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AUTOMOTIVE SYSTEMS

Introduction to Class-D audio amplifiers

2007-01-12, Knott Arnold, aknott@harmanbecker.com

High-Tech driven by Passion.

- 1 Introduction
  - 1.1 Requirements
  - 1.2 Block diagram
- 2 Realization
  - 2.1 Error Amplifier
  - 2.2 Modulator
  - 2.3 Power Stage
  - 2.4 Filter
  - 2.5 Feedback
- 3 Summary

§ 1. Introduction

§ 1.1 Requirements

§ Transducer efficiency is low (< 3 %)

§ High electrical power levels required

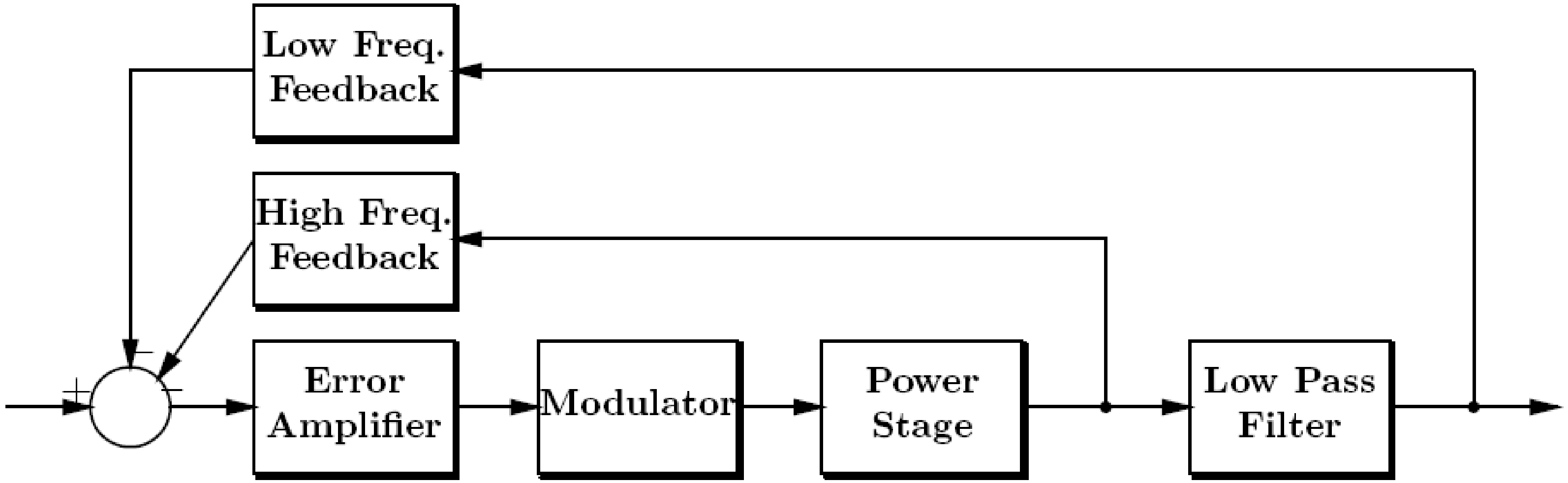
Typical sound	$P_{acoustic}$	$P_{electric}$
Refrigerator (background noise)	0.1 uW	3.3 uW
Talking (moderate music level)	10 uW	0.3 mW
Playing kids (typical listening level)	10 mW	33 mW
Trumpet (high listening level)	0.3 W	10 W
Concert (very high listening level at long distance)	100 W	3.3 kW

[1]

- Signal quality needs to be high since the human ear is the most sensible organ in the human body
- Signal to noise ratio (SNR)
  - Consumer and automotive: > 110 dB
  - Professional equipment: very strong dependent on distance from speaker to listener
- Distortion: < 0.01 %
- Frequency range: 20 Hz to 20 kHz
  - Note that the eye can not follow 100 Hz at the TV!

- 1. Introduction
  - 1.2 Block Diagram

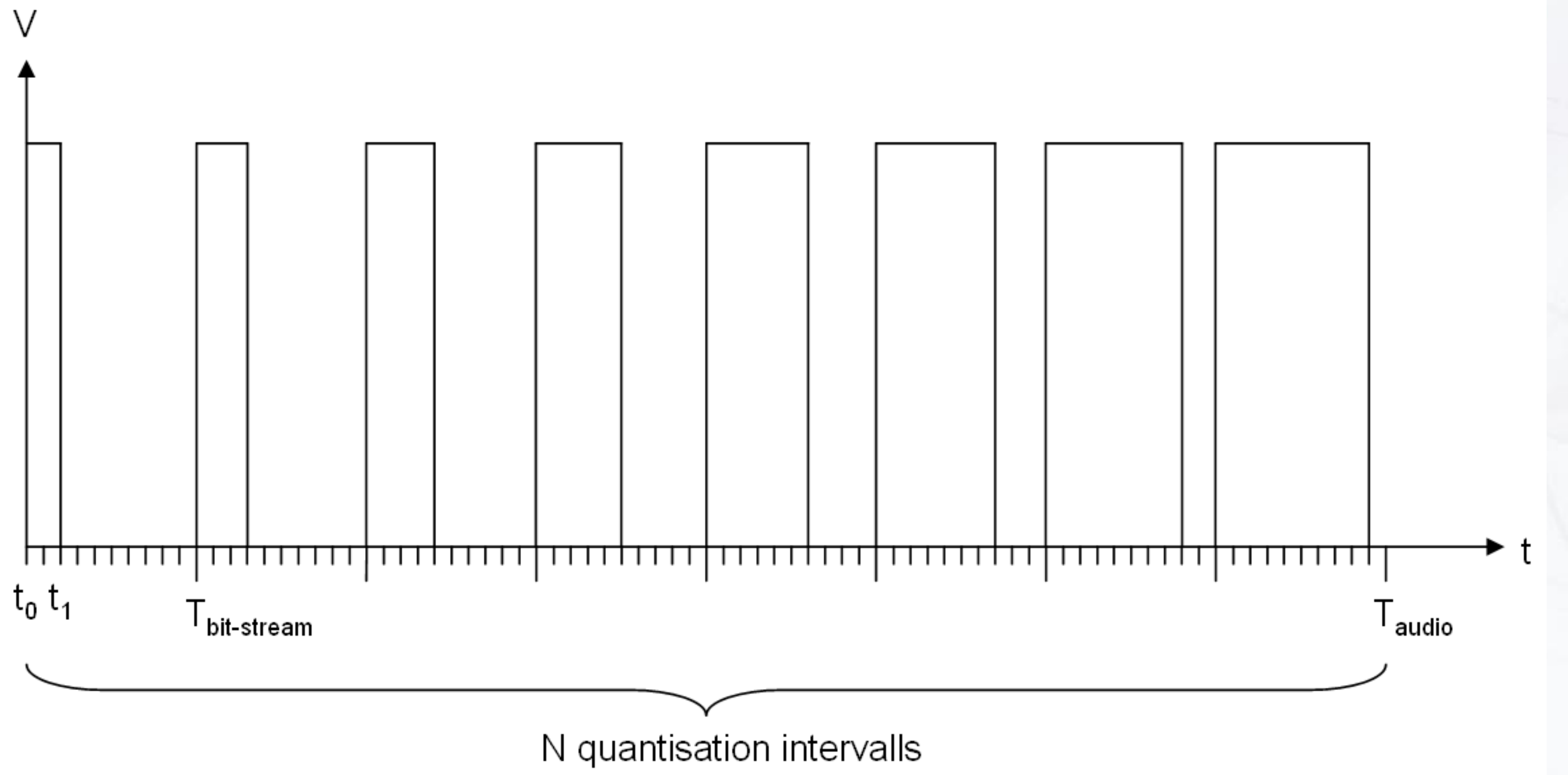
1.2 Block Diagram



- 2. Realization
  - 2.1 Error Amplifier
    - 2.1.1 Digital

- Digital control usually intrinsically contains the modulator
- Power stage requires a single bit stream
- => sequential coding
- SNR and highest audio frequency determine the speed of the microcontroller or digital signal processor (DSP)

Intro
Realization
Summary



- Quantization interval: $\Delta t = t_1 - t_0$
- $T_{bit\text{-}stream}$: period of switching frequency
- T_{audio}: period of highest audio frequency
- Sampling theorem: $T_{bit-stream} \leq \frac{T_{audio}}{2}$

2.1.1 Error Amplifier – digital – DSP speed

- SNR should be 110 dB
  - => Bit depth

$$N = \log_2\left(10^{\frac{110}{20}}\right) = 18.3\ bit$$

  - => One quantization interval:

$$\Delta t = \frac{1}{2^{19} \cdot 20\ \mathrm{kHz}} \approx 95.4\ \mathrm{ps}$$

  - => DSP output frequency:

$$f_{DSP} = \frac{1}{\Delta t} \approx 10.5\ \mathrm{GHz}$$

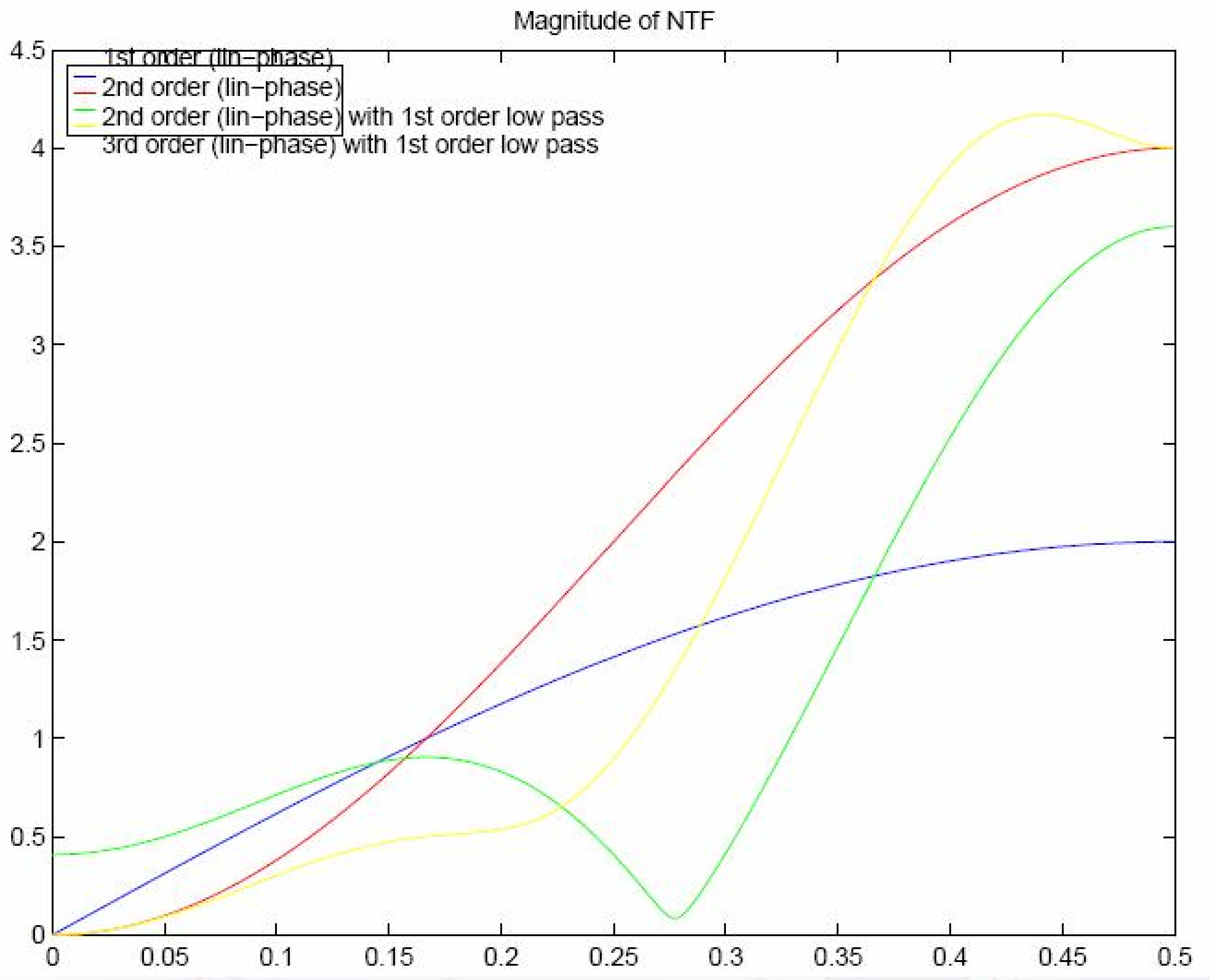
- Not achievable with DSPs known in the art
- Solutions: PEDEC [2], [3] and noise shapping

Intro

Realization

Summary

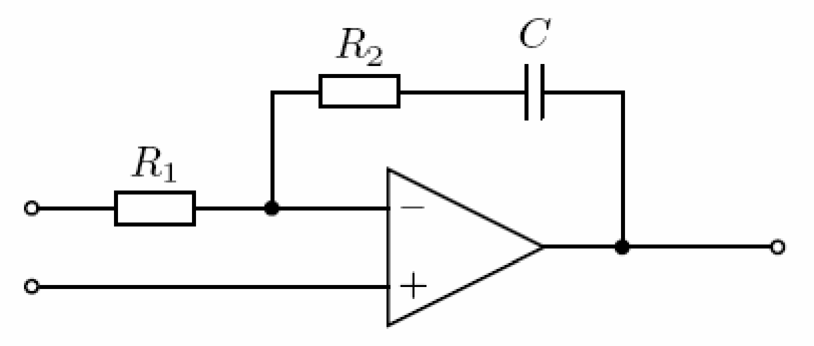
§ Noise shaping transfers noise from one frequency band into another one



- 2. Realization
  - 2.1 Error Amplifier
    - 2.1.2 Analog

- Analog error amplifiers usually are operational amplifiers (OPAMP)
- SNR of the system is determined by the noise floor of the OPAMP
- Distortion of the system is mainly determined by the linearity of the OPAMP

- Simple case: PI controller



$$\underline{H}(\underline{s}) = \frac{R_2}{R_1} + \frac{1}{\underline{s}R_1C}$$

- For stability reasons zeros are required
- Those might require further poles for compensation

- For 30 V output voltage:
  - 225 W into 4 Ohm load

$$N_{out} = \frac{S_{out}}{10^{\frac{110}{20}}} \approx 95\ \mu\text{V}$$

- Gain from error amplifier to output stage:
  - 60 V supply @ power stage (= V_{rail}),
  - 5 V supply @ error amplifier

$$G = \frac{V_{supply_{power-stage}}}{V_{supply_{error-amplifier}}} = 12$$

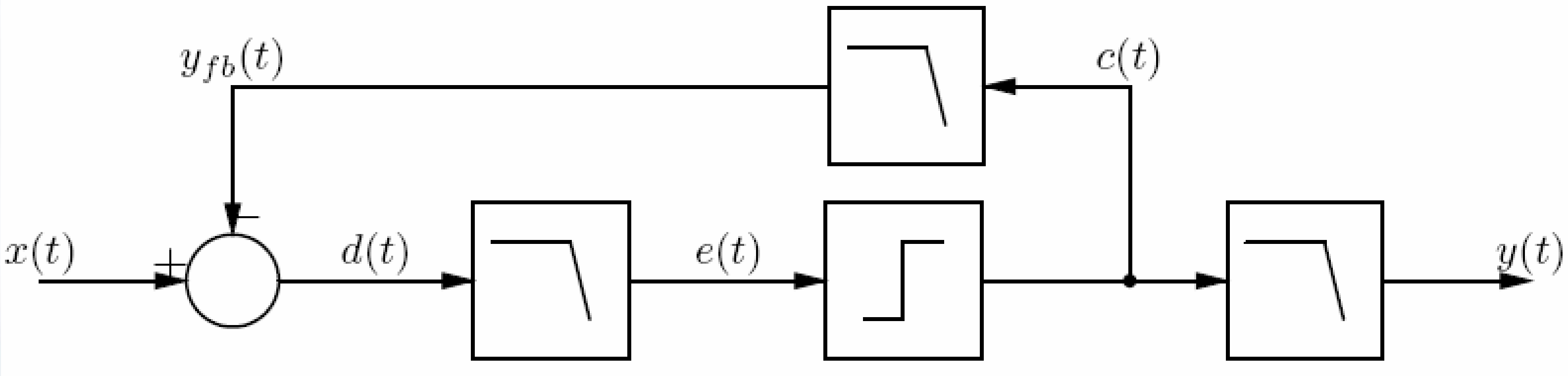
- Error amplifier noise:

$$N_{ea} = \frac{S_{out}}{G} \approx 8\ \mu\text{V}$$

- Most critical is the noise level in the frequency range from 1 .. 4 kHz

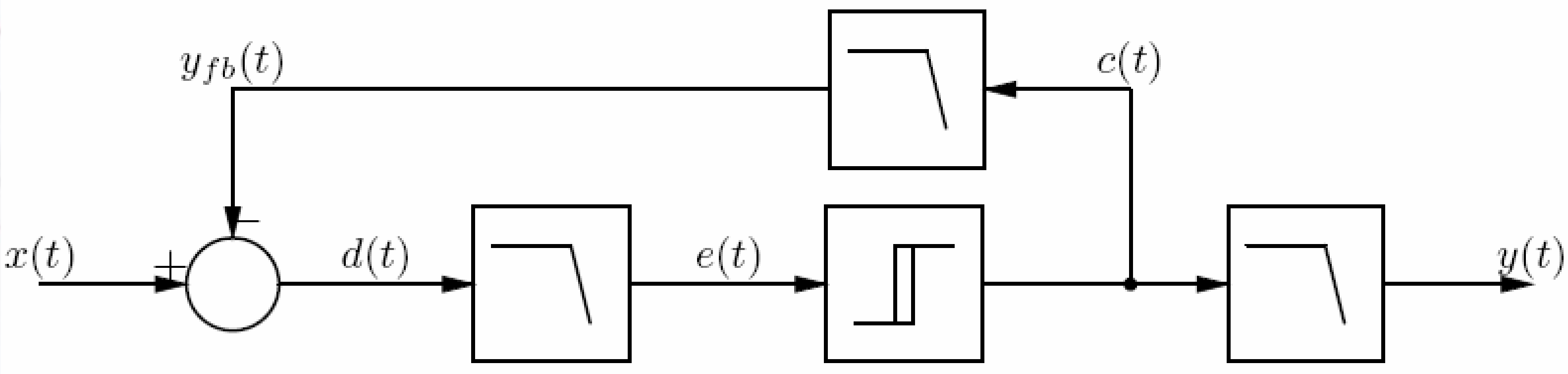
- 2. Realization
  - 2.2 Modulator
    - 2.2.1 Self Oscillating

§ Phase shift controlled oscillating modulator



[4]

§ Hysteretic controlled oscillating modulator

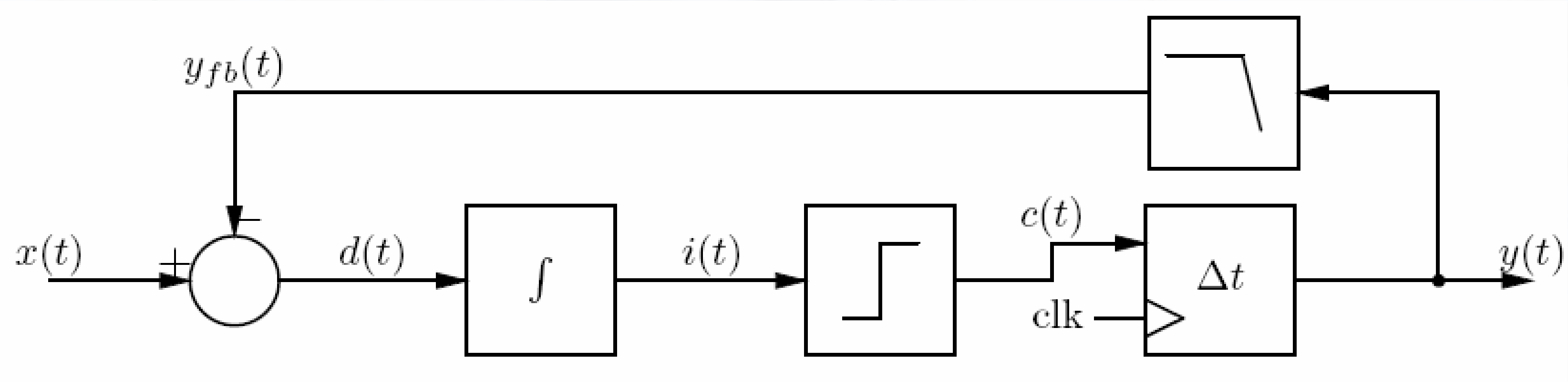


[5] & [6]

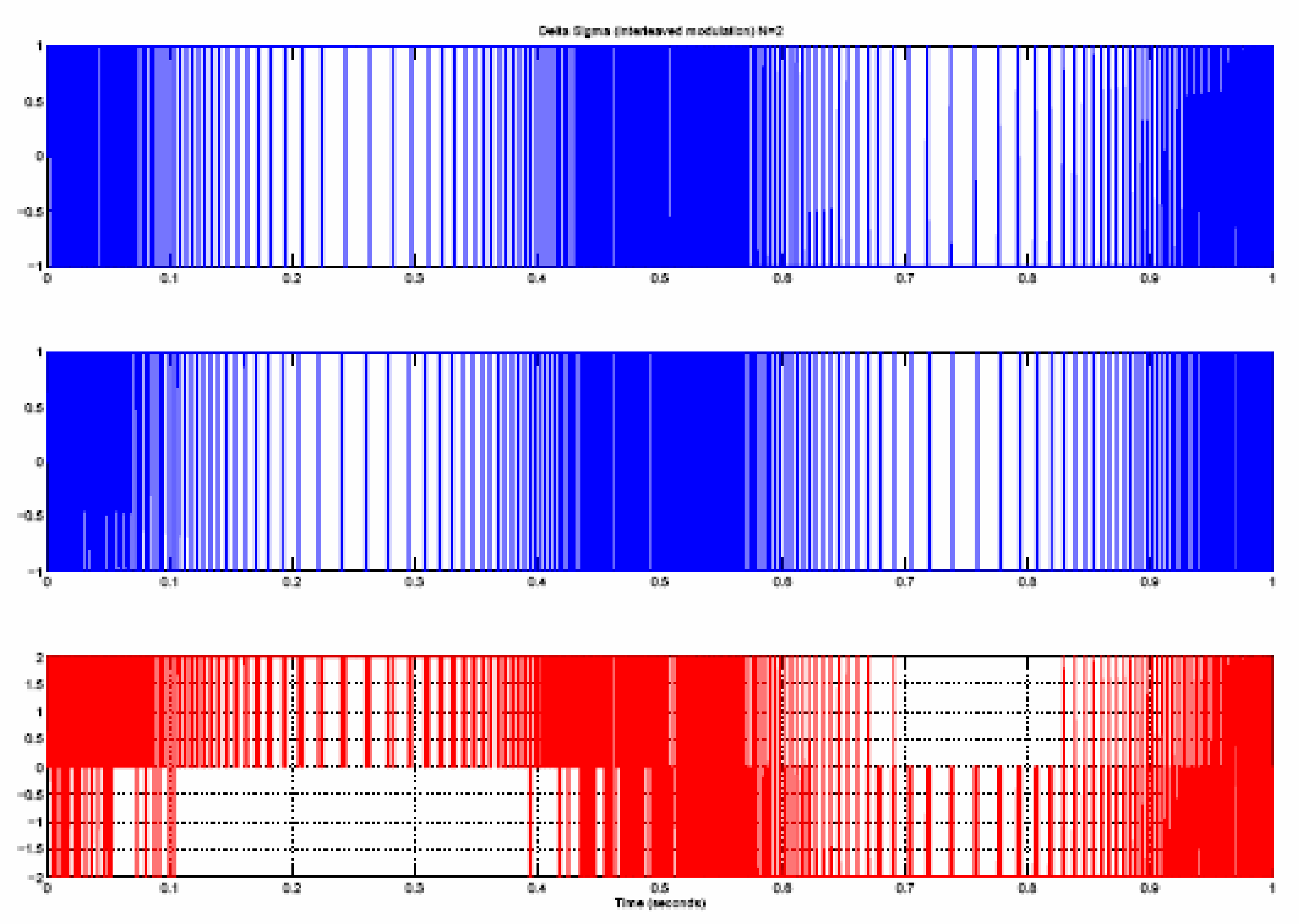
- Varying switching frequency in dependency of input level
- Conditionally stable intrinsically
  - => no stability problems
- High gain-bandwidth product
- Hysteretic varies frequency wider than phase shifted
- Other variants:
  - natural self oscillating modulator
  - Delay controlled oscillating modulator
- Higher EMC
- Less controllable EMC

- 2. Realization
  - 2.2 Modulator
    - 2.2.2 Sigma Delta

2.2.2 Modulator – sigma delta – block diagram

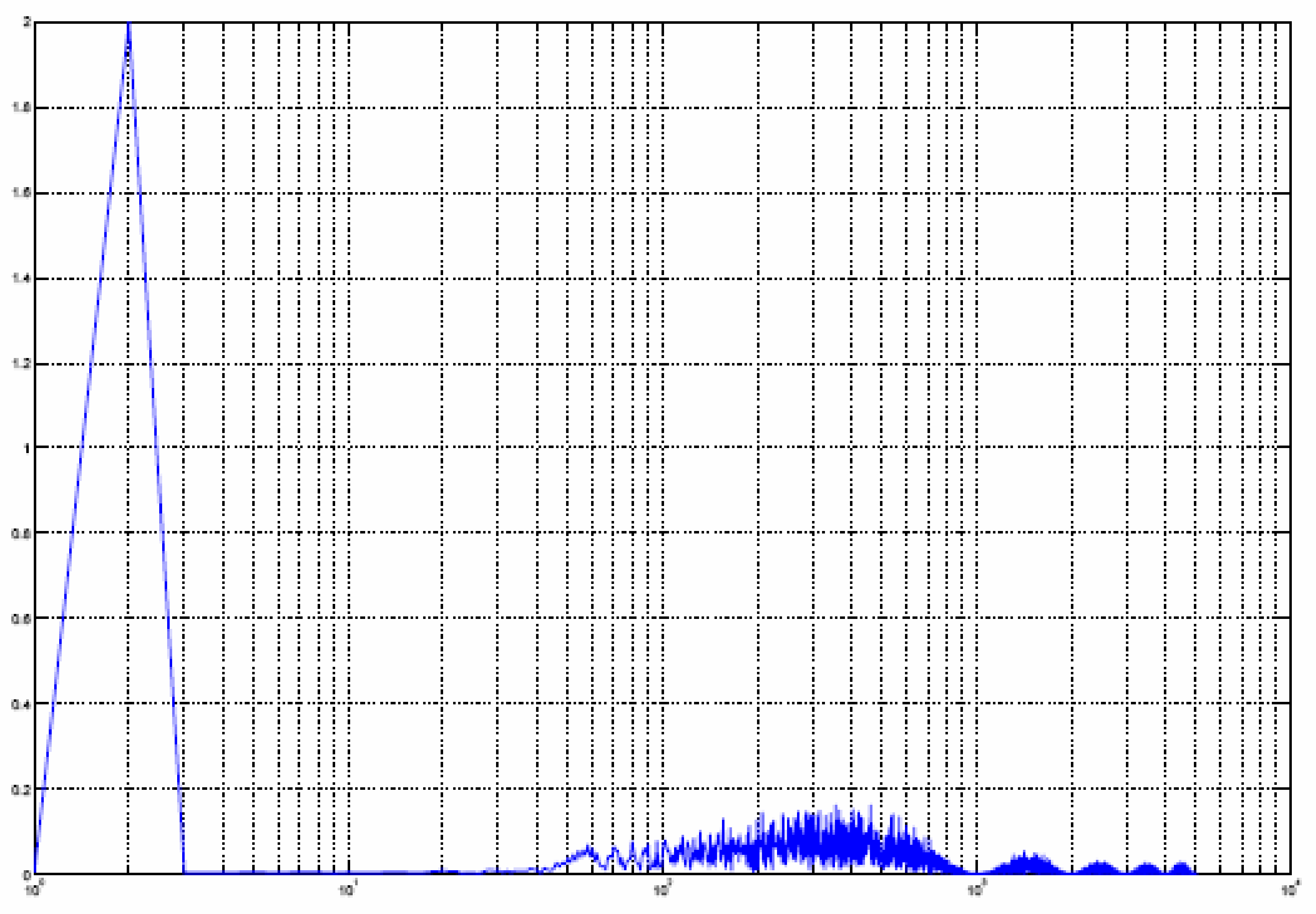


- As known from digital to analg converters (DACs) and analog to digital converters (ADCs)



§ Inphase, quadrature and interleave

2.2.2 Modulator – sigma delta – spectrum



- Interleaved frequency contents

2.2.2 Modulator – Sigma-Delta – Pros and Cons

- Pros
  - Simple feedback
  - Preferred for digital inputs
  - Simple noise shaping possibilities
  - Interleave possible
- Cons
  - High out-of-band noise levels (EMC)
  - Clock generator required

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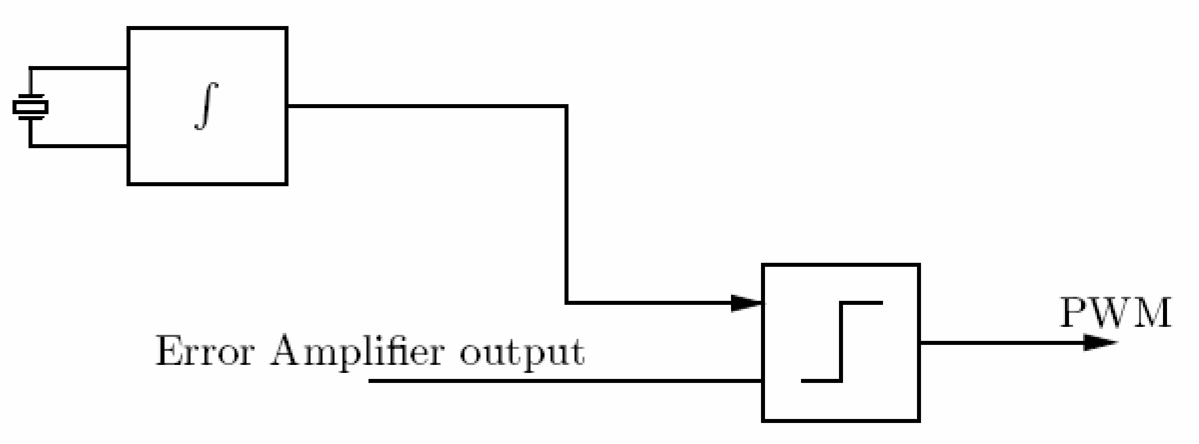
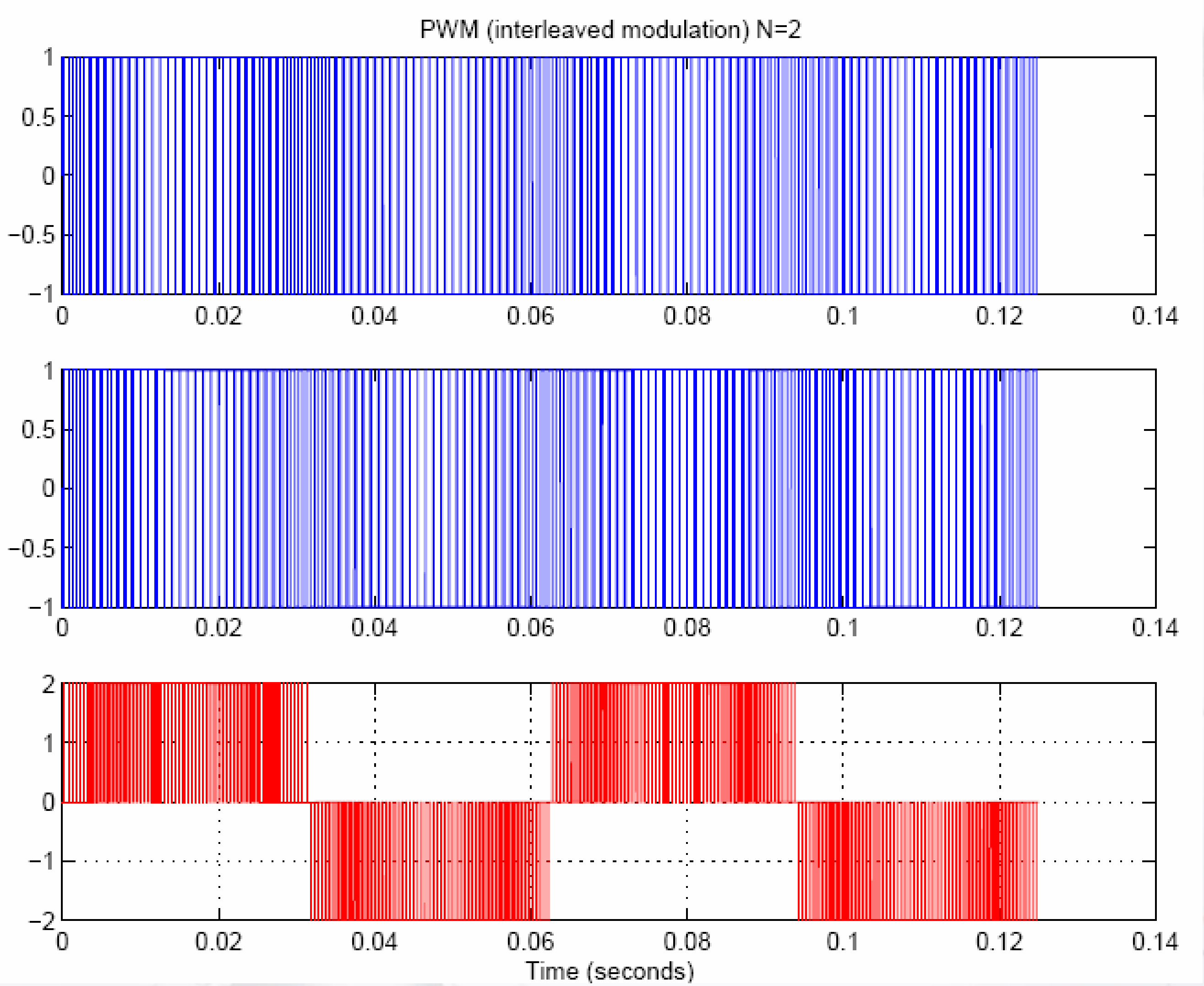
- 2. Realization
  - 2.2 Modulator
    - 2.2.3 Fixed Frequency

2.2.3 Modulator – fixed frequency (PWM) – block diagram



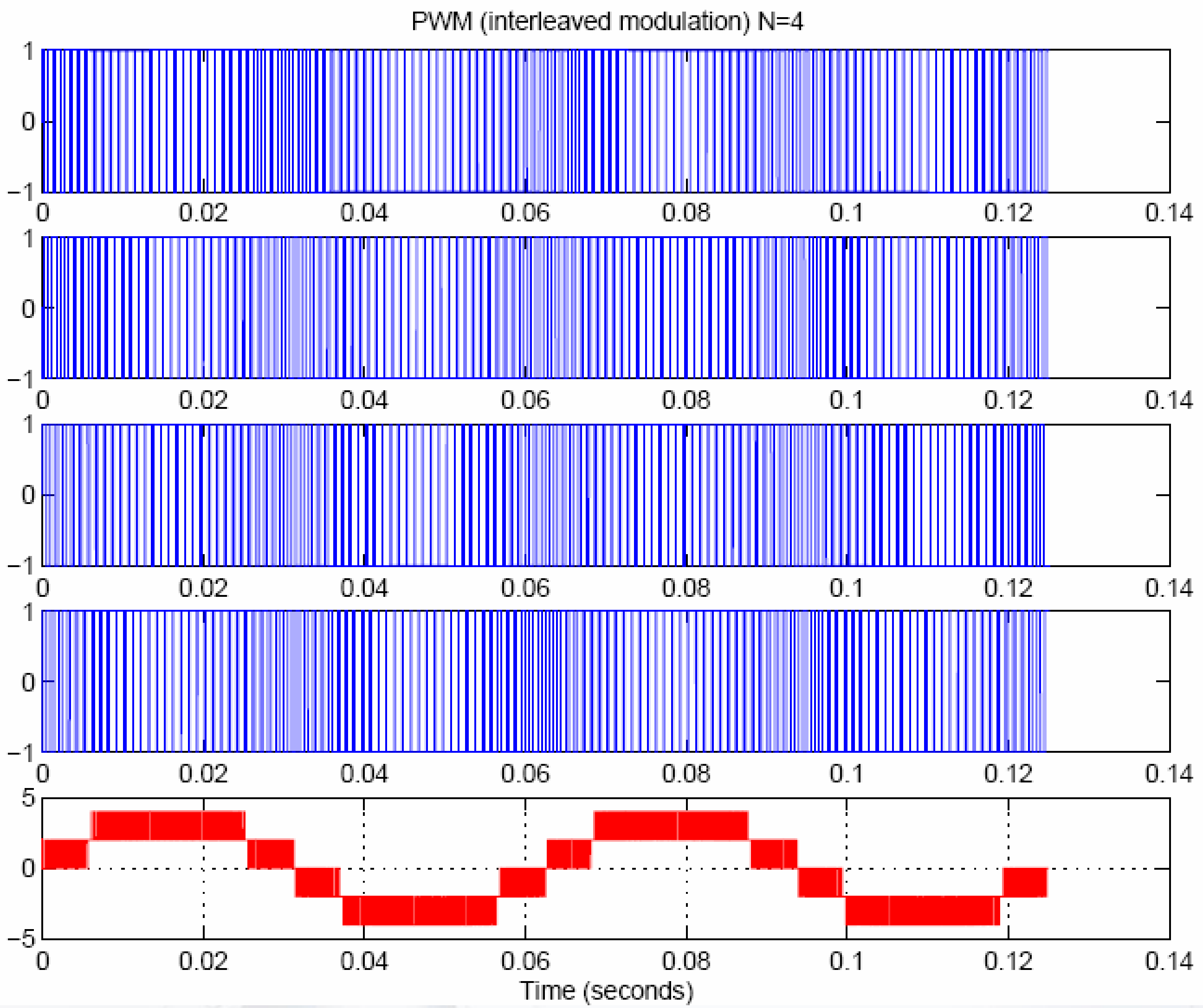
- Output of clock generator (carrier / reference) can either be a sawtooth or a triangle waveform
- This determines about single edge modulation or double edge modulation
- Multiple carriers can generate interleave
- Further overview: [7]

2.2.3 Modulator – fixed frequency (PWM) – signals



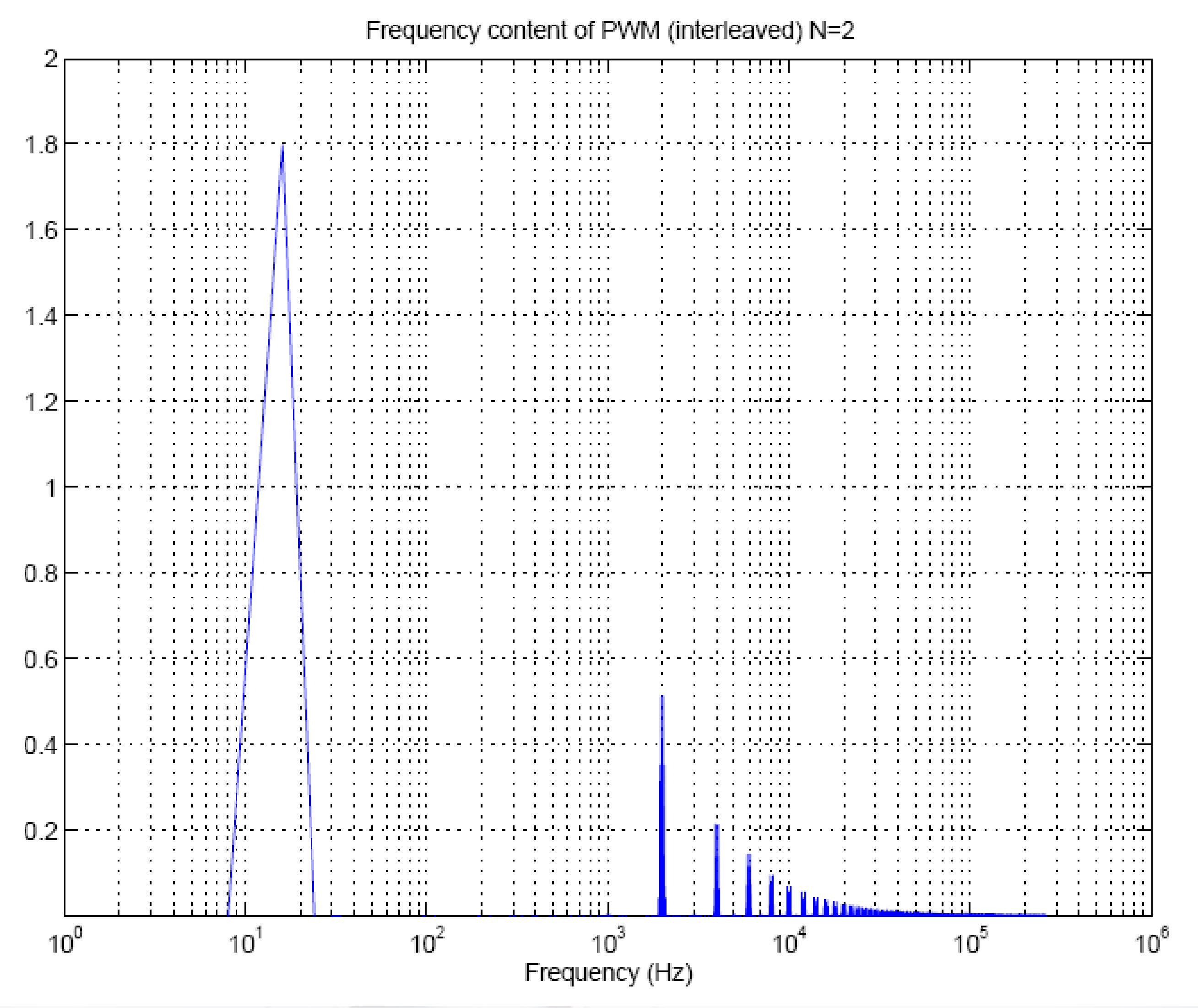
- Inphase, quadrature and interleave N=2

2.2.3 Modulator – fixed frequency (PWM) – signals



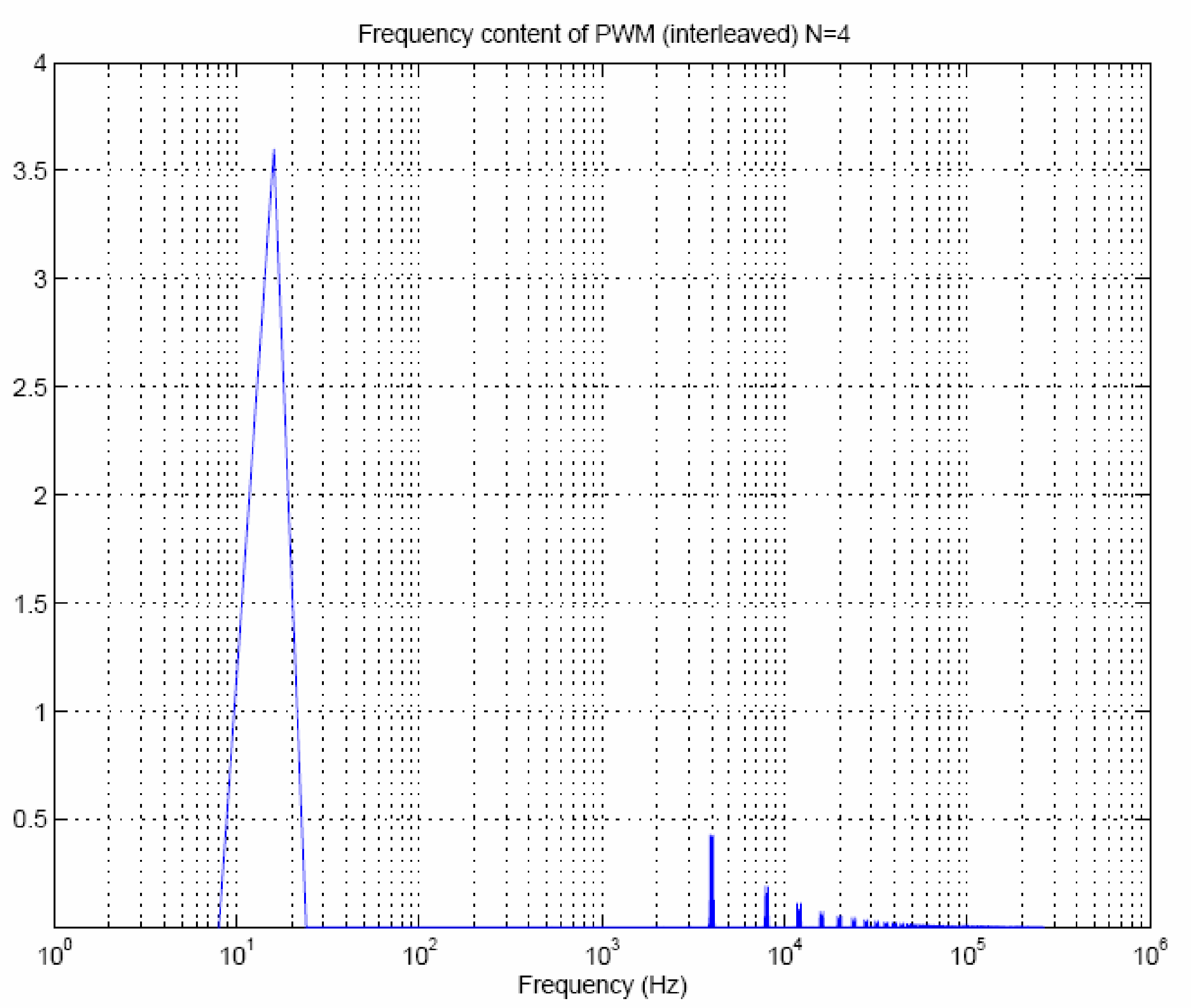
- Inphase, quadrature and interleave N=4

2.2.3 Modulator – fixed frequency (PWM) – spectrum



- Interleave N=2

2.2.3 Modulator – fixed frequency (PWM) – spectrum



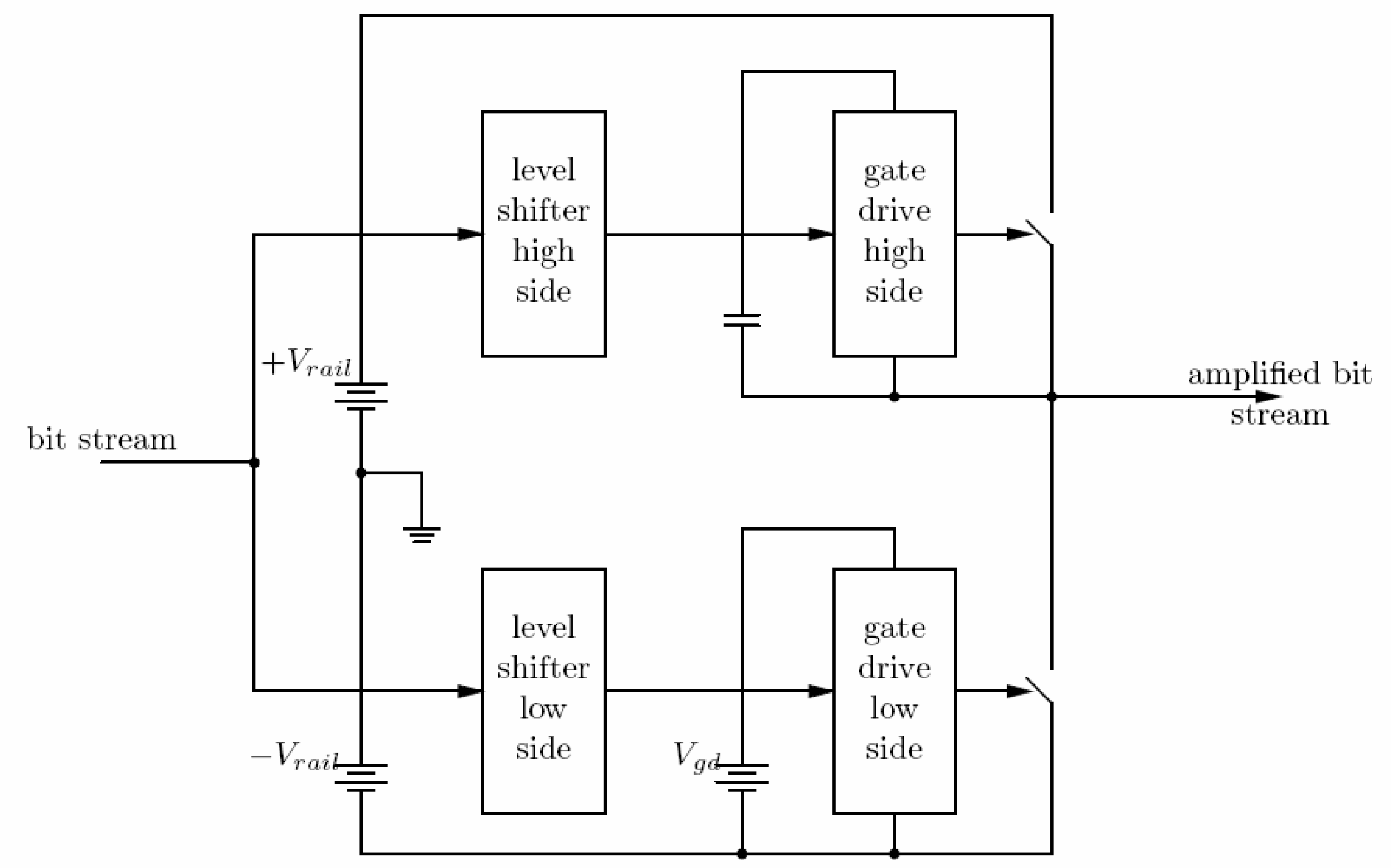
- Interleave N=4

2.2.3 Modulator – fixed frequency (PWM) – properties

- Fixed frequency modulators need an external clock generator
- PWM has higher predictable EMC
- Interleave is possible
- Further information about interleave can be found in [8]

- 2. Realization
  - 2.3 Power Stage

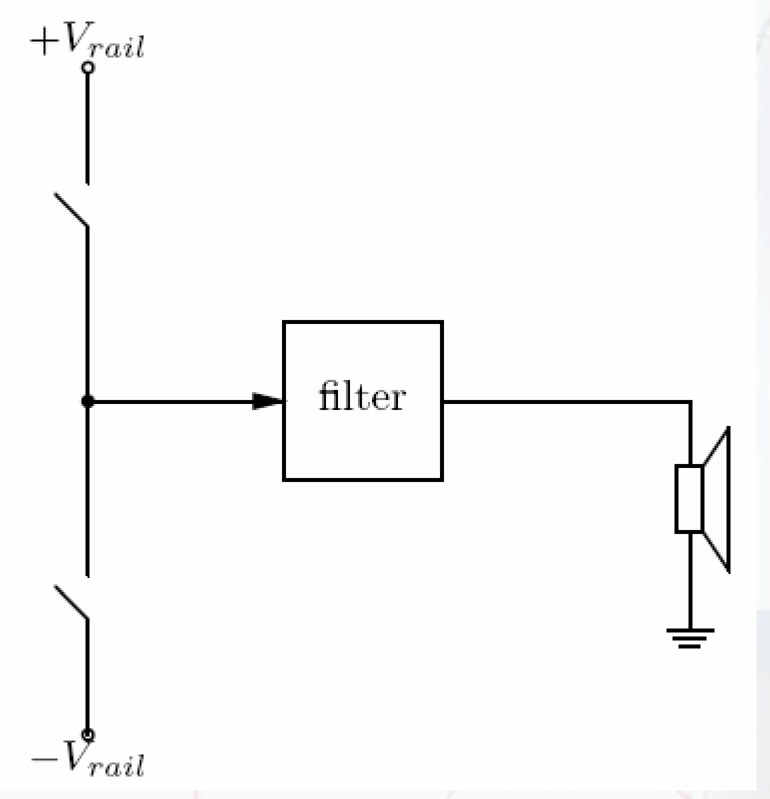
2.3 Power Stage – block diagram



- Increases signal level
- MOSFETs: n / n or p- / n-channel versions
- Power supplies need to be chosen carefully

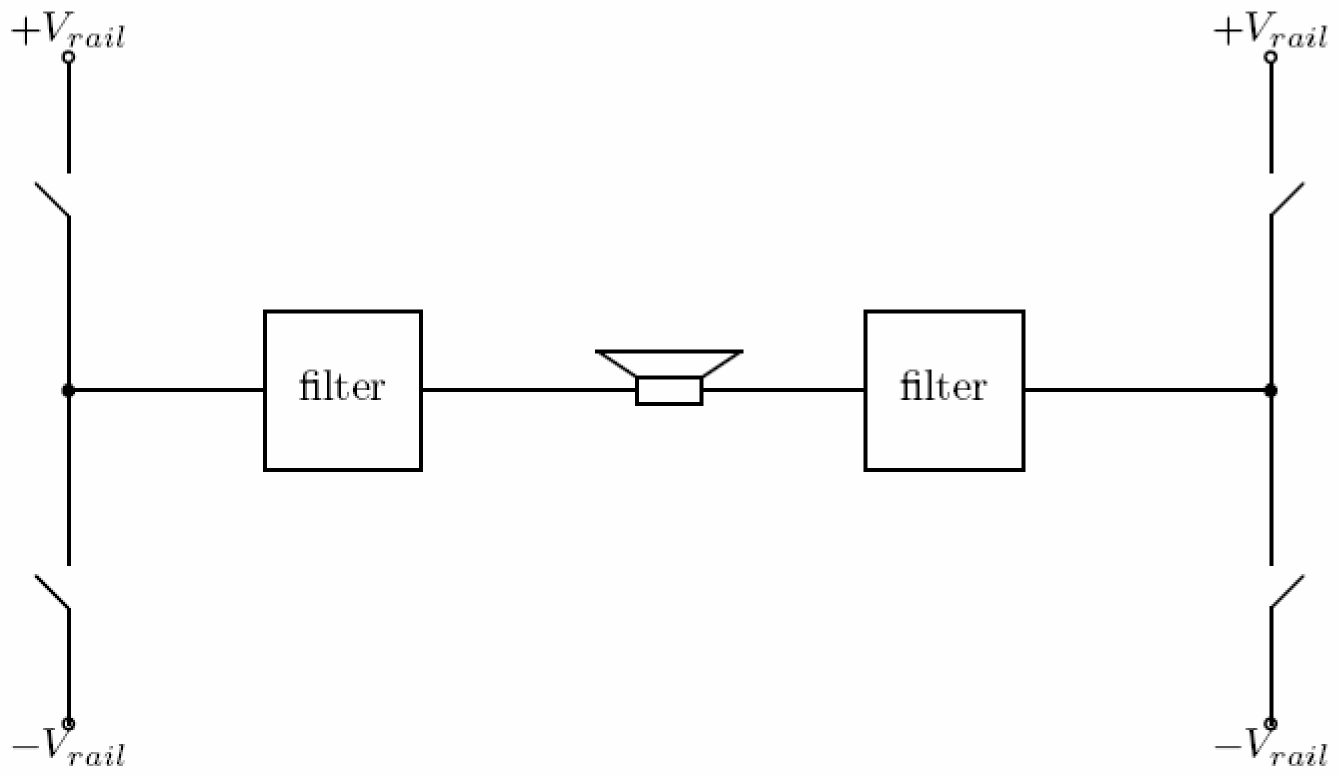
- 2. Realization
  - 2.3 Power
    - 2.3.1 Half Bridge

2.3 Power Stage – half bridge



- Power supply pumping
- No interleave possible
- Limited output power
- Requires balanced power supply
- Less board or chip area required

- 2. Realization
  - 2.3 Power
    - 2.3.2 Full Bridge



- No power supply pumping
- Interleave possible (even higher than 2)
- Theoretical unlimited output power
- Can be supplied with single supply
- More board or chip area required

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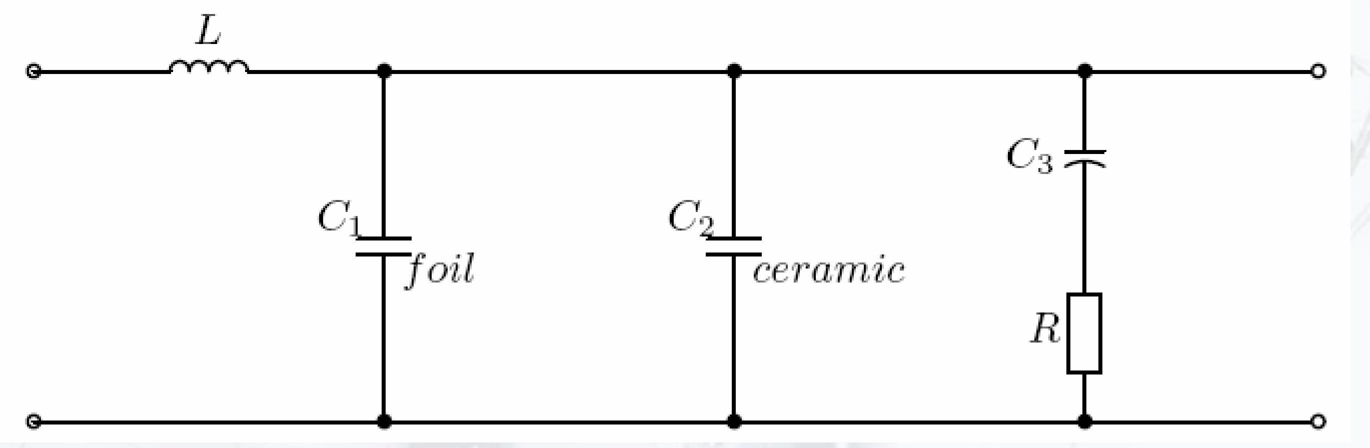
§ 2. Realization

§ 2.4 Filter

- Filter suppresses energy in EMC interested frequency ranges
- Filter passes audio unchanged
- => Low Pass
- Filter is applied to the amplified bit-stream
- => High energy levels are driven through the filter

- The energy levels driven through the filter usually never allow an active filter and none of those is known in the art.
- The filter is required to be lossless to keep the advantages of the efficiency common to all Class-D amplifiers, therefore consisting only of reactive components.
- The cut-off frequency of the filter needs to be between the highest audio frequency and the lowest switching frequency, to allow undamped passing of the audio signal and provide suppression of the high frequency material.

- The lower the cut off frequency should be, the bigger the capacitors and inductors in the filter are. Big values in those places cause increased parasitics within those, which have negative impact on the overall performance of the filter.
- The higher the frequency rises, the more also the traces on a board take effect.
- Undamped filters cause an overshoot in the spectral output of the amplifier while damping introduces losses.
- The materials used in the filter components – especially the cores of the inductors, as those are getting magnetized – need to be carefully chosen together with the used switches and the switching frequency (or switching frequency range) as a trade off between static and dynamic losses. Both of those loss mechanisms can be seen in all components which are applied to high voltage or high current stress. A more detailed reflection on those choices can be found in [9]



- Typical cutoff frequency: 50 kHz
- Typical switching frequencies: 200 kHz .. 500 kHz
- Typical values:
  - L: 10 uH .. 40 uH
  - C_1: 100 uF .. 500 uF
  - C_2: multiple hundred nF
  - C_3: multiple hundred nF
  - R: multiple Ohms

§ 2. Realization

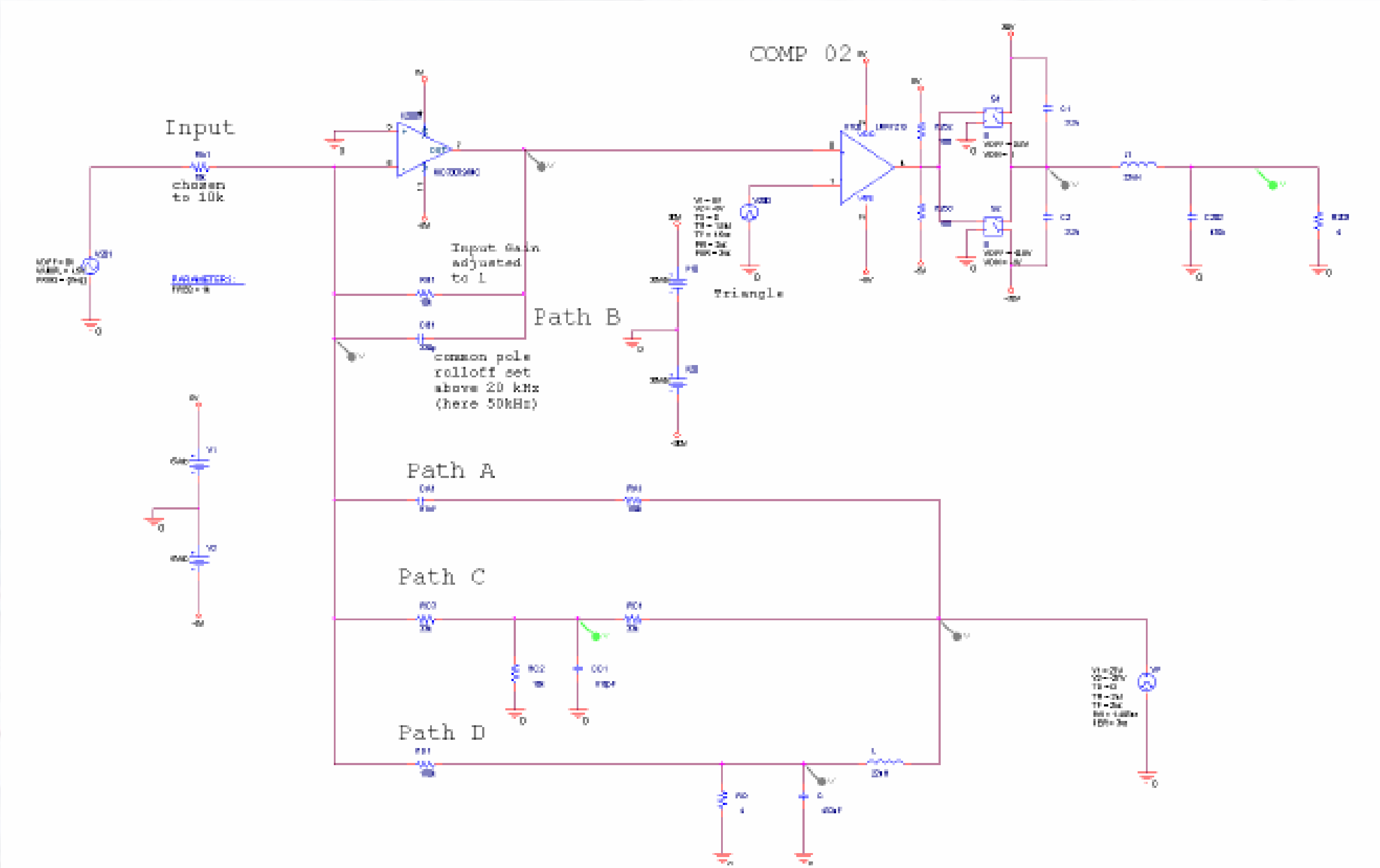
§ 2.5 Feedback

- Delay times in comparator, level shifter, gate drive and switches,
- Finite rise and fall times of the signal edges due to finite gain-bandwidth products in components,
- Nonlinearities in all of the above components and the output filter,
- Power supply perturbations,
- Varying component characteristics with temperature and humidity as well as varying operation points (due to the large signal nature of an amplifier)

- 2. Realization
  - 2.5 Feedback
    - 2.5.1 High Frequency Feedback

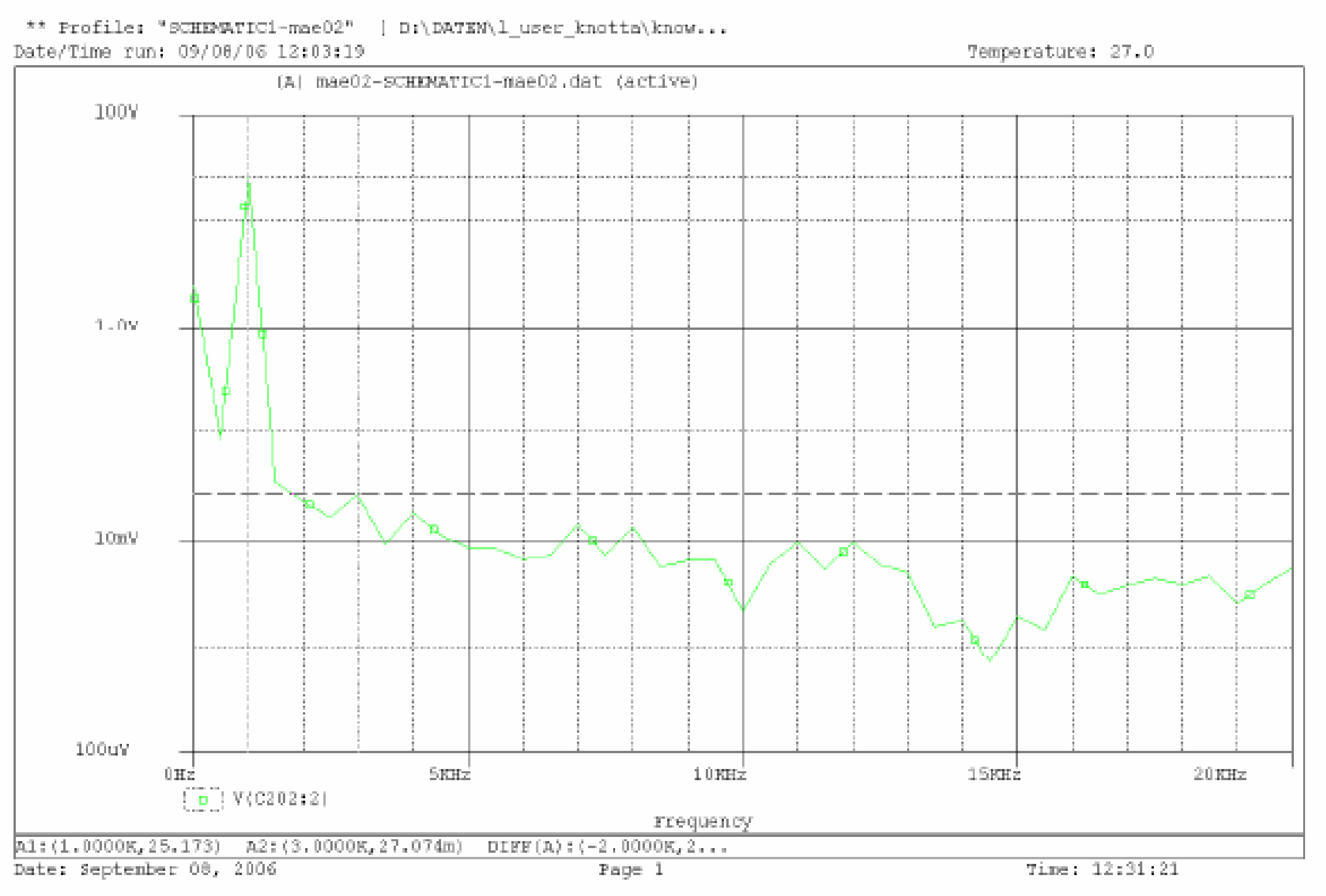
- High frequency feedback is taken from amplified bit-stream
- Modulators are multiplying signals
  - => frequencies can be added and subtracted
  - => subtracted frequencies can be mixed down from high frequency band into audio band
  - => need suppression

2.5.1 Feedback – high frequency feedback – open loop model



§ **Loops not closed, but high frequency fed into input => aliasing distortion!**

2.5.1 Feedback – high frequency feedback – aliasing distortion



- § 3 kHz component causes 0.108 % third harmonic distortion

- 2. Realization
  - 2.5 Feedback
    - 2.5.1 Low Frequency Feedback

2.5.1 Feedback – high frequency feedback

- Low frequency feedback is taken from behind the filter
  - => 180 ° phase shift involved
  - => impacts stability

2.5.1 Feedback – high frequency feedback – closed loops model

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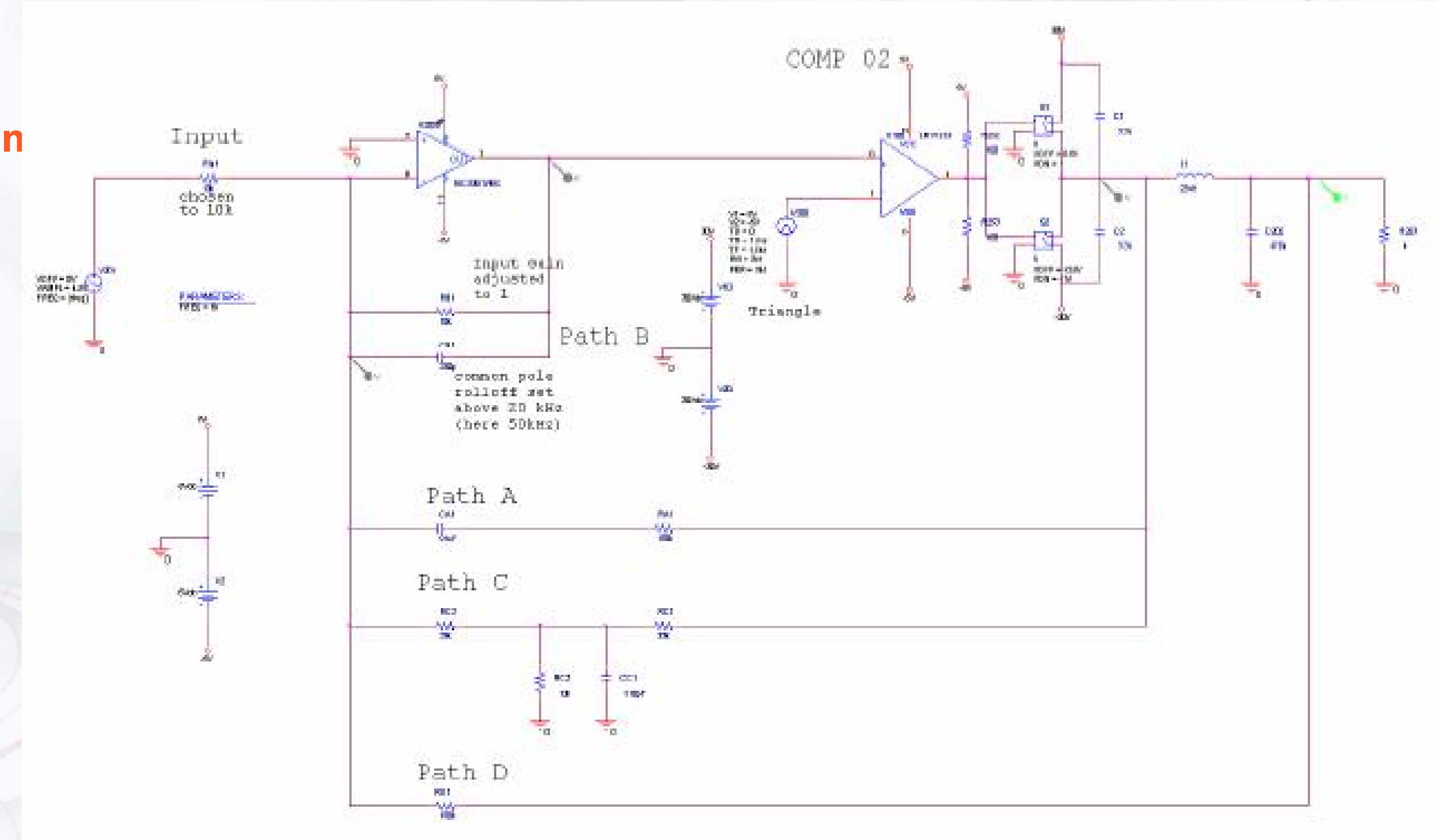
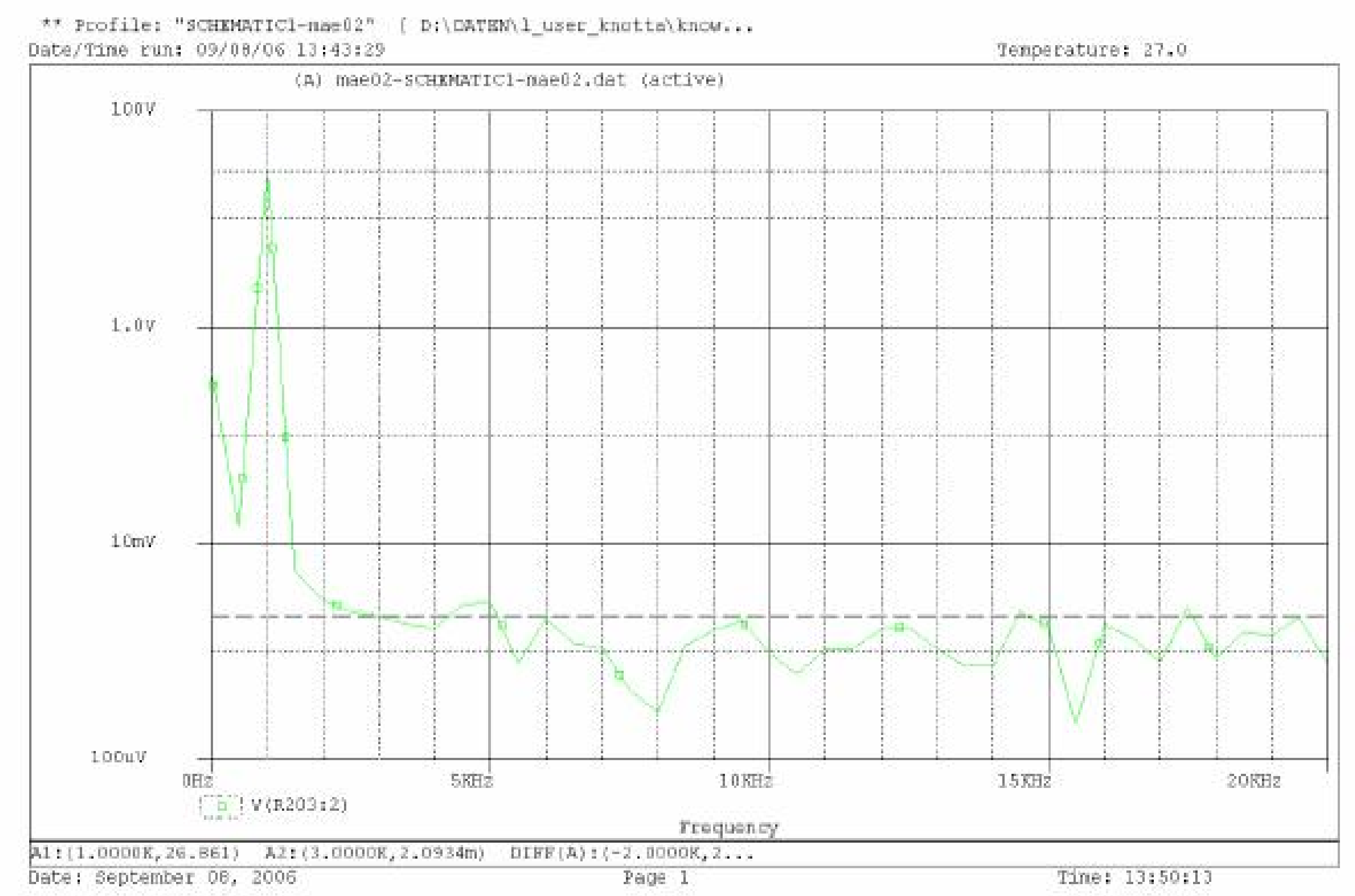


§ Loops closed similar to [10] & [11]

2.5.1 Feedback – high frequency feedback - results



- 22.2 dB suppression at 3 kHz
- => 0.008 % third harmonic distortion

- Switch mode amplifier design involves a lots of engineering disciplinaries:
  - circuitry
  - power electronics
  - active and passive components
  - high frequency circuit design
  - EMC
  - control theory
  - information theory
  - signal theory and waveform analysis
  - measurement technology
  - digital technology
  - programming
  - Microelectronics
- As well as: mechanics, acoustics, physics, biology, project management, economics and a LOTS OF FUN!

References

- [1] http://de.wikipedia.org/wiki/Schallleistung , 06. December 2006.
- [2] Karsten Nielsen. Pulse Edge Delay Error Correction (PEDEC)-A Novel Power Stage Error Correction Principle for Power Digital-Analog Conversion. AES Convention, Preprint 4602, 103, August 1997.
- [3] Karsten Nielsen. Digital PulseModulation Amplifier (PMA) Systems Based on PEDEC Control. AES Convention, Preprint 4942, 106, April 1999.
- [4] Thomas Frederiksen. A novel audio power amplifier topology with high efficiency and state-of-the-art performance. AES Convention, Preprint 5197, 109, September 2000.
- [5] Elbo GmbH. "selbstschwingender digitalverstärker". German Patent DE19838765, 26. August 1998.
- [6] Lars Risbo. Discrete-time modeling of continous-time pulse width modulator loops. AES Convention on Efficient Audio Power Amplification, 27th, September 2005.
- [7] Ph.D. Karsten Nielsen. Audio Power Amplifier Techniques With Energy Efficient Power Converion. Department of Applied Electronics, Technical University of Denmark, DK-2800, Lyngby, 30. April 1998.
- [8] Gerald R. Stanley, Kenneth M. Bradshaw. Precision DC-to-AC Power Conversion by Optimization of the Output Current Waveform - The Half Bridge Revisited. IEEE Transactions on Power Electronics, 14(2), March 1999.
- [9] Robert W. Erickson, Dragan Maksimovitc. Fundamentals of Power Electronics. Kluwer Academic Publishers, 101 Philip Drive, 2004.
- [10] Risbo; Claus E. Neesgaard Lars. Loop filter for class d amplifiers. US-Patent US7002406, 21. February 2006.
- [11] Claus Neesgaard Lars Risbo. Pwm amplifier control loops with minimum aliasing distortion. In 120th AES Convention, May 2006.

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Thank you for your interest!

I am looking forward to your questions!