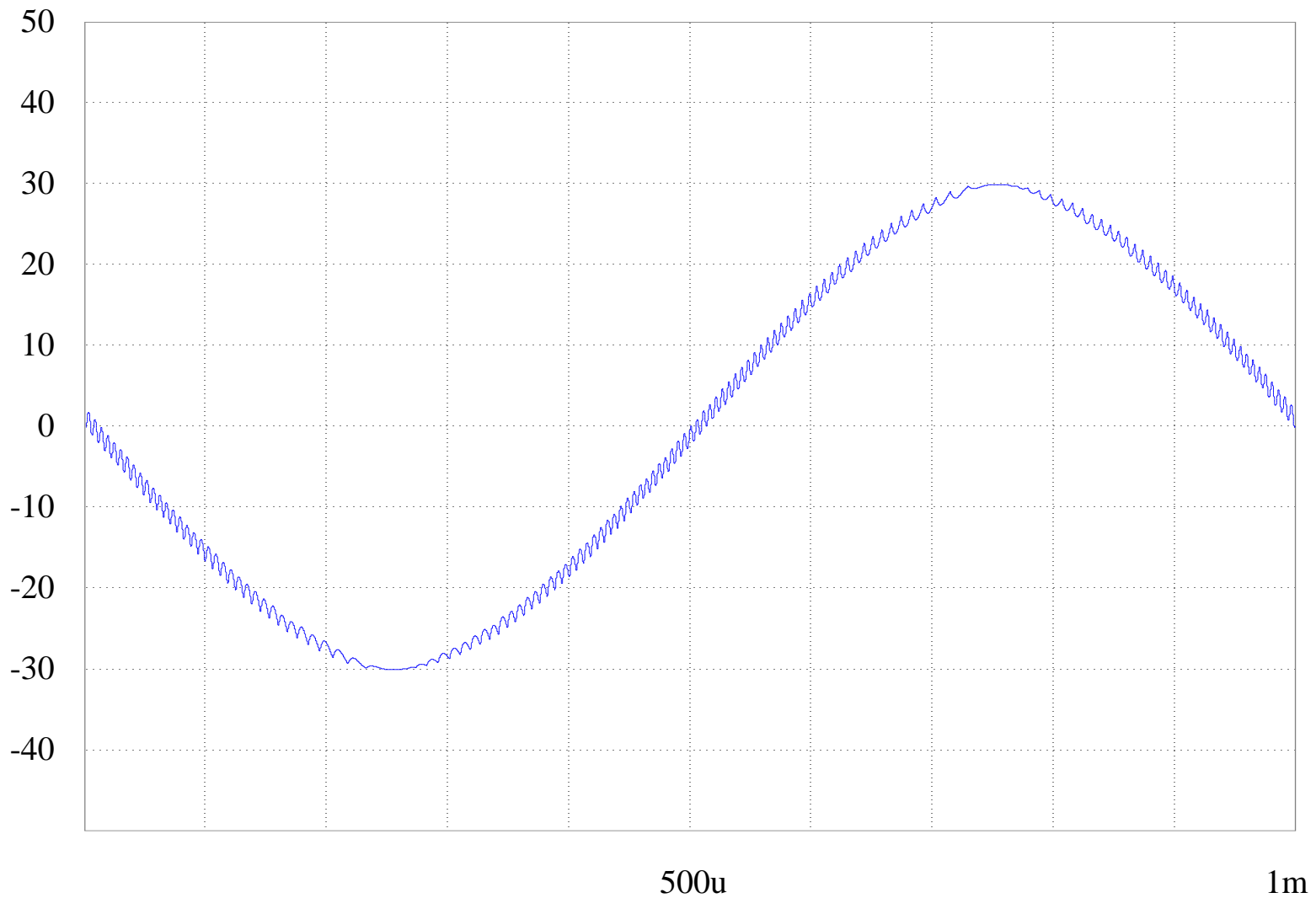
Operation

- Oscillation frequency set by loop phase



Phase-shift controlled oscillation

Output signal

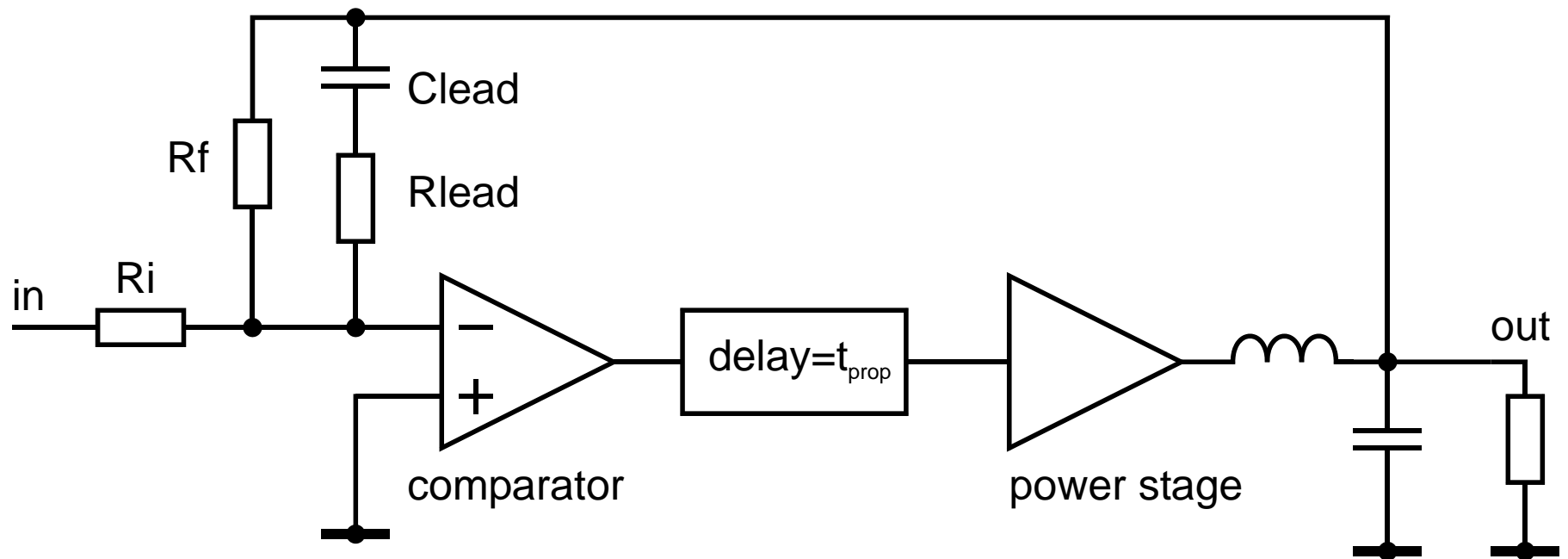


Phase-shift controlled oscillation

- Nonlinear, depends on design
- Switching frequency is more stable

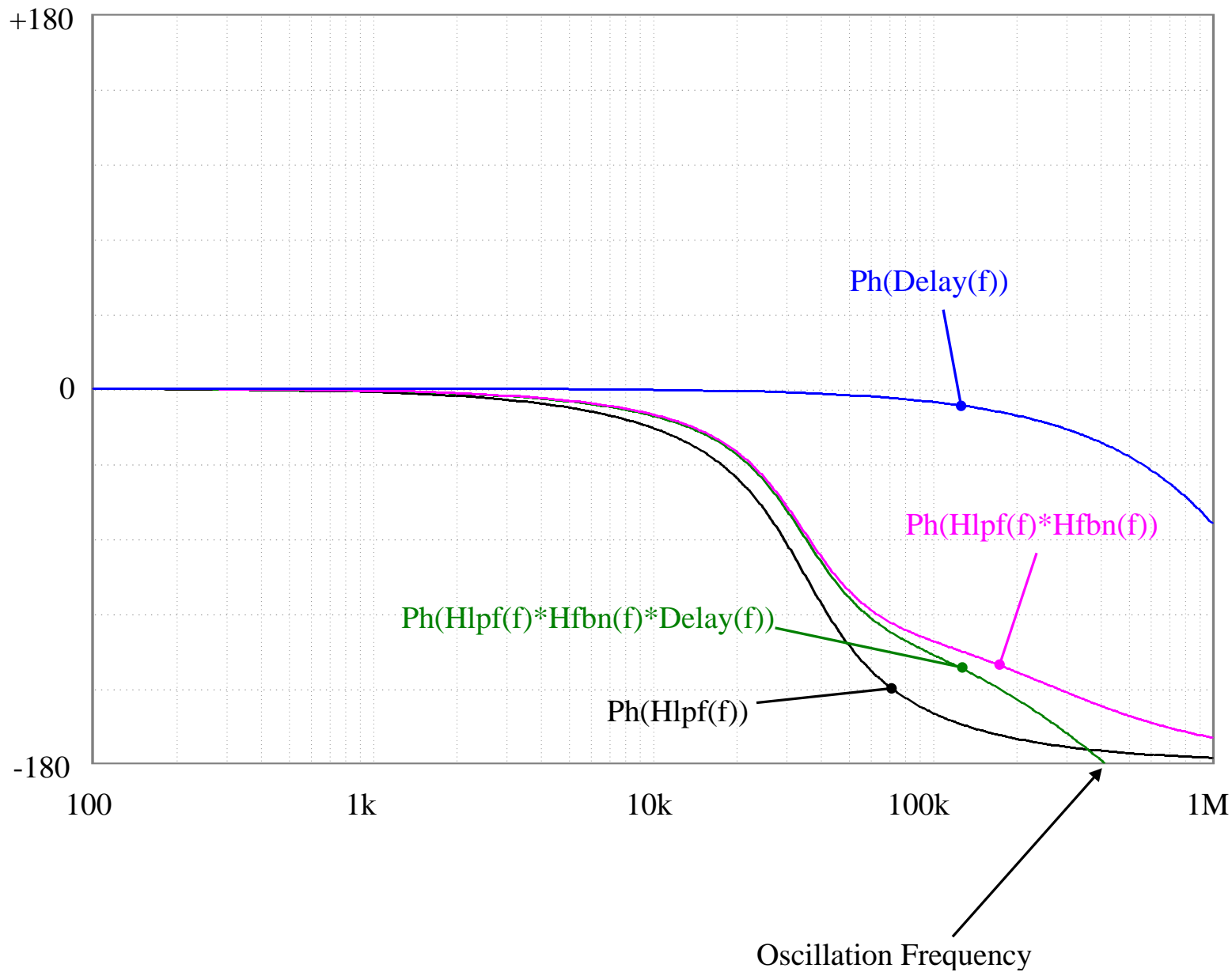
Phase-shift controlled oscillation

Phase shift controlled oscillator with global loop (UcD)



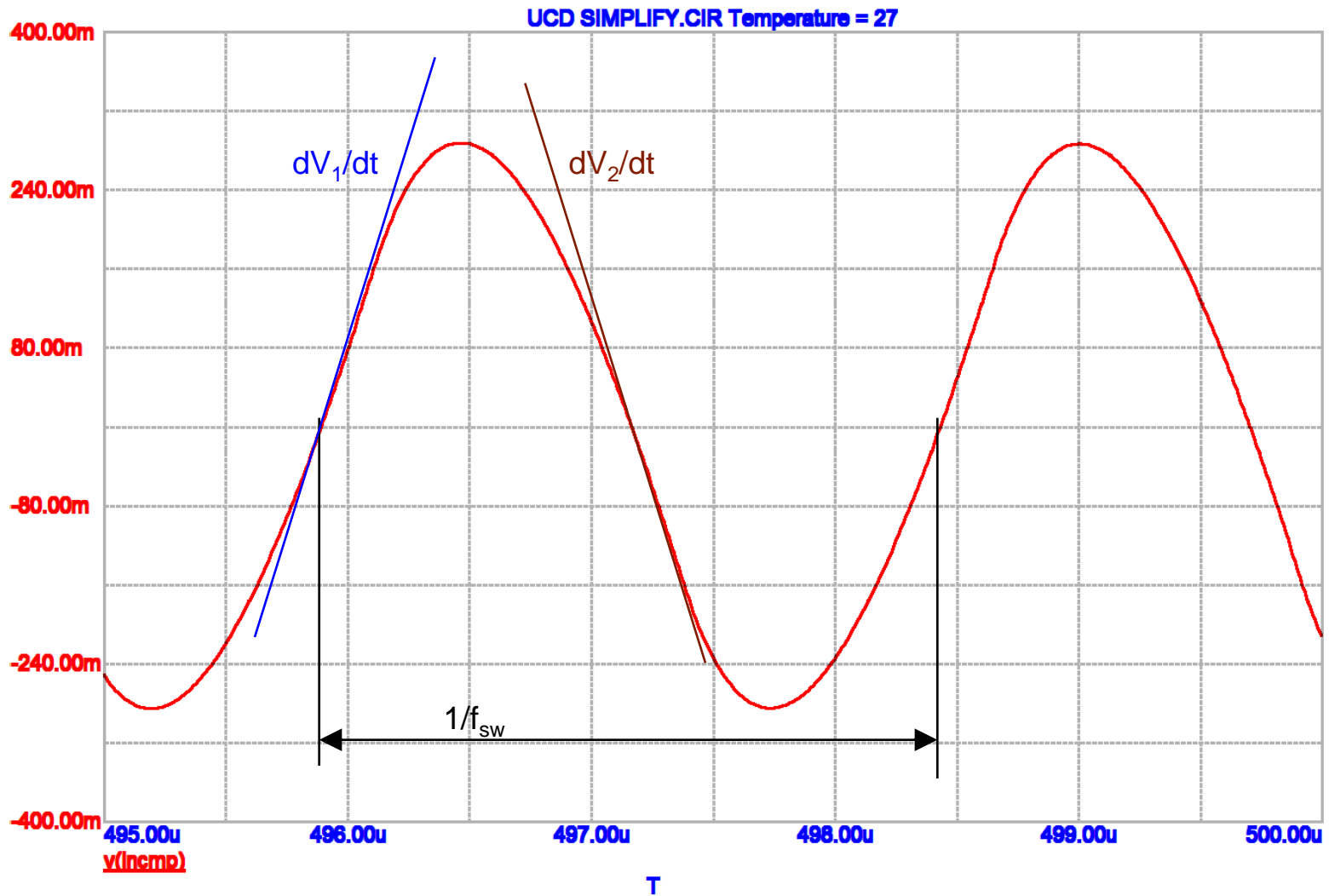
Operation

- Combined phase shift of output filter, lead network and propagation delay set f_{osc} .
- Extra pole may be added



Phase-shift controlled oscillation

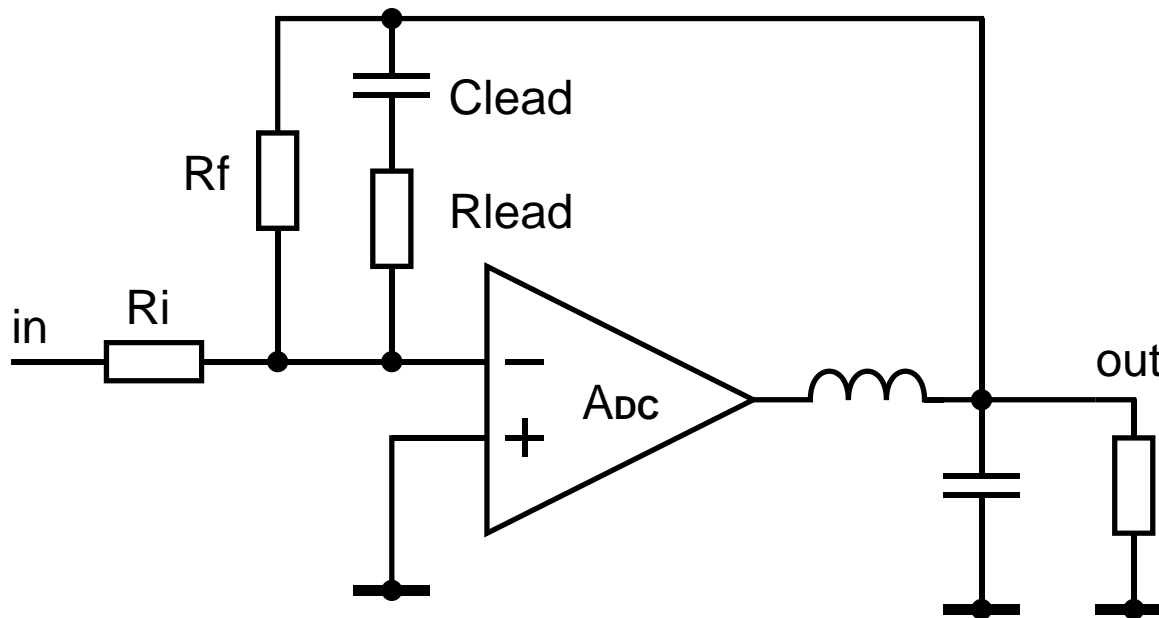
Modulator gain



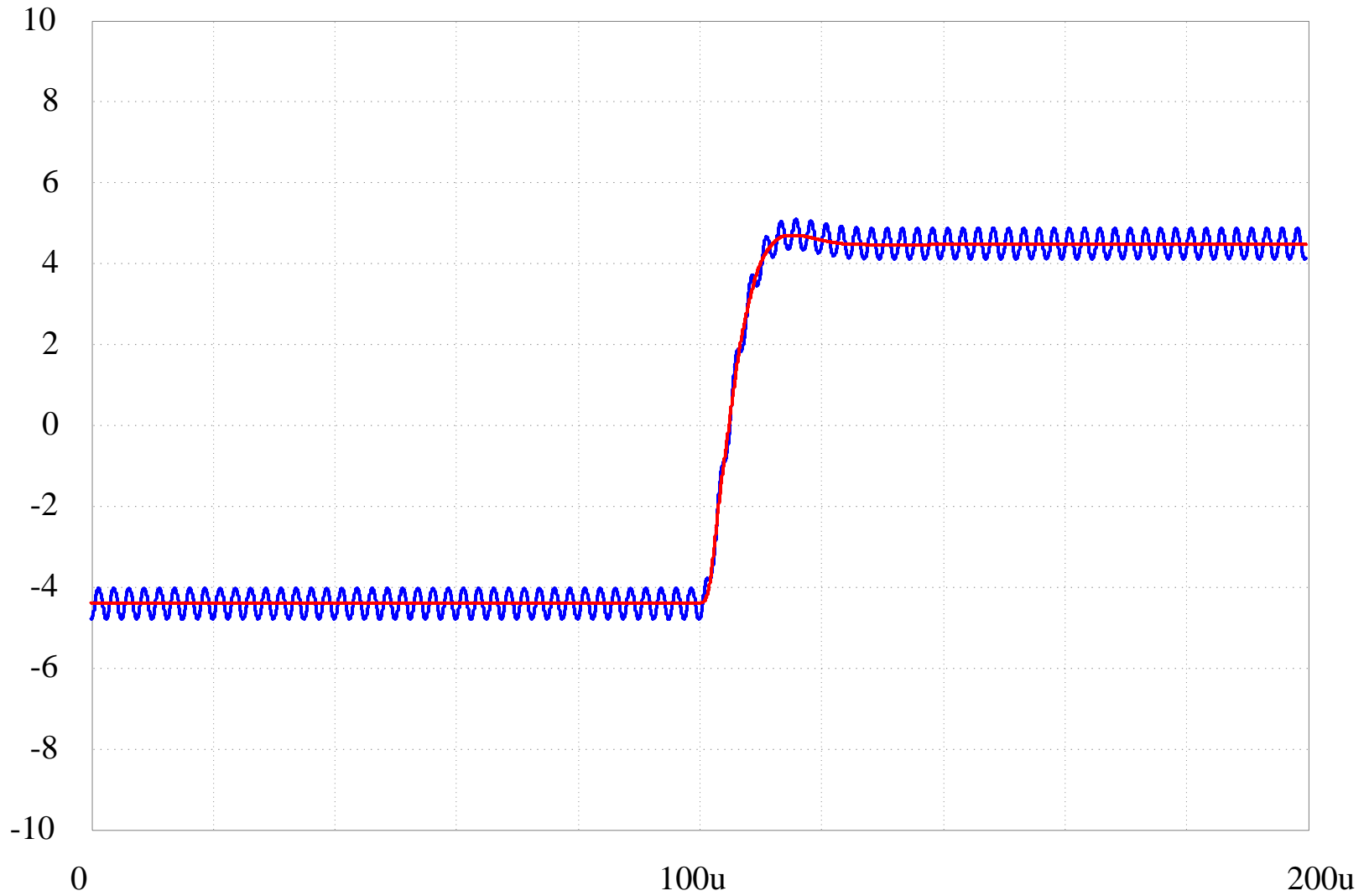
Phase-shift controlled oscillation

Small-signal linearized model

$$A_{DC} = 2 \cdot V_{CC} \cdot f_{sw} \cdot \left(\frac{1}{dV1/dt} - \frac{1}{dV2/dt} \right)$$



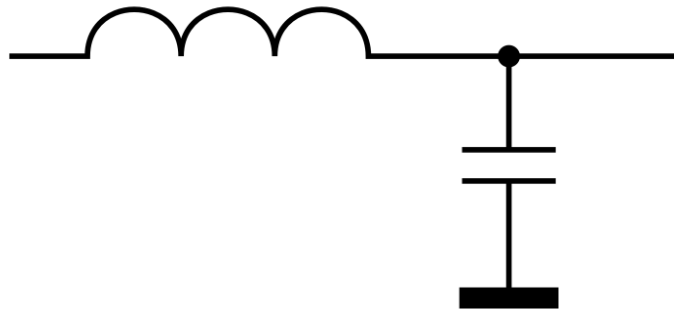
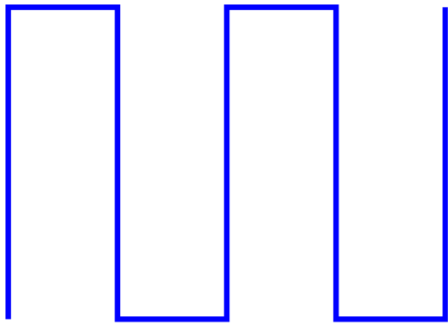
Phase-shift controlled oscillation



Class D and EMI

Low-frequency EMI: Carrier and low harmonics.

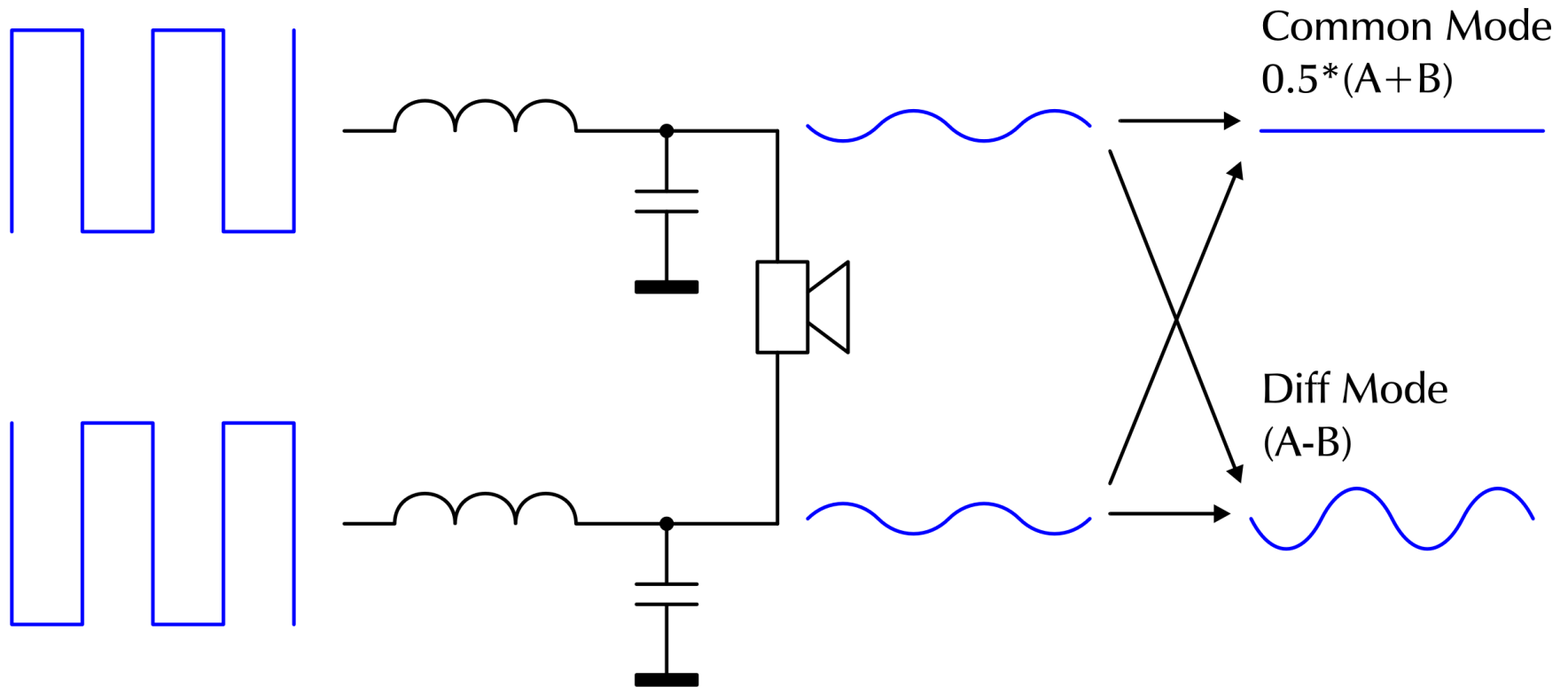
- Close match with theory.
- Ripple cancelling possible.
- Not an EMI issue except for long cables
- Not a tweeter issue (come off it!)



Class D and EMI

Common and Differential Mode in H-Bridge Class D

- “Class AD”. Carriers and modulation are out of phase

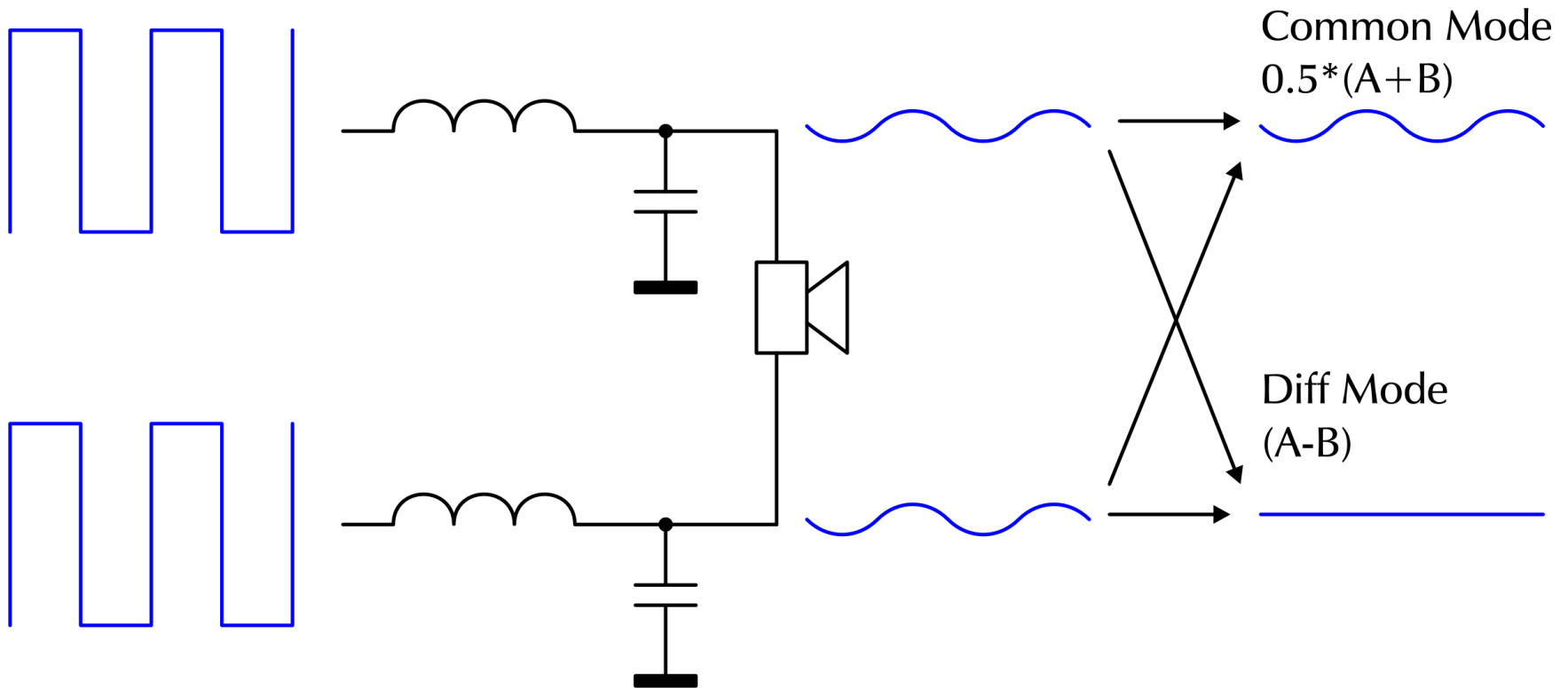


Note: Common-mode is what radiates off cables.

Class D and EMI

“Class BD”.

- Carriers are in phase. Modulation is out of phase.



HF across load is reduced but CM increases.

Class D and EMI

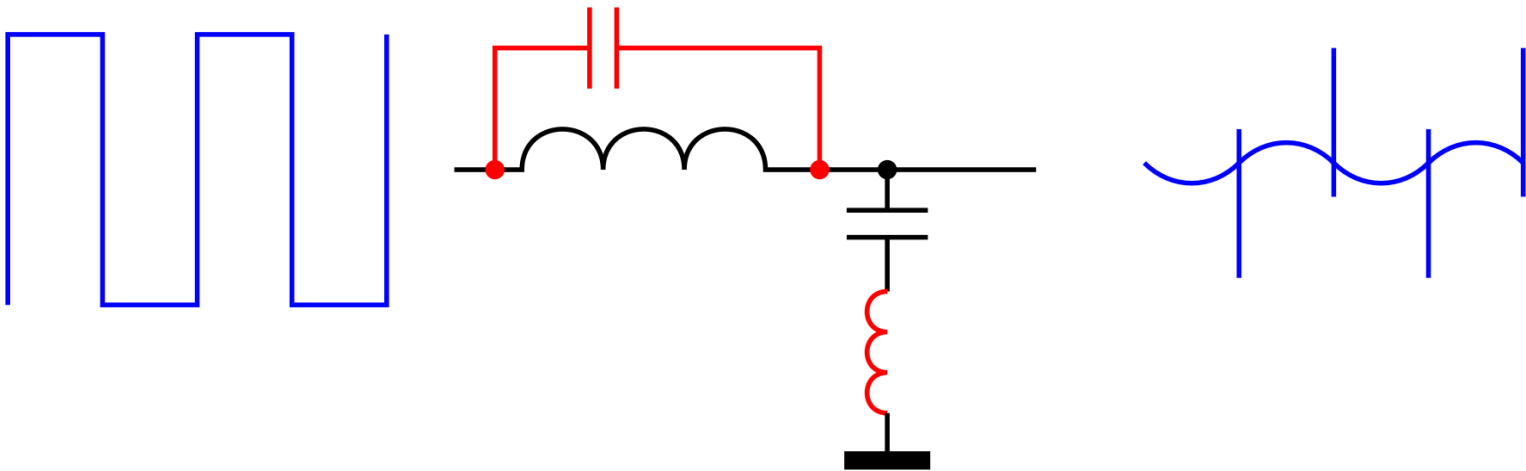
Half bridge vs Full Bridge, Class AD vs BD

- Half-bridge
 - Can't cancel either CM or DM
 - Common-mode is half of differential mode
- AD
 - Common-mode voltage theoretically 0
 - Differential mode same as half bridge
- BD
 - Differential mode cancels at low modulation...
...but that was not really a problem anyway.
 - Common-mode voltage same as half bridge

Class D and EMI

High-Frequency EMI: Leaking switching transients

- Theoretical modeling is useless.
 - Capacitors become inductive
 - Inductors become capacitive
 - PCB becomes jumble of L's and C's.
- No tricks. Only good hardware design helps.
- Direct EMI problem under all circumstances.



Class D and EMI

Sensitive item 1: The capacitor.

- Myth of the “Low Inductance Capacitor”.
(An Audiophile Favourite)
 - All modern film caps have sprayed end contacts.
 - Inductance is determined by geometry only (mostly size).



Bad.



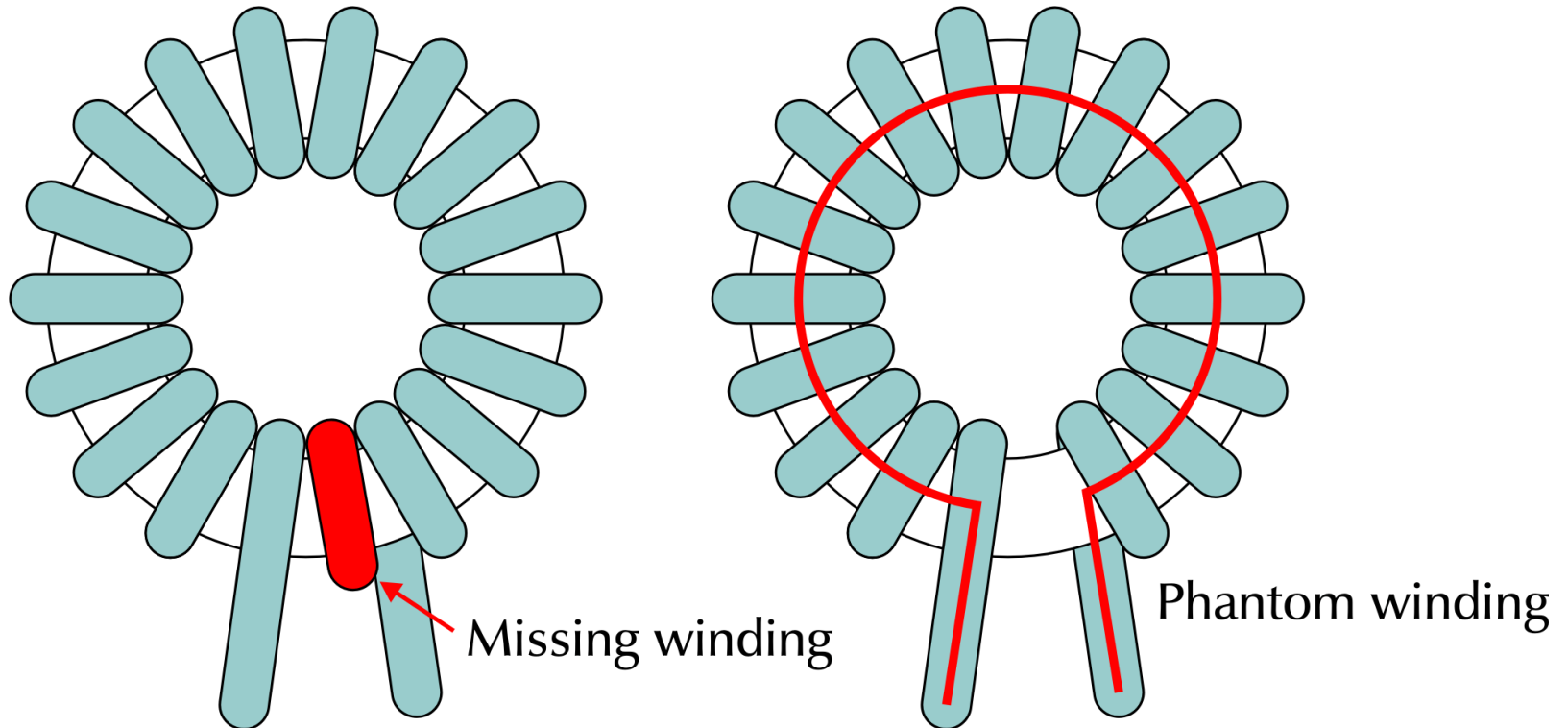
Good.

Period.

Class D and EMI

Sensitive item 2: The inductor.

- Stray fields out of toroids

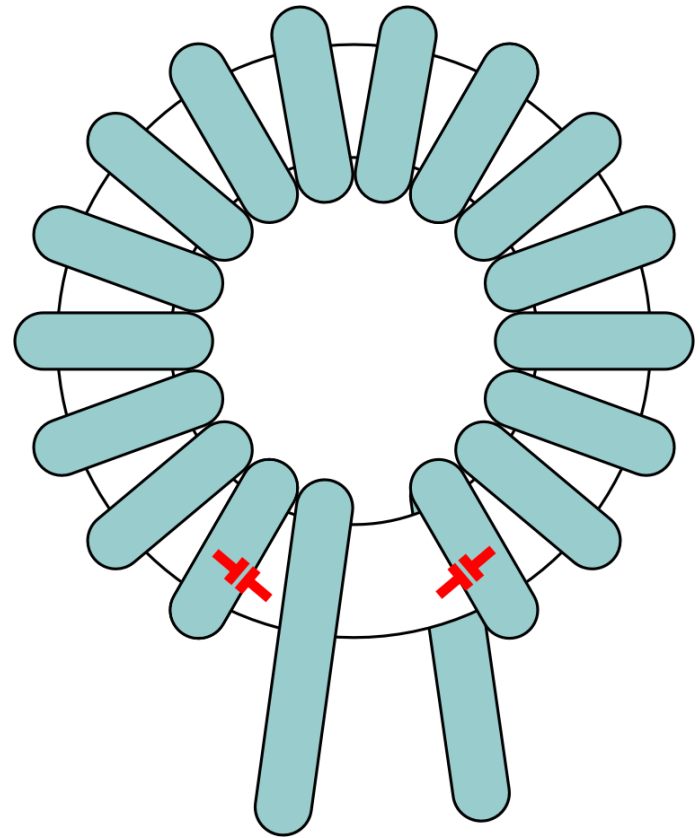


- Upright mounted toroids are worst.

Class D and EMI

Sensitive item 2: The inductor.

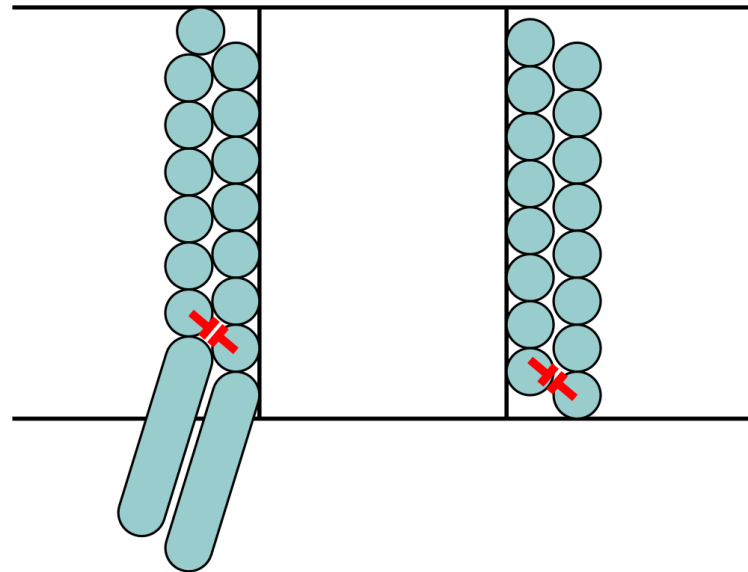
- Beware of indirect Capacitive Coupling through Core
 - Tight windings are better magnetically but worse electrostatically.
 - No external electrostatic shield: Capacitive coupling to chassis etc. can get significant.
- Toroids are not always optimal



Class D and EMI

Sensitive item 2: The inductor.

- Ferrite inductors: avoid direct capacitive coupling between windings

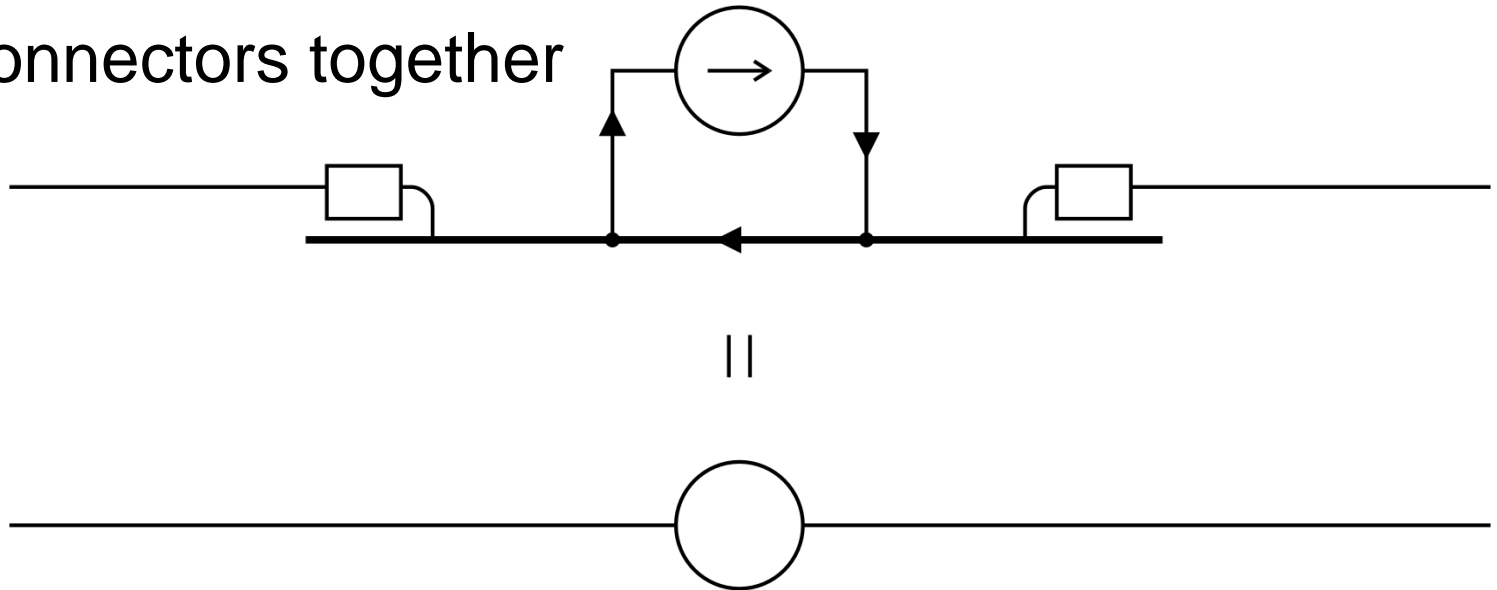


- “Hot” end sees “Cold” end
- 2 layers is worst case situation
- 1 layer is best

Class D and EMI

Sensitive item 3: The PCB layout.

- Contiguous ground plane
- Keep connectors together



- Avoid capacitive coupling to external parts
- Minimize loop area (\neq short traces)

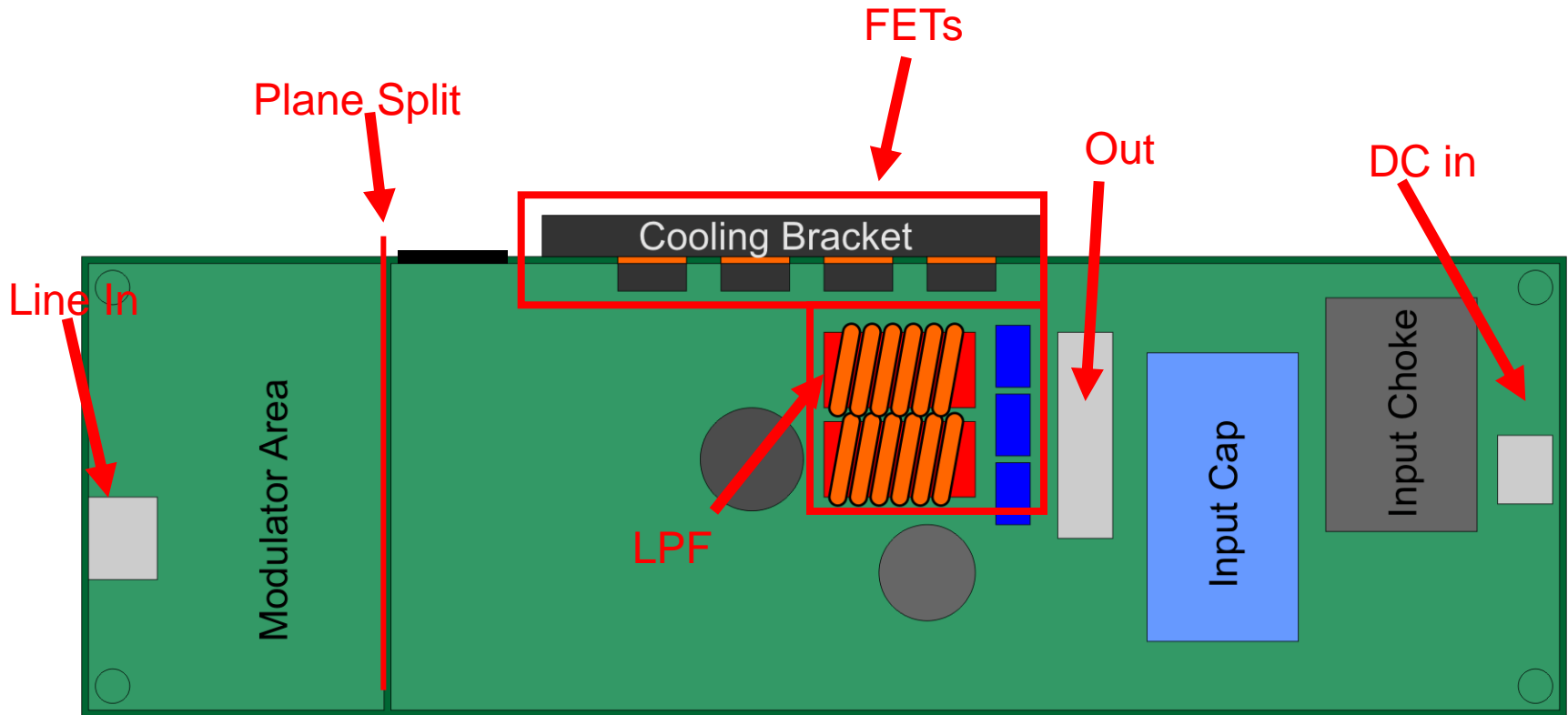
Class D and EMI

Checking for EMI without Spectrum Analyser

- Just probe around the external connections with a scope!!!
- If you see rubbish, there is rubbish
- The higher the frequency, the more you should worry

Class D and EMI

Example: Amplifier A, rated 160W

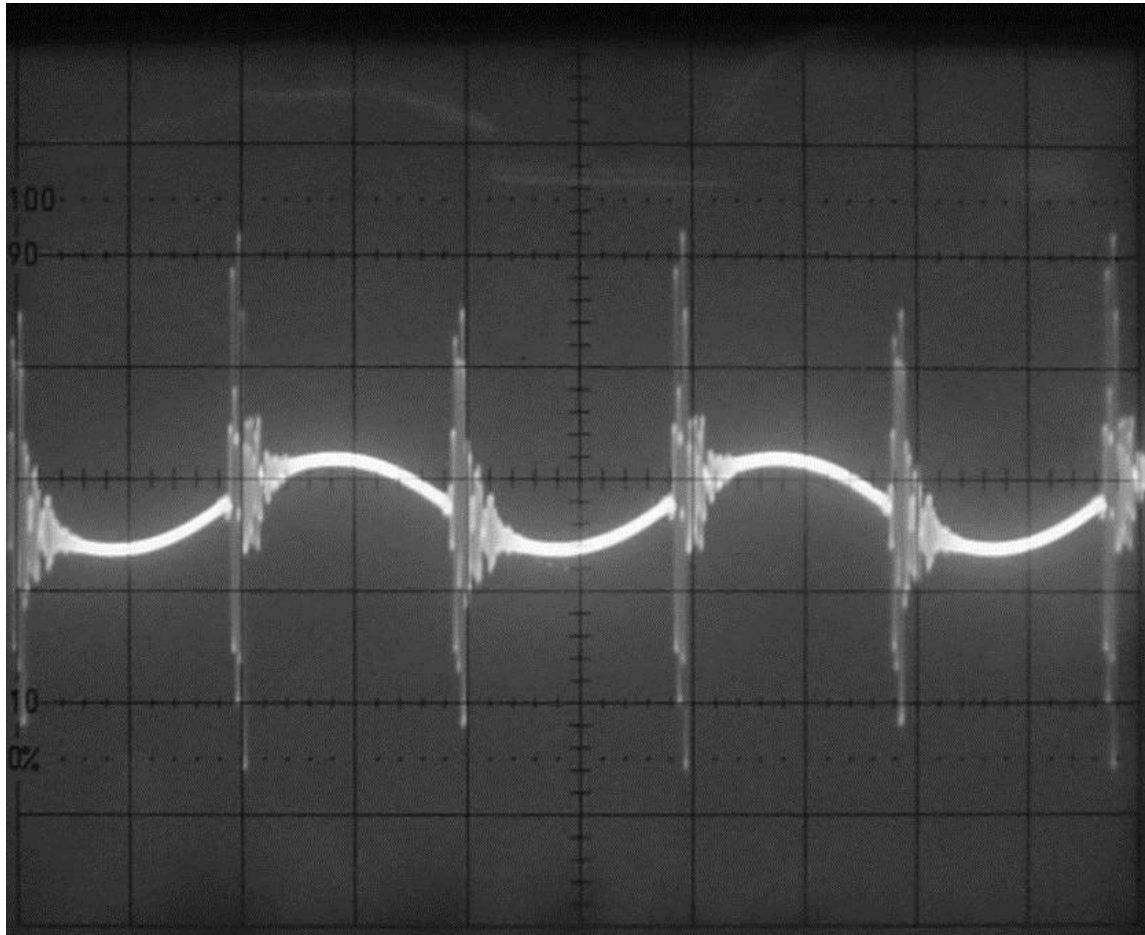


(sketch of circuit board found in commercially available amp)

Class D and EMI

Amplifier A, one output line

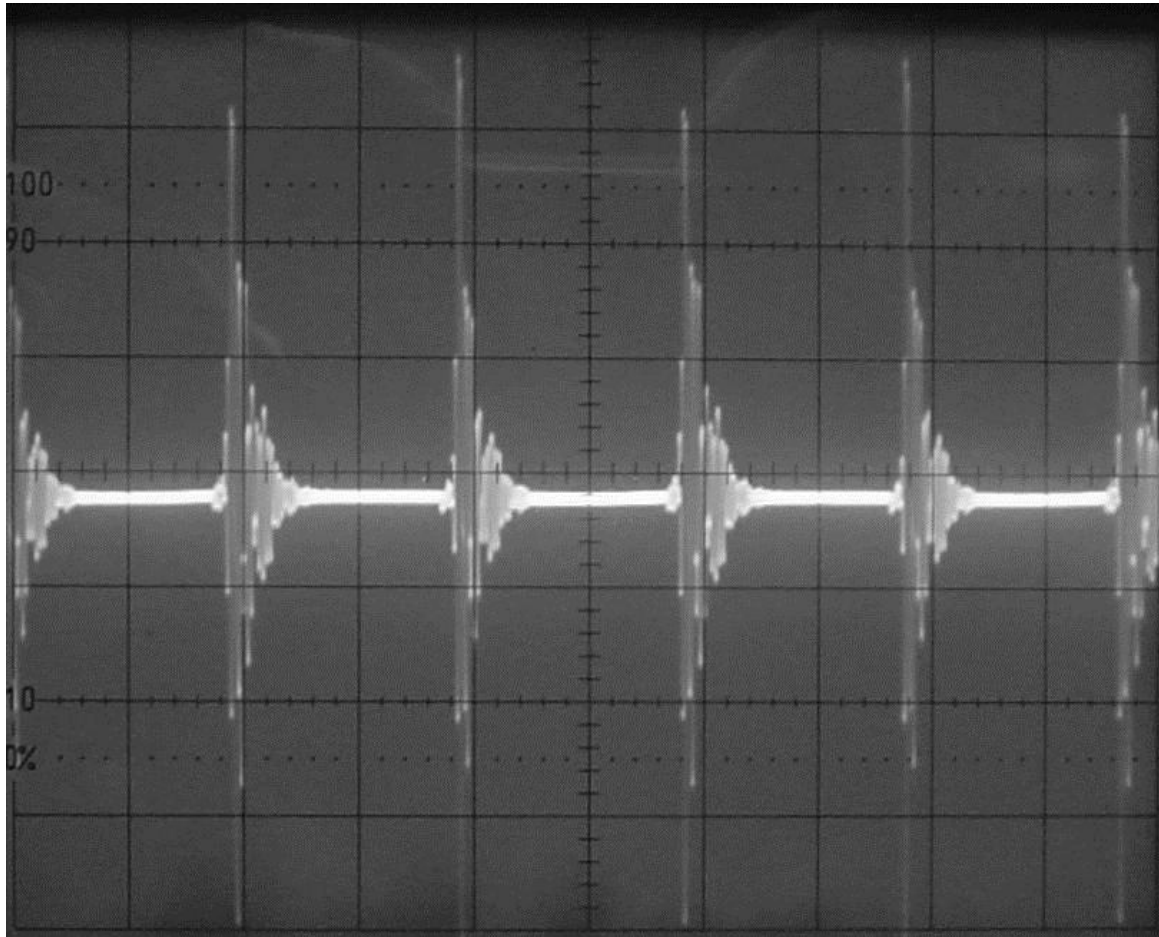
- 1V/div. Probe clip at RCA ground.



Class D and EMI

Amplifier A, common mode

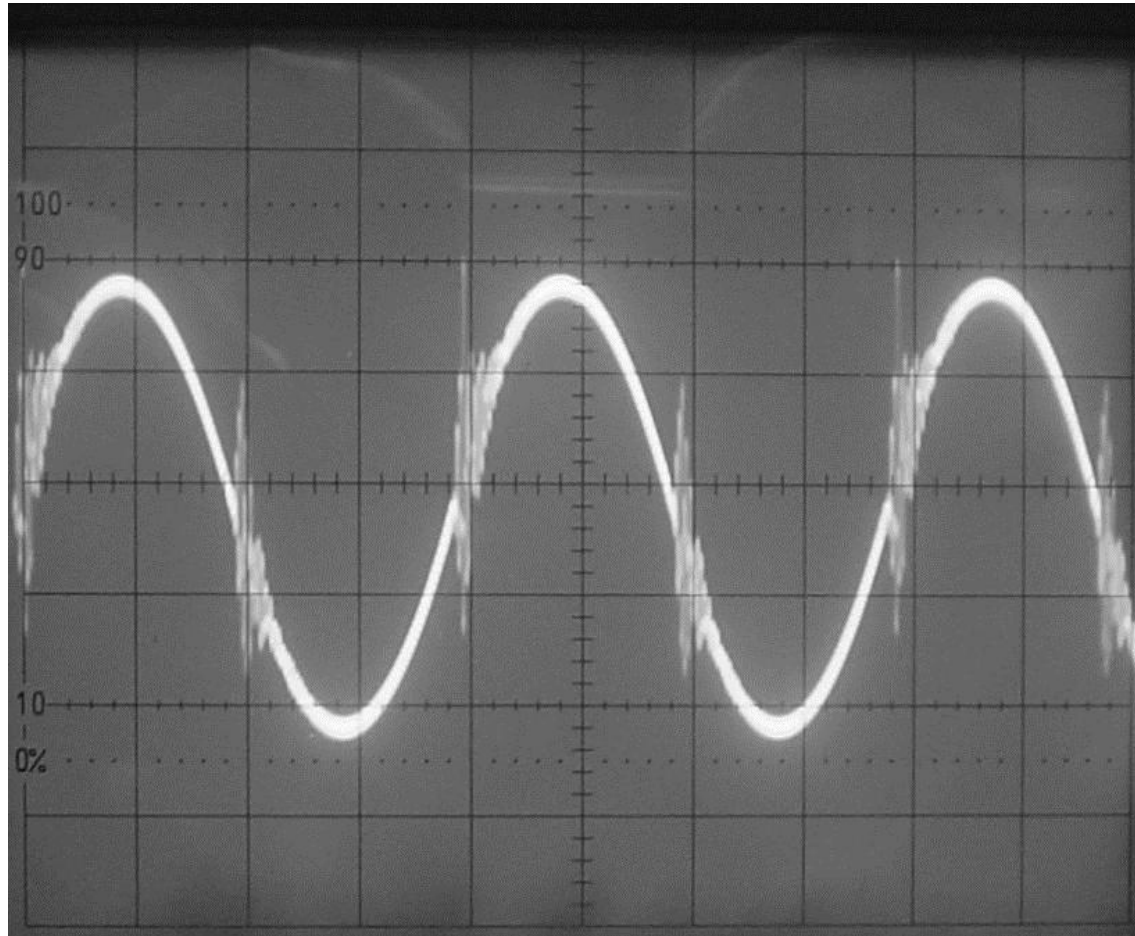
- 500mV/div. Amp is claimed to pass FCC???



Class D and EMI

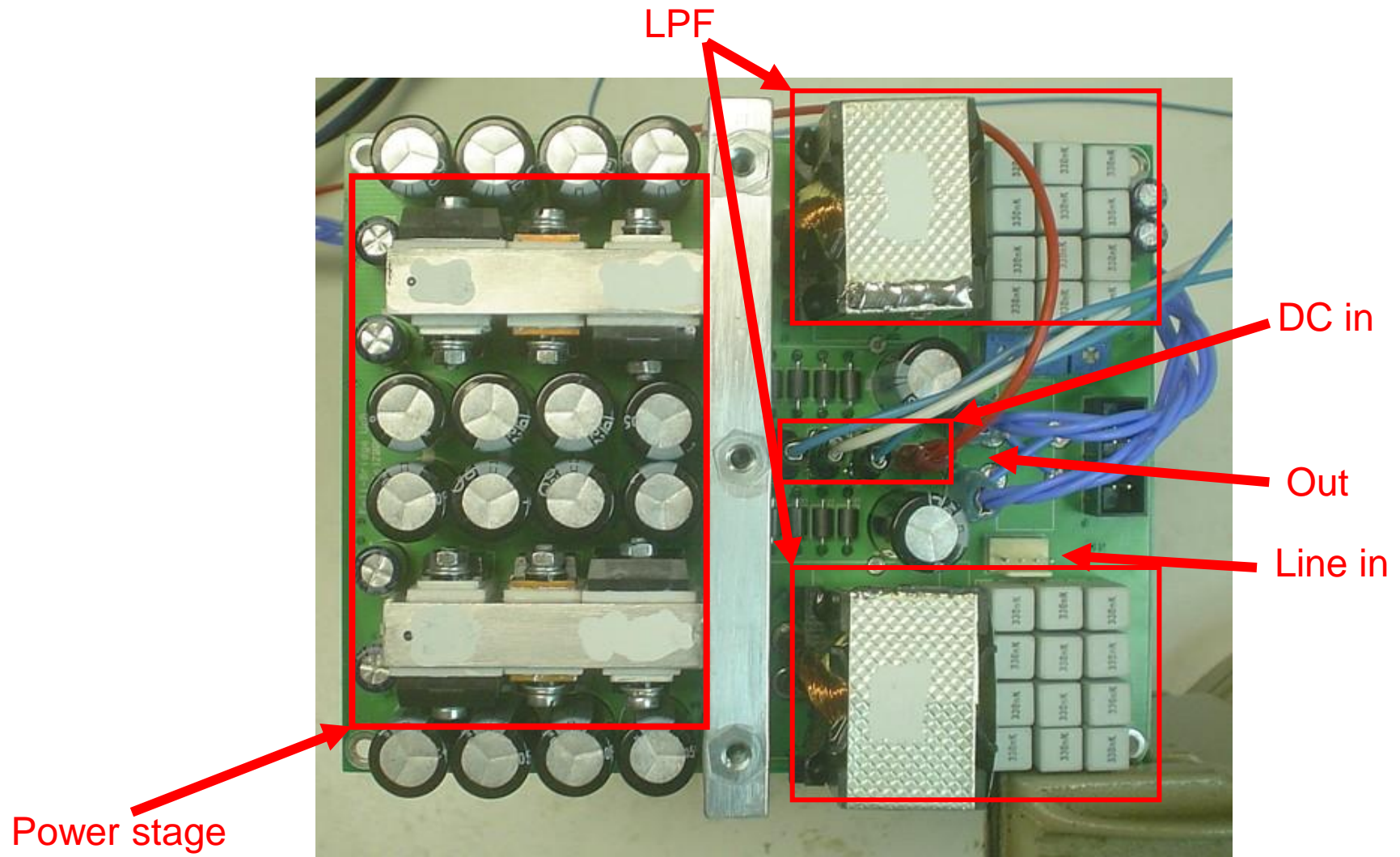
Amplifier A, differential mode

- 500mV/div. Note: relatively clean.



Class D and EMI

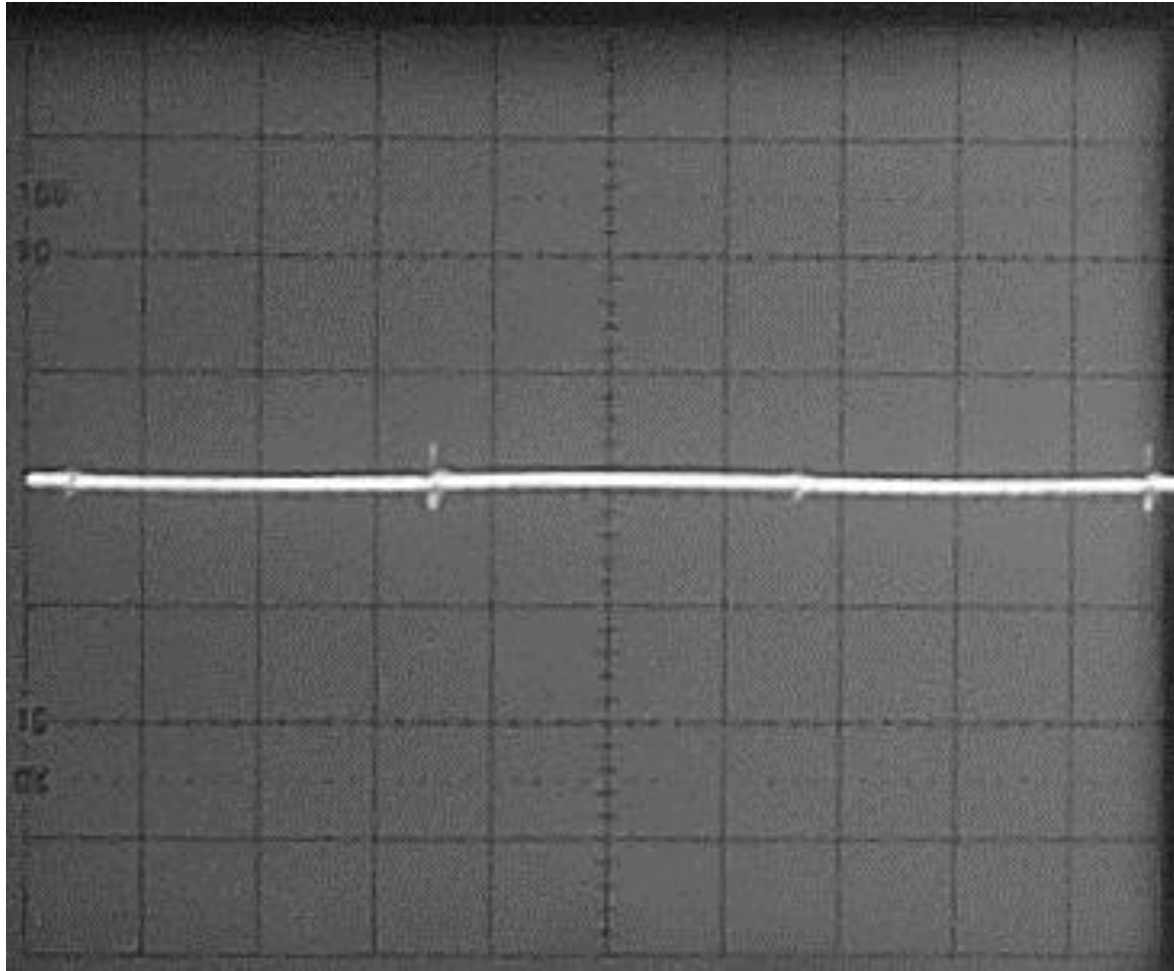
Example: Amplifier B, rated 2kW



Class D and EMI

Amplifier B, common mode

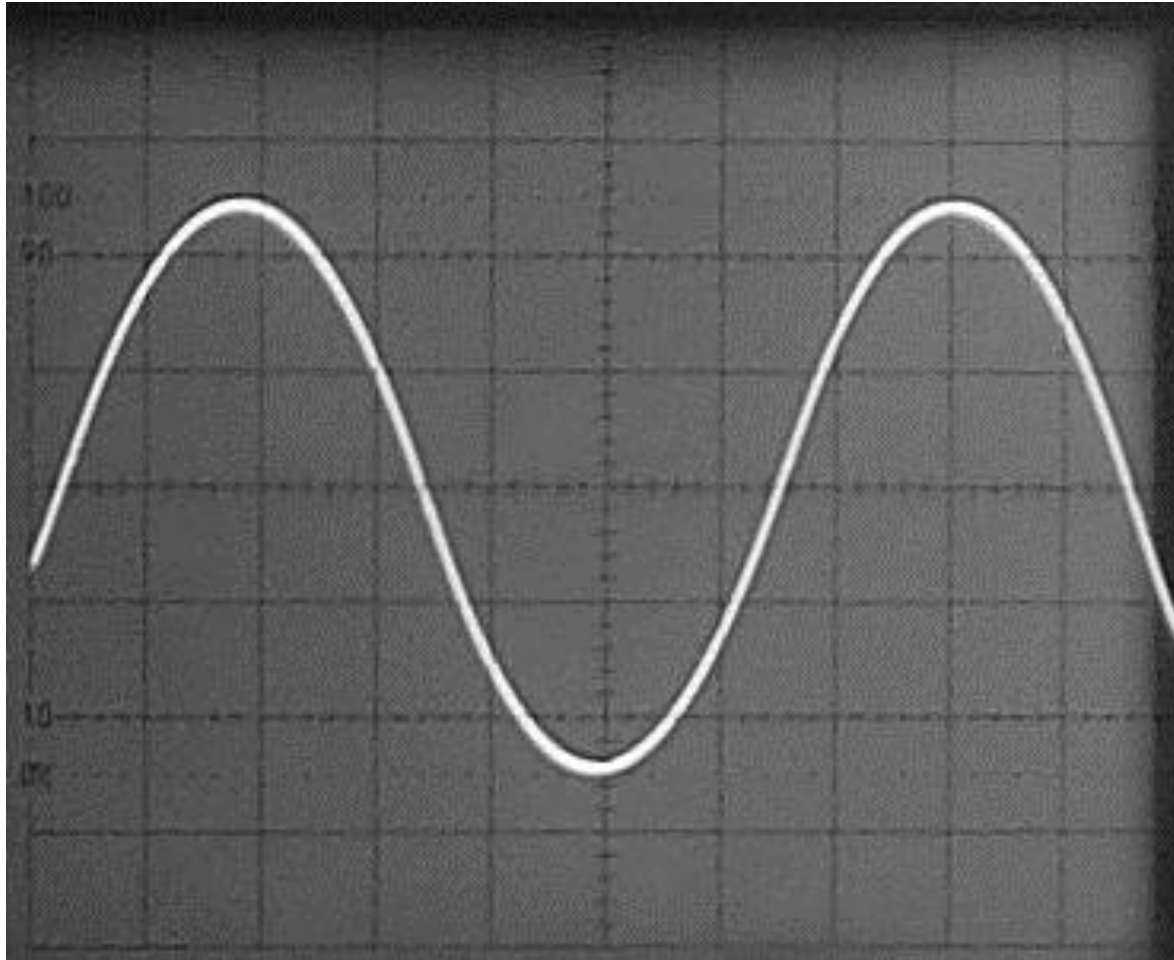
- 250mV/div. Probe clip at power GND faston tab



Class D and EMI

Amplifier B, differential mode

- 500mV/div.



Class D and EMI

Class D EMI is no mystery

- Eyeballing components and PCB gives good indication
- Invest in an analogue scope
- Don't bother EMC testing if the scope pic isn't squeaky clean

Summary

All “Unique Class D Technologies” are related

- All draw from a limited set of concepts
 - Modulation technique
 - Power stage arrangement
 - Loop control
- Not all are optimal
 - Too complex
 - Missed opportunities

Summary

Good design criteria: “black box”

- Audio performance
- Robustness
- Simplicity
- EMC, efficiency...

Bad design criteria: “open box”

- Perceived novelty and uniqueness
- Belief system
 - Digitalness
 - Feedbacklessness
- Powerpoint appeal

Summary of summaries

The Road To Heaven

- Specify the performance and accept the design

The Road To Hell

- Specify the design and accept the performance

Thank you!

