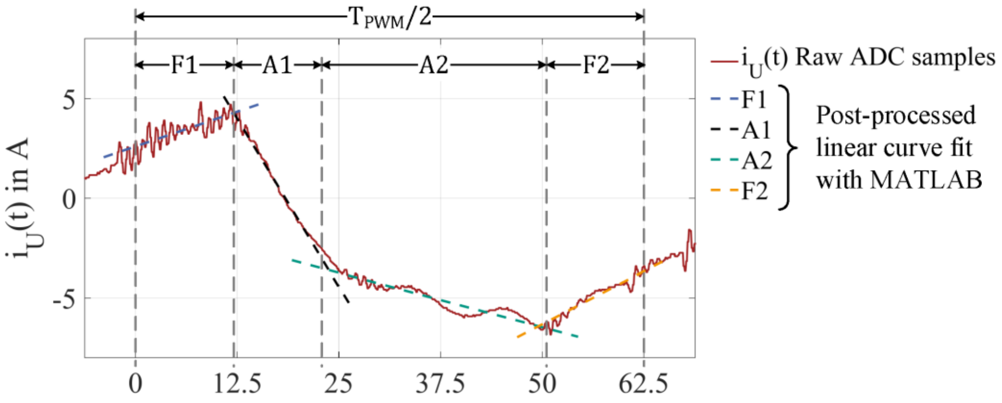
Measurement of Inverter Induced Current Slopes

for Control and Identification Algorithms in Power Electronics and Electrical Drives Applications

Dr. Andreas Liske



„Measuring di/dt"

What's it good for?

- ✓ Online Parameteridentification
- ✓ Gradient based control
- ✓ Sensorless control
- ✓ Failure detection

Challenges to tackle:

- very short measurement times → high switching frequencies & small duty cycles
- noise → Fast and hard switching power semiconductors, EMI
- low cost demand

Agenda

I. Motivation

II. Methods to identify the current slopes

   a) Direct methods

      1. Dedicated di/dt-sensors
      2. Analog Differentiation
      3. PCB-integrated planar Rogowski-coil

   b) Indirect methods

      I. Oversampling – Least Latency Least-Squares-Estimator
      II. Sub-Sampling – „Easy Current Slope Detection“

III. Conclusion

Agenda

I. Motivation
1. Online Parameter Identification

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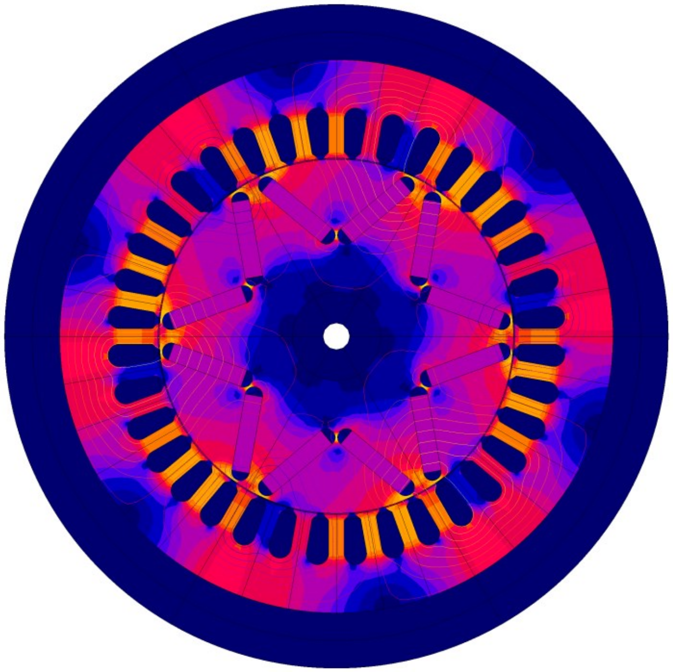
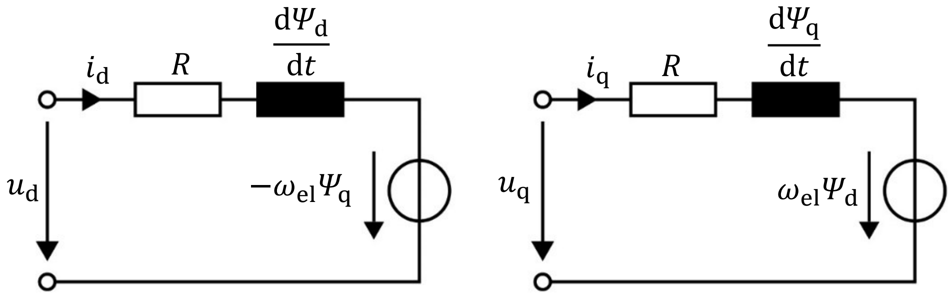


System equations in dq reference frame

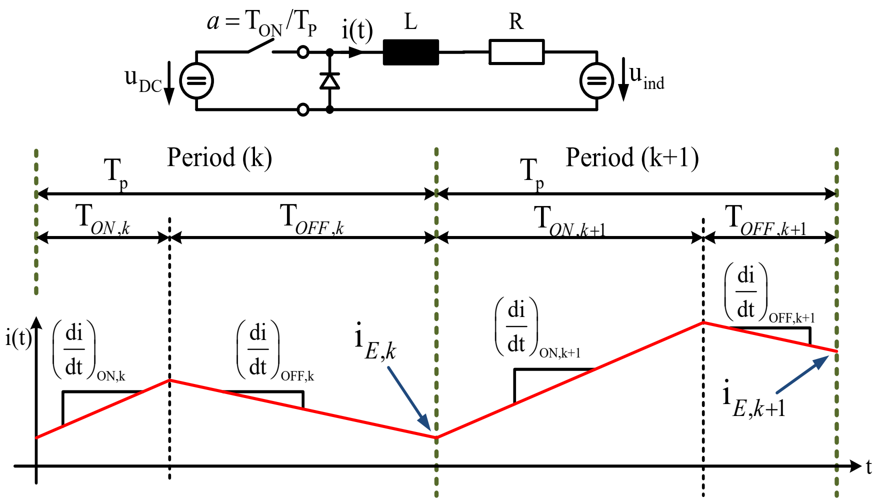
$$u_d = R \cdot i_d + L_{dd} \cdot \frac{di_d}{dt} + L_{dq} \cdot \frac{di_q}{dt} - \omega_{el} \cdot \Psi_q$$

$$u_q = R \cdot i_q + L_{dq} \cdot \frac{di_d}{dt} + L_{qq} \cdot \frac{di_q}{dt} + \omega_{el} \cdot \Psi_d$$



I. Motivation

2. Direct Adaptive Current Control - Basic Working Principle



$$i_{E,k+1} = i_{E,k} + T_{ON,k+1}\left(\frac{di}{dt}\right)_{ON,k} + T_{OFF,k+1}\left(\frac{di}{dt}\right)_{OFF,k}$$

with u_{DC}, L, R, u_{ind} $\approx$ const. for $2 \cdot T_P$

Knowledge of the ***current slopes***, depending on each ***switching state***

Duty cycle for a given current setpoint can be calculated

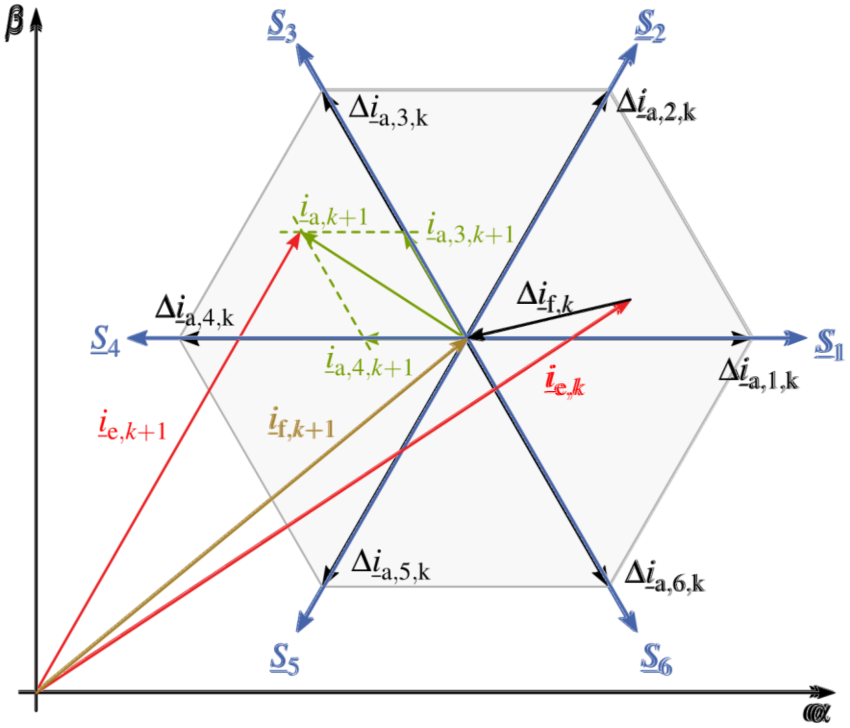
No control path parameters required!

I. Motivation

2. Direct Adaptive Current Control – Isotropic PMSM (L_d=L_q)

„Current Gradients“

- For isotropic PMSM, the six $\Delta i_{a,n}$ span an equilateral hexagon
- Setpoint steps inside the hexagon can be set accurately within one period (deadbeat)



I. Motivation

2. Direct Adaptive Current Control – Anisotropic PMSM ($L_d \neq L_q$)

„Current Gradients“

$$\Delta \underline{i}_{a,n} = \frac{2u_s T_P}{3(L_A^2 - L_B^2)} \left(L_A e^{j\varphi_n} - L_B e^{j[2\gamma(t)-\varphi_n]} \right)$$

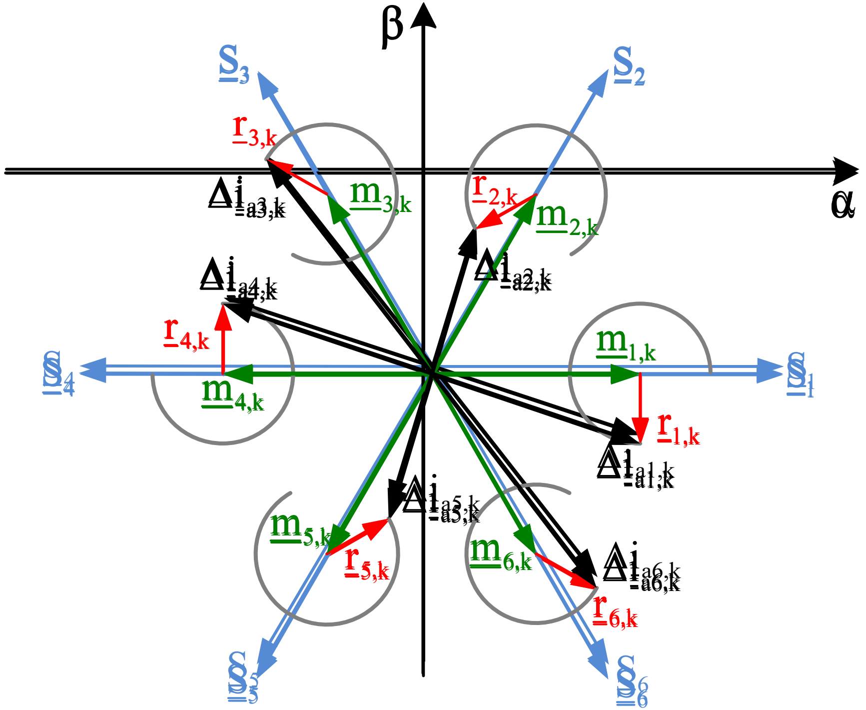
$$= \underline{m}_n + \underline{r}_n$$

$$\underline{m}_n = \frac{2u_s T_P}{3(L_A^2 - L_B^2)} \cdot L_A \cdot e^{j\varphi_n}$$

$$\underline{r}_n = \frac{2u_s T_P}{3(L_A^2 - L_B^2)} \cdot L_B \cdot e^{j[2\gamma(t)-\varphi_n]}$$

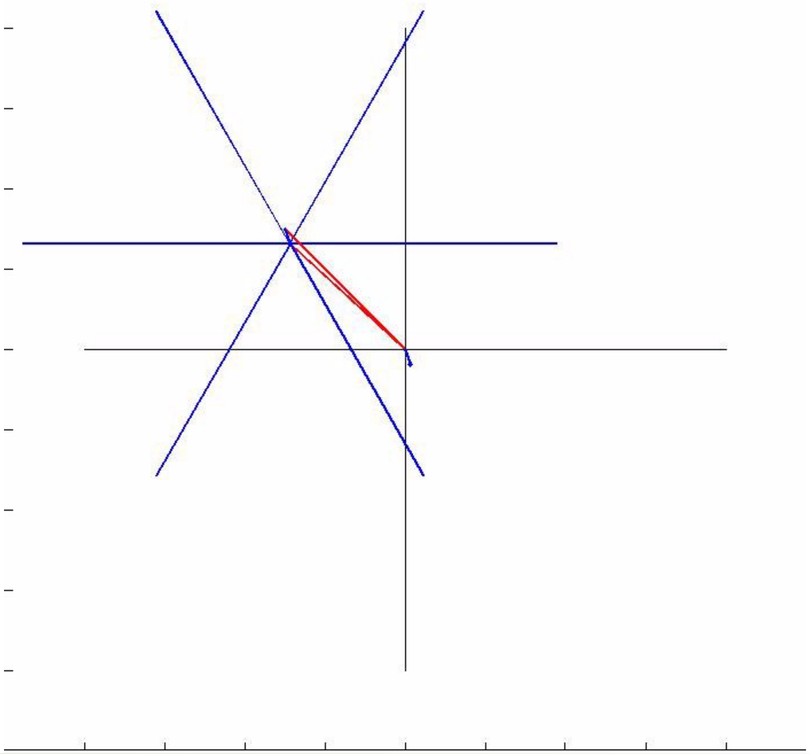
$$L_A = \frac{1}{3}(L_d + L_q)$$

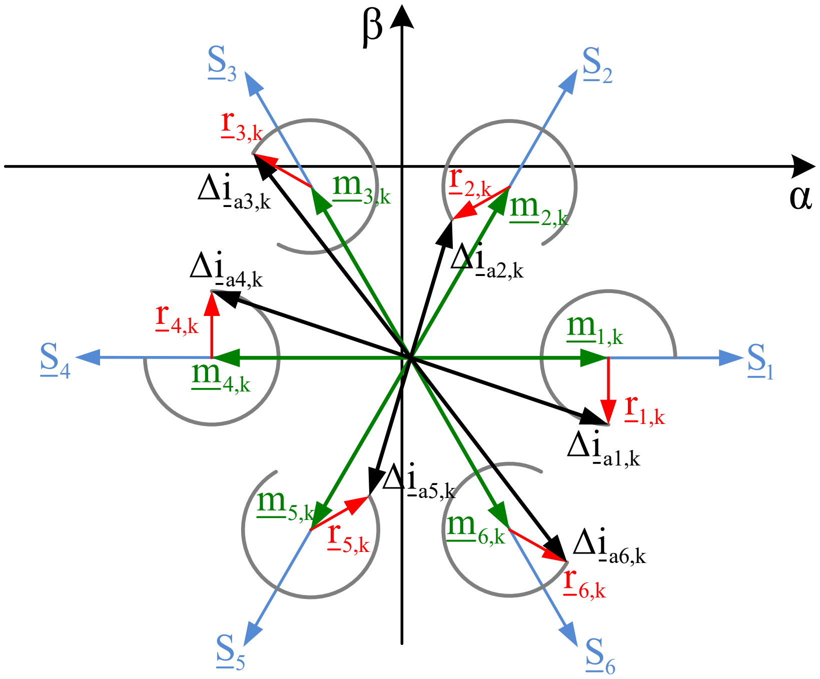
$$L_B = \frac{1}{3}(L_d - L_q)$$



I. Motivation

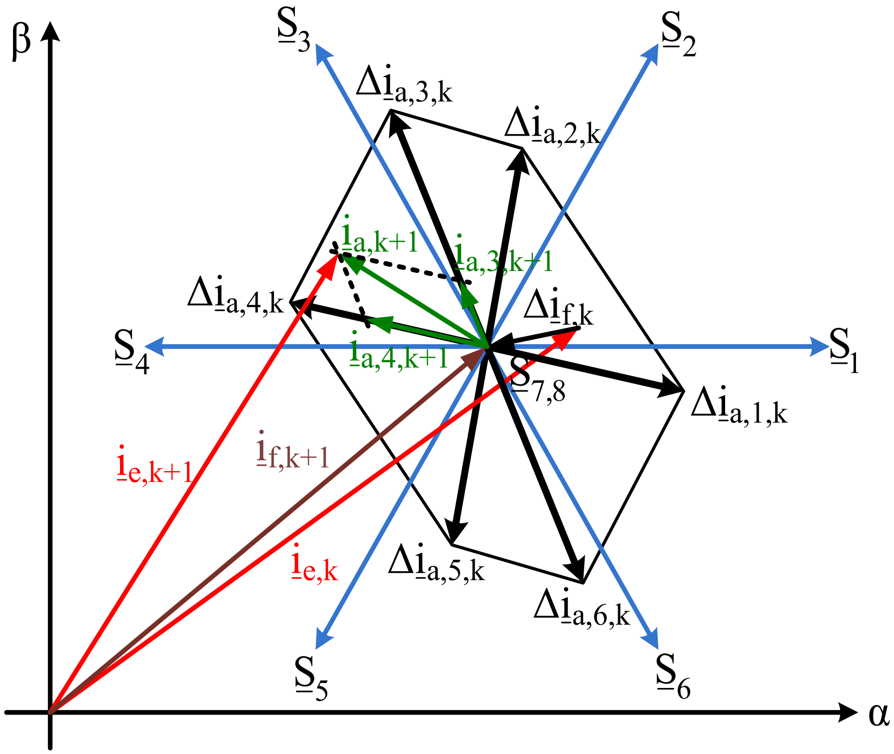
2. Direct Adaptive Current Control – Adaption on anisotropic PMSM ($L_d \neq L_q$)





I. Motivation

2. Direct Adaptive Current Control – Anisotropic PMSM ($L_d \neq L_q$)



- With $L_d \neq L_q$ the six $\Delta i_{a,n}$ show different lengths and the anglesdiffer from those of the switching states vectors $\underline{S}_n$
- The hexagon is symmetric but not equilateral and in addition time variant
- Control mechanism:
  Synthesis of $\underline{i}_{a,k+1}$ by projection to the adjacent $\Delta i_{a,n}$

I. Motivation
3. Sensorless control

For anisotropic machines, the inverter induced $\frac{di}{dt}$ depends on the doubled rotor angle:

$$\Delta i_{a,n} = \frac{di}{dt}_{a,n} \cdot T_p = \frac{2u_S T_p}{3(L_A^2 - L_B^2)} \left(L_A e^{j\varphi_n} - L_B e^{j[2\gamma(t) - \varphi_n]} \right) \sim e^{j2\gamma(t)}$$

- By measuring di/dt → no special testsignals necessary
- One switching period is enough for identification
- works at low speed and standstill
- significant magnetic anisotropy necessary
- 180°-ambiguity

Agenda

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II. Methods to identify the current slopes

a) Direct methods

1. Dedicated di/dt-sensors
2. Analog Differentiation
3. PCB-integrated planar Rogowski-coil

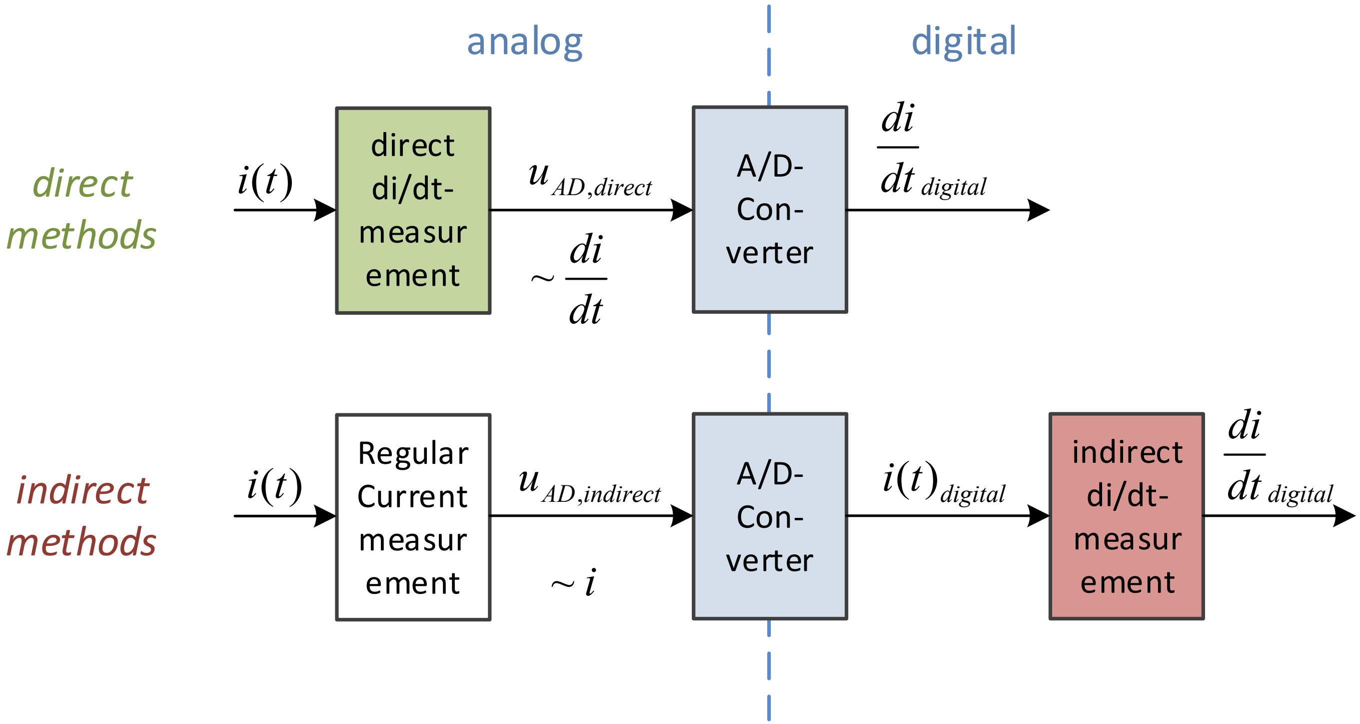
b) Indirect methods

I. Oversampling – Least Latency Least-Squares-Estimator

II. Sub-Sampling – „Easy Current Slope Detection“

III. Conclusion

Classification of Current slope measurement methods



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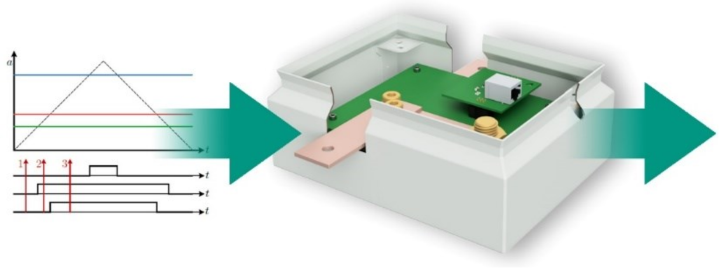
II. a) Direct Methods – Dedicated di/dt-sensors

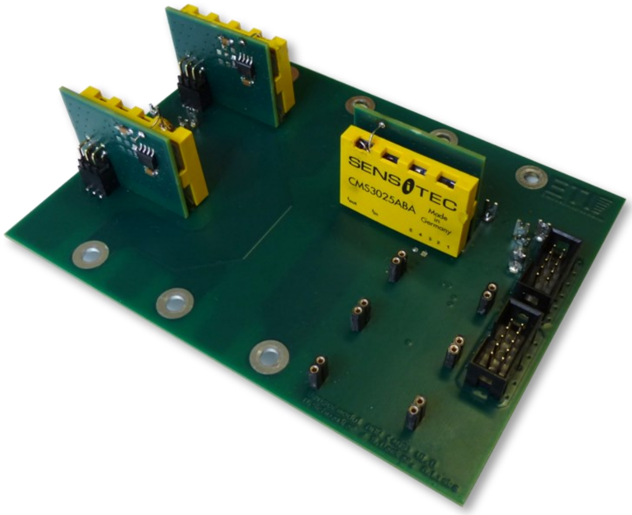
- Measuring the current slopes with dedicated hardware
- Sampling of the current gradient signal at standard sampling times



- ✓ High dynamics
- ✓ No special / extra fast A/D-converters necessary
- ✓ Easy to integrate into existing digital signal processing systems
- ✗ The gradient / d/dt of noise is also measured
- ✗ Difficult at high switching frequencies & small duty cycles

II. a) Direct Methods – Dedicated di/dt-sensors

- Prototype based on Sensitec CMS3025 current sensor
- Sensitivity: $41\,\frac{\mathrm{mV}}{\mathrm{kA/s}}$ at $25\mathrm{A}$ nominal current
- di/dt- measurement with Rogowski-coil, attached at the opposite site of the current rail of the CMS3025. The induced voltage in the sensor-coil is amplified with an integrated analog amplifier



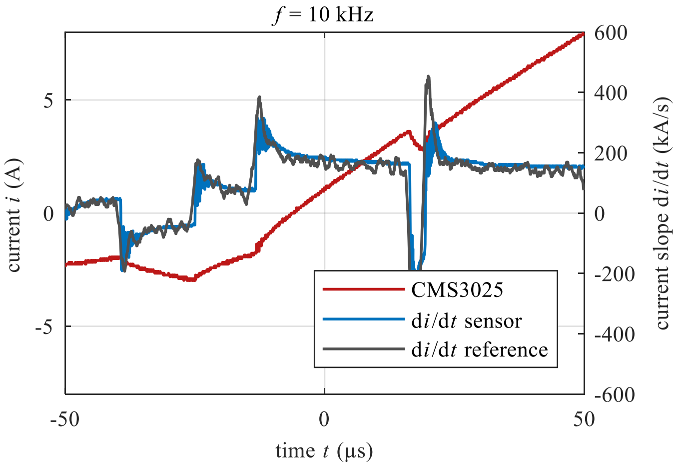
II. a) Direct Methods – Dedicated di/dt-sensors

Big self inductance:

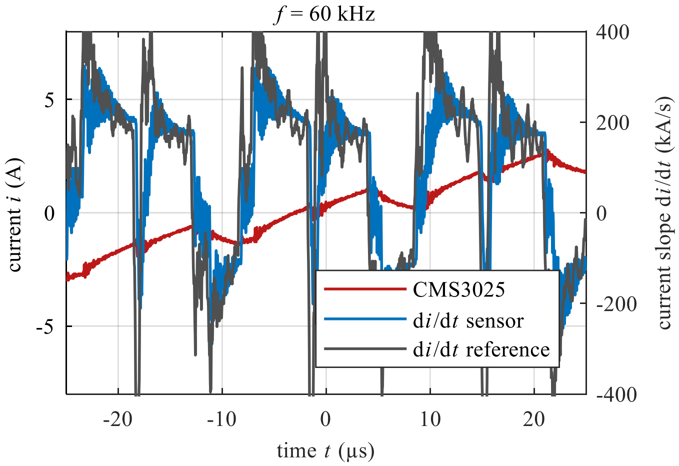
✓ Sensor coil signal is relatively high $u_L = L\frac{di}{dt}$

× Long settling time → L limits dynamics

f_{PWM} = 10 kHz



f_{PWM} = 60 kHz

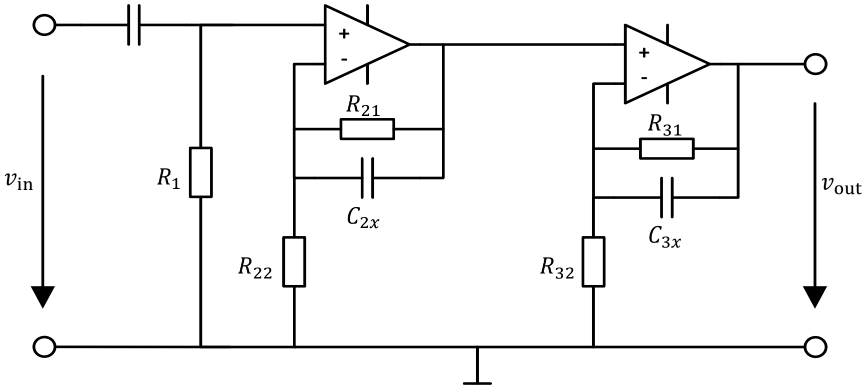


II. a) Direct Methods – analog differentiation circuit

- LEM LAH 25-NP current transducer to measure the absolute value of the current
- Input voltage v_{in} directly from current transducer
- Passive 1st order high pass with following 2-stage amplifier

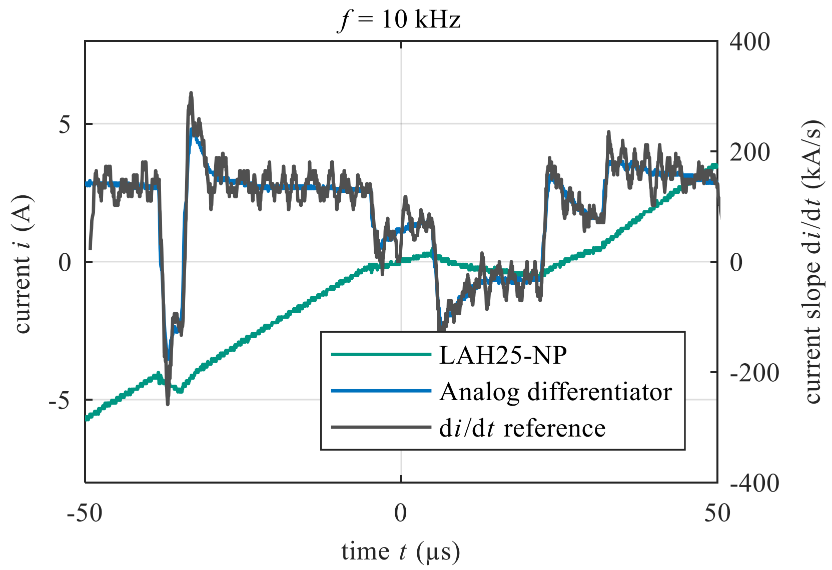
$$v_{\mathrm{out}} = \left(R_1 C_1 \frac{\mathrm{d}v_{\mathrm{in}}}{\mathrm{d}t}\right) \cdot \left(1 + \frac{R_{21}}{R_{22}}\right) \cdot \left(1 + \frac{R_{31}}{R_{32}}\right)$$

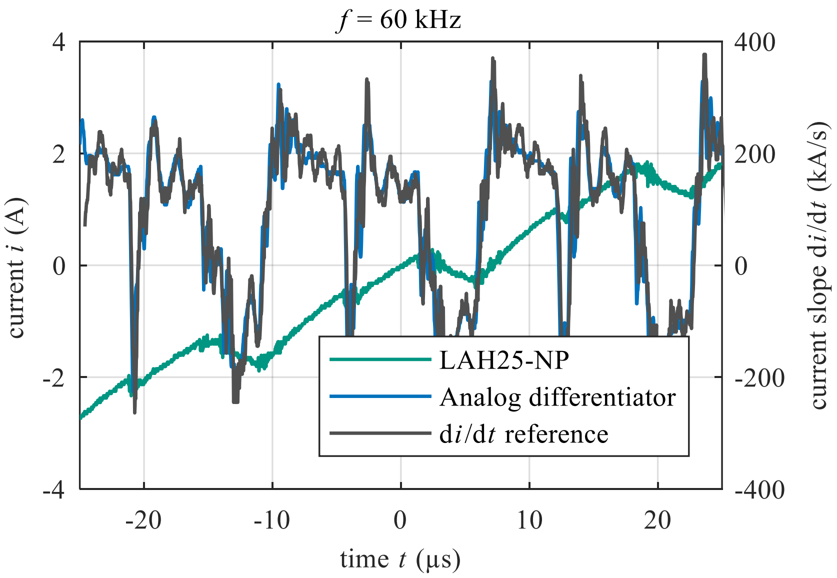
- Switching frequency and minimal on-time as design parameter for $\tau = R_1 C_1$
- Designed for 10kHz and bandwith of 60 kHz



II. a) Direct Methods – analog differentiation circuit

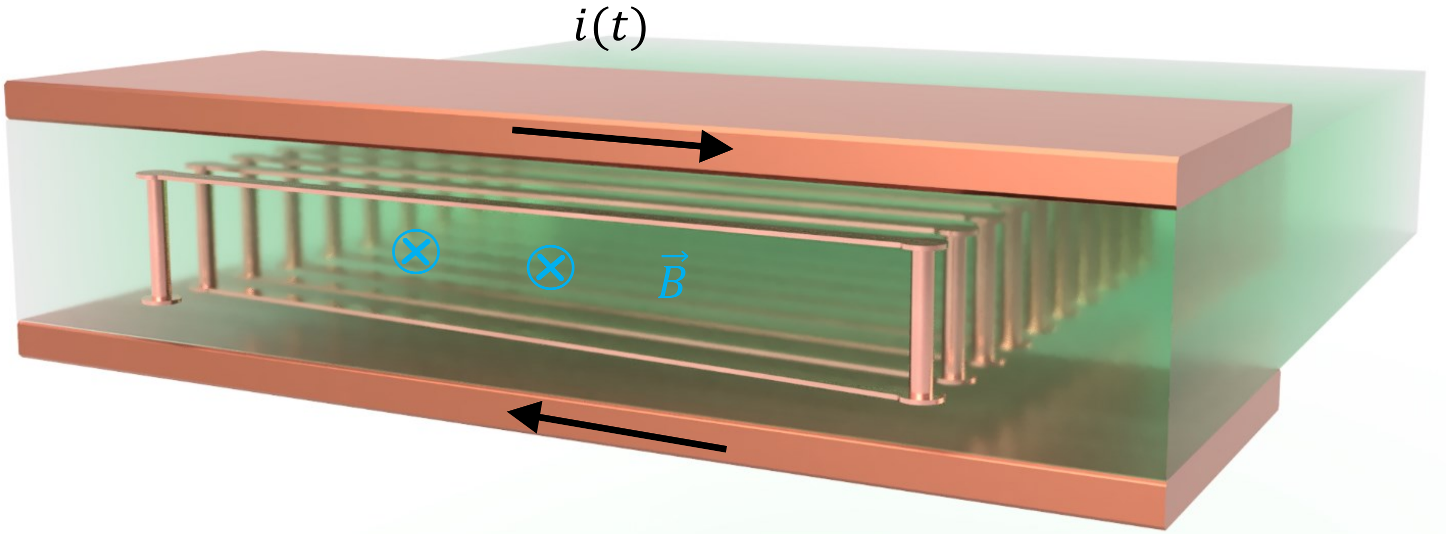
- Quality of the current slope signal heavily depends on the quality of the current transducer
- Good results, but very sensitve to noise in the the current signal





II. a) Direct Methods – PCB-integrated sensor coil

- Magnetic field: $\vec{B}(r) = \mu_0 \frac{i(t)}{2\pi \cdot r}$
- Magnetic Flux in coil: $\psi = \int_A \vec{B}(r) \mathrm{d}A$
- Induced voltage in coil: $u_{\mathrm{ind}} = \frac{\mathrm{d}\psi}{\mathrm{d}t} = M \cdot \frac{\mathrm{d}i(t)}{\mathrm{d}t}$



II. a) Direct Methods – PCB-integrated sensor coil

Output voltage (simplified)

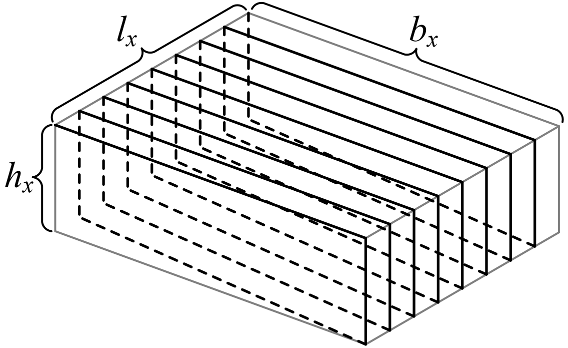
$$V_{\text{Coil}} = M \cdot \frac{\mathrm{d}i_1}{\mathrm{d}t}$$

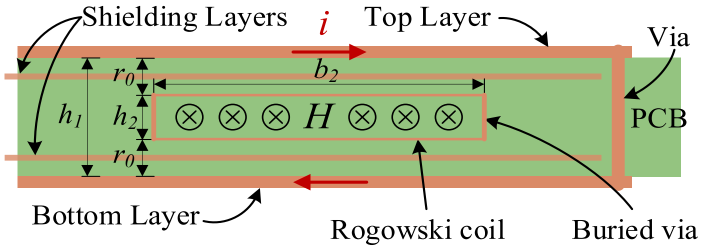
Mutual inductance

$$M = \frac{\mu_0 \cdot N_1 \cdot N_2 \cdot b}{2\pi} \cdot \ln\left(\frac{h}{\frac{l_2}{4} + \frac{\left(l_1 - N_1 \cdot \frac{w_1}{2}\right)}{2} + r_0} + 1\right)$$

Coupling capacitance (simplified)

$$C_\text{C} = 2\frac{\epsilon_0 \cdot \epsilon_\text{r}}{\text{r}_0}\text{N}_2 \cdot w_2$$

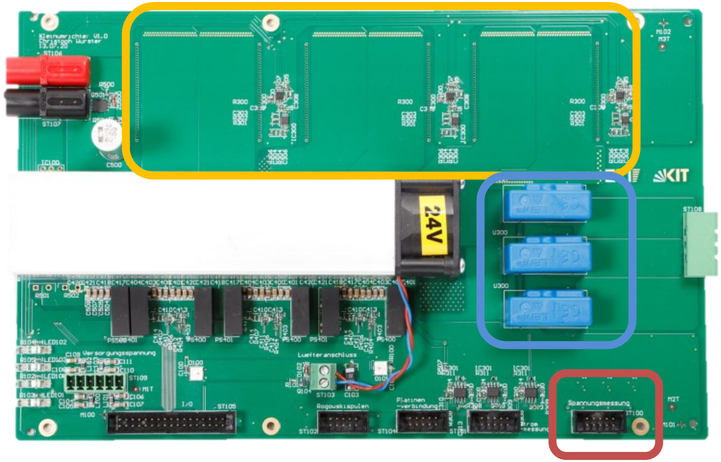


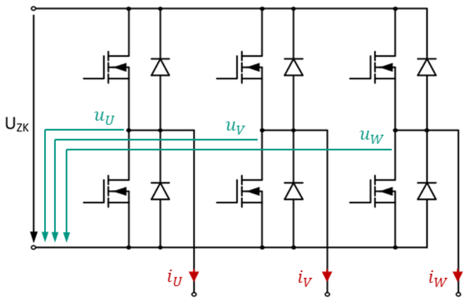


II. a) Direct Methods – PCB-integrated sensor coil

3-ph 2-level low-voltage inverter

- 100 kHz switching frequency
- 60 V DC-link voltage
- 25 A_{RMS} phase current
- 1.4 kW Power

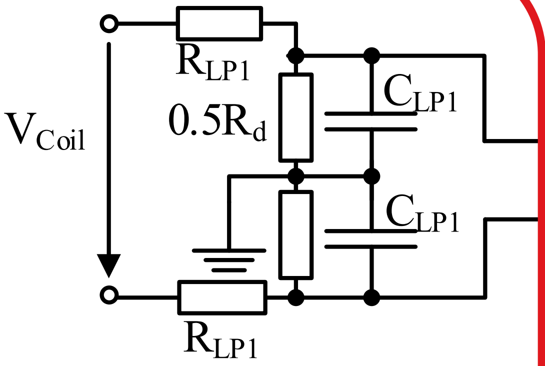




Measurements

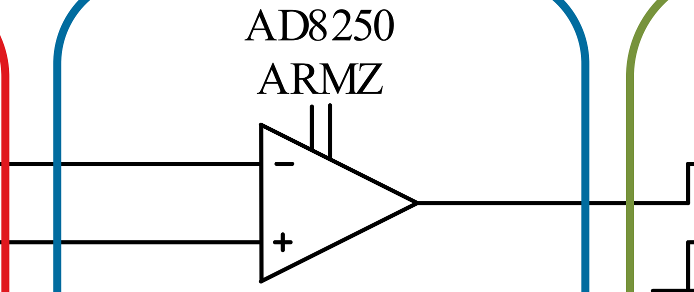
- **planar Rogowski coil** $\left(\frac{di}{dt}\right)$ up to 2 MHz
- **Phase and DC-Link voltage** up to 2 MHz
- **Phase currents** i_U, iV, iW up to 200kHz using LAH25NP

II. a) Direct Methods – PCB-integrated sensor coil



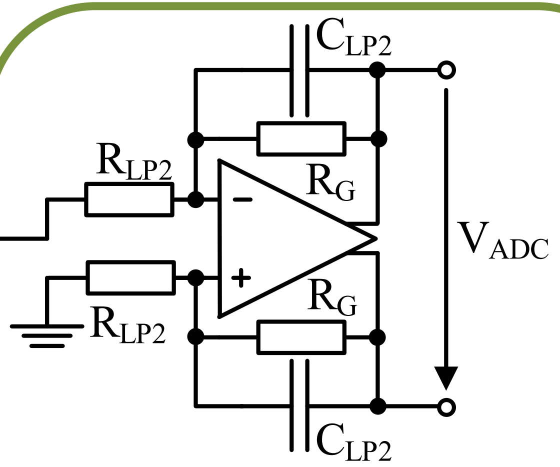
Differential and Common Mode Filter

- Damping of coil resonance
- common mode disturbance reduction



Variable Gain OpAmp

- Variable gain for different machines and operating points



Fixed Gain differential OpAmp

- increased interference immunity of ADC signal
- Voltage level adaption to ADC

II. a) Direct Methods – PCB-integrated sensor coil

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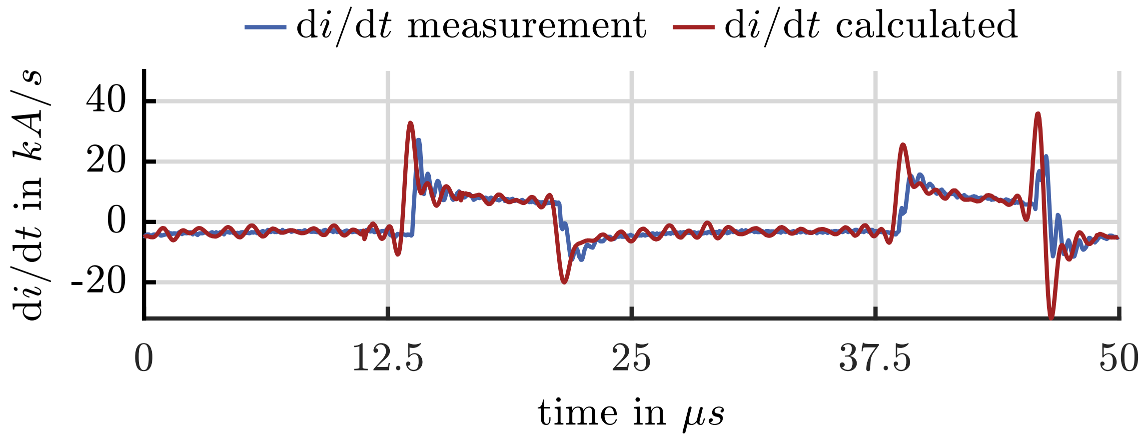

Operating Point - inverter	
PWM Frequency	20 kHz
DC-Link Voltage	15 V
Rotational speed	800 rpm
RMS Phase Current	0.5 A

Parameter PMSM	
p	3
R_s	0.135 Ω
L_d	0.2 mH
L_q	0.2 mH
Ψ_{pm}	11.7 mVs

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II. Methods to identify the current slopes

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b) Indirect methods

I. Oversampling – Least-Latency Least-Squares-Estimator

II. Sub-Sampling – „Easy Current Slope Detection“

III. Conclusion

II. b) Indirect Methods

Assumptions:

- $\frac{di}{dt} \approx const.$ during one period → current waveform are straight line segments
- This is given, if $\tau_{\text{plant}} \gg T_{\text{PWM}}$

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Curve fit with linear equations

$f_{\text{AD}} \gg f_{\text{PWM}}$	$f_{\text{AD}} \not\gg f_{\text{PWM}}$

• Oversampling possible
• **Least-Squares-Estimator**
• Very well suited for
  • moderate switching frequency
  • Traction / Drive applications
	• oversampling impossible
	• **„Easy Current Slope Detection“**
	• Very well suited for
	  • high switching frequency
	  • low-cost DC/DC-Converters

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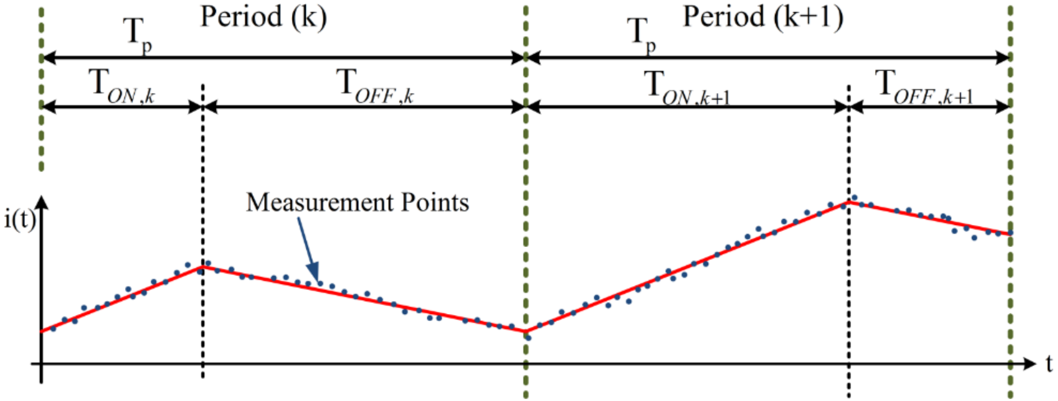
II. b) Indirect Methods – Least-Latency LS-Estimator

- Measurement with fast oversampling
- Calculation of slope with Least-Squares-Schätzer



✓ Very robust against disturbances

✓ Very fast convergence and very good accuracy

✓ supplies (besides the slope) also the filtered absolute value

✘ Fast A/D converters and signal processing required

✘ not suited for high switching frequencies and short duty cycles

✘ depending on implementation: high computational effort (QR factorization, etc.)

✘ Possible: numerical instability and latency in recursive algorithms

II. b) Indirect Methods – Least-Latency LS-Estimator

LS method with pure vector product with the "pseudoinverse":

$$(p)_N = \begin{pmatrix} i_E \\ \left(\frac{di}{dt}\right) \end{pmatrix} = (O)_N^{+} \cdot (i)_N = \underbrace{\begin{pmatrix} E_{N,1} & \dots & E_{N,n} & \dots & E_{N,N} \\ S_{N,1} & \dots & S_{N,n} & \dots & S_{N,N} \end{pmatrix}}_{\text{Constants of the Pseudoinverse}} \cdot \underbrace{\begin{pmatrix} i(1 \cdot T_{AD}) \\ \vdots \\ i(n \cdot T_{AD}) \\ \vdots \\ i(N \cdot T_{AD}) \end{pmatrix}}_{\text{Measured values}}$$

The vector product can be updated online with each new sample:

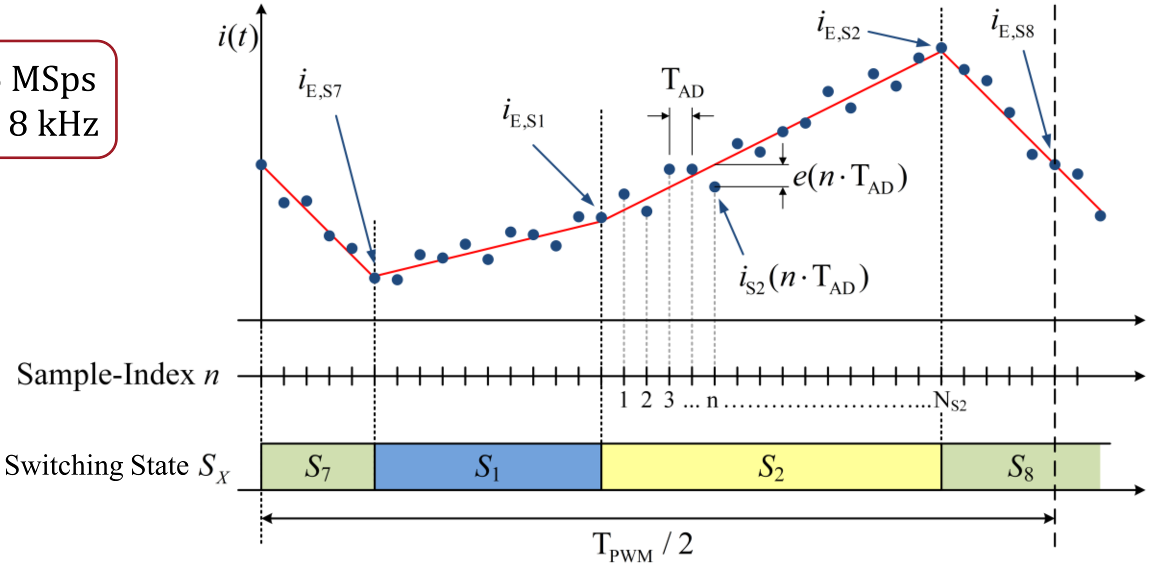
$$i_E = E_{N,1} \cdot i(1T_{AD}) + \dots + E_{N,n} \cdot \ i(nT_{AD}) + \dots + E_{N,N} \cdot \ i(N \cdot T_{AD})$$

$$\left(\frac{di}{dt}\right) = S_{N,1} \cdot i(1T_{AD}) + \dots + S_{N,n} \cdot \ i(nT_{AD}) + \dots + S_{N,N} \cdot \ i(N \cdot T_{AD})$$

1. the number N of measured values per switching state must be known!
2. the constants of the pseudoinverse must be known!

II. b) Indirect Methods – Least-Latency LS-Estimator

$f_{AD} = 6$ MSps
$f_{PWM} = 8$ kHz



Depending on duty cycle, the number of samles N per swithcing state varies between 1 und N_{max} with:

$$N_{max} = \frac{T_{PWM}/2}{T_{AD}} = \frac{f_{AD}}{f_{PWM}/2} = \frac{6\ MSps}{16\ kHz} = 375$$

II. b) Indirect Methods – Least-Latency LS-Estimator

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Solving the LS-Problem with the Pseudoinverse

$$(p)_N = \begin{pmatrix} i_E \\ \left(\frac{di}{dt}\right) \end{pmatrix} = (O)_N^+ \cdot (i)_N$$ Solution of the LS-Estimator

$$(O)_N^+ = [(O)_N^T (O)_N]^{-1} \cdot (O)_N^T$$ „Pseudoinverse“

with $$(O)_N = \begin{pmatrix} 1 & -(N-1)\cdot T_{AD} \\ \vdots & \vdots \\ 1 & -(N-n)\cdot T_{AD} \\ \vdots & \vdots \\ 1 & -1\cdot T_{AD} \\ 1 & -0\cdot T_{AD} \end{pmatrix}$$ for every $N \in \{1 \ldots N_{max}\}$

Online-Calculation of the Pseudoinverse according to this formula requires way too high computational effort!

II. b) Indirect Methods – Least-Latency LS-Estimator

Lookup-table with complete offline calculated Pseudoinverse:

$$\mathrm{LUT_{PSI}} = \begin{bmatrix} (O)_1^+ \\ (O)_2^+ \\ \vdots \\ (O)_N^+ \\ \vdots \\ (O)_{\mathrm{N_{max}}}^+ \end{bmatrix}$$

$$= \begin{bmatrix} \begin{pmatrix} E_{1,1} \\ S_{1,1} \end{pmatrix} \\ \begin{pmatrix} E_{2,1} & E_{2,2} \\ S_{2,1} & S_{2,2} \end{pmatrix} \\ \vdots & \vdots & \ddots \\ \begin{pmatrix} E_{N,1} & E_{N,2} & \cdots & E_{N,n} & \cdots & E_{N,N} \\ S_{N,1} & S_{N,2} & \cdots & S_{N,n} & \cdots & S_{N,N} \end{pmatrix} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \\ \begin{pmatrix} E_{\mathrm{N_{max}},1} & E_{\mathrm{N_{max}},2} & \cdots & E_{\mathrm{N_{max}},n} & \cdots & \cdots & \cdots & E_{\mathrm{N_{max}},\mathrm{N_{max}}} \\ S_{\mathrm{N_{max}},1} & S_{\mathrm{N_{max}},2} & \cdots & S_{\mathrm{N_{max}},n} & \cdots & \cdots & \cdots & S_{\mathrm{N_{max}},\mathrm{N_{max}}} \end{pmatrix} \end{bmatrix}$$

- For every measurement interval $N = 1 \dots \mathrm{N_{max}}$ exists one Pseudoinverse $(O)_N^+$
- every Pseudoinverse $(O)_N^+$ consists of 2 rows and N columns:
  - The first row contains the constants for the absolute value: $E_{N,n}$
  - The second row contains the constants for the slope: $S_{N,n}$

II. b) Indirect Methods – Least-Latency LS-Estimator

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Number $\mathrm{M_{PSI}}$ of constants that must be saved in the LUT:

$$\mathrm{M_{PSI}} = \frac{\mathrm{N_{max}}}{2} \cdot (\mathrm{N_{max}} + 1) \cdot 2 = \mathrm{N_{max}} \cdot (\mathrm{N_{max}} + 1)$$

With $\mathrm{N_{max}} = 375$ that‘s 141.000 constants (each 70.500 for $E_{N,n}$ and $S_{N,n}$).

Assuming a wordlength of 32 bit this would result in **4.512Mb memory requirement**

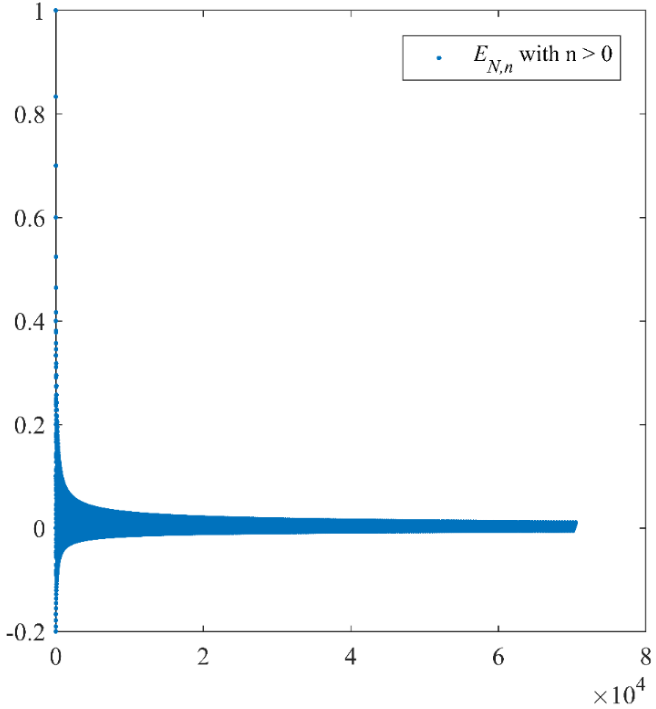
⇩

- Depending on the FPGA the LUT can‘t be stored inside the FPGA
- External memory becomes necessary

II. b) Indirect Methods – Least-Latency LS-Estimator

Plot of the complete LUT with all $\mathrm{N}_{\mathrm{max}}$ Pseudoinverses

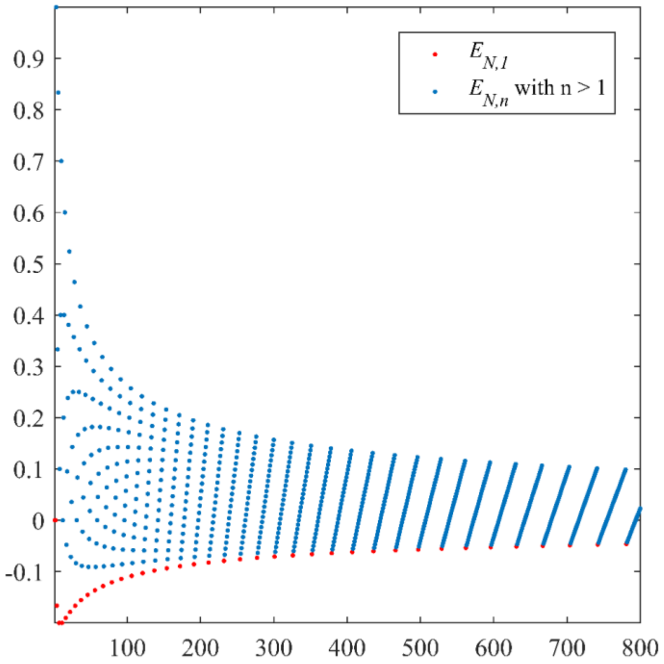
All 70.500 constants $E_{N,n}$ of the $\mathrm{LUT}_{\mathrm{PSI}}$



II. b) Indirect Methods – Least-Latency LS-Estimator

Plot of the complete LUT with all $\mathrm{N_{max}}$ Pseudoinverses – closer look No.1

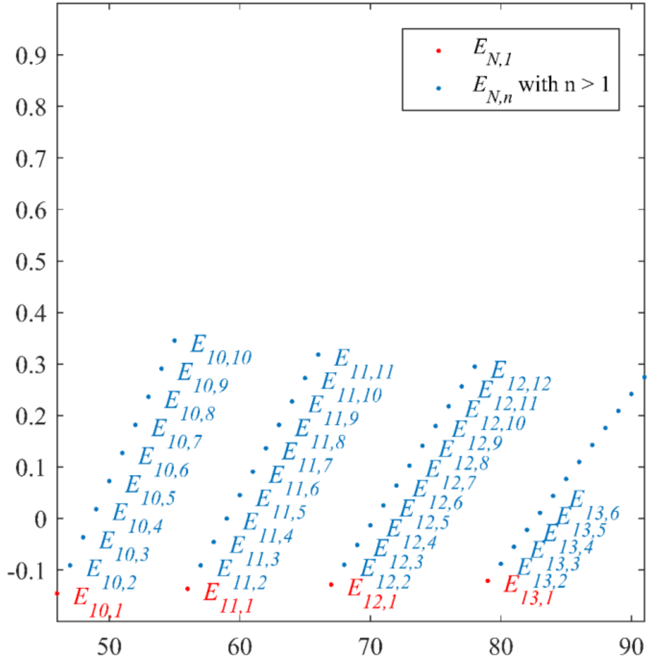
First 800 constants $E_{N,n}$
of the $\mathrm{LUT_{PSI}}$



II. b) Indirect Methods – Least-Latency LS-Estimator

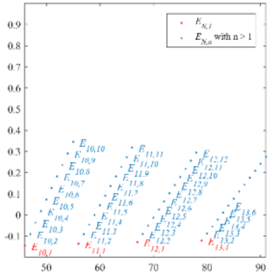
Plot of the complete LUT with all N_{max} Pseudoinverses – closer look No.2

Constants $E_{10,1}$ to $E_{13,13}$ of the LUT_{PSI}



II. b) Indirect Methods – Least-Latency LS-Estimator

A detailed mathematical analysis of the pseudoinverse shows:



1. The **elements can be calculated analytically**, without any matrix operation

$$E_{N,n} = \frac{2(2N-1) - 6(N-n)}{N(N+1)}$$

$$S_{N,n} = \frac{12}{N{T_{AD}}^2(N^2-1)}(n-N)T_{AD} + \frac{6}{T_{AD}N(N+1)}$$

2. The **elements of each row vector** of the pseudoinverse matrix **are equidistant**

$$\Delta E_{N,n}(N) = E_{N,n}(n) - E_{N,n}(n-1) = \frac{6}{N(N+1)}$$

$$\Delta S_{N,n}(N) = S_{N,n}(n) - S_{N,n}(n-1) = \frac{12}{T_{AD}N(N^2-1)}$$

Partially online-calculation of the Pseudoinverse is possible by:

1. Knowledge of the first elements $E_{N,1}$ und $S_{N,1}$
2. Adding the increment $\Delta E_N(N)$ and $\Delta S_N(N)$ gives the following elements

II. b) Indirect Methods – Least-Latency LS-Estimator

The huge, complete LUT with all $\mathrm{N_{max}}$ Pseudoinverses („old“)…

$$\mathrm{LUT_{PSI}} = \begin{bmatrix} (O)_1^+ \\ (O)_2^+ \\ \vdots \\ (O)_N^+ \\ \vdots \\ (O)_{\mathrm{N_{max}}}^+ \end{bmatrix} = \begin{bmatrix} \begin{pmatrix} E_{1,1} \\ S_{1,1} \end{pmatrix} & & & & & & & \\ \begin{pmatrix} E_{2,1} & E_{2,2} \\ S_{2,1} & S_{2,2} \end{pmatrix} & & & & & & & \\ \vdots & \vdots & \ddots & & & & & \\ \begin{pmatrix} E_{N,1} & E_{N,2} & \cdots & E_{N,n} & \cdots & E_{N,N} \\ S_{N,1} & S_{N,2} & \cdots & S_{N,n} & \cdots & S_{N,N} \end{pmatrix} & & & & & & & \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \\ \begin{pmatrix} E_{\mathrm{N_{max}},1} & E_{\mathrm{N_{max}},2} & \cdots & E_{\mathrm{N_{max}},n} & \cdots & \cdots & \cdots & E_{\mathrm{N_{max}},\mathrm{N_{max}}} \\ S_{\mathrm{N_{max}},1} & S_{\mathrm{N_{max}},2} & \cdots & S_{\mathrm{N_{max}},n} & \cdots & \cdots & \cdots & S_{\mathrm{N_{max}},\mathrm{N_{max}}} \end{pmatrix} \end{bmatrix}$$

II. b) Indirect Methods – Least-Latency LS-Estimator

… can be replaced by a very small LUT, only containing the first elements and the increments:

$$\mathrm{LUT_{S/I}} = \begin{bmatrix} \begin{pmatrix} E_{1,1} \\ S_{1,1} \end{pmatrix} & \\ \begin{pmatrix} E_{2,1} & \Delta E_2 \\ S_{2,1} & \Delta S_2 \end{pmatrix} \\ \vdots & \vdots \\ \begin{pmatrix} E_{N,1} & \Delta E_N \\ S_{N,1} & \Delta S_N \end{pmatrix} \\ \vdots & \vdots \\ \begin{pmatrix} E_{\mathrm{N_{max}},1} & \Delta E_{\mathrm{N_{max}}} \\ S_{\mathrm{N_{max}},1} & \Delta S_{\mathrm{N_{max}}} \end{pmatrix} \end{bmatrix}$$

II. b) Indirect Methods – Least-Latency LS-Estimator

Number $M_{S/I}$ of constants in the new $LUT_{S/I}$: $M_{S/I} = 4 \cdot N_{max}$

- With $N_{max} = 375$ that's **only 1.500 constants**
- Assuming gain a wordlength of 32 bit, this results in **just 48 kb memory requirement!**

Comparison to the complete LUT: $$\frac{M_{PSI}}{M_{S/I}} = \frac{N_{max}(N_{max}+1)}{4 \cdot N_{max}} = \frac{N_{max}+1}{4}$$

With N_{max}=375 ***Memory requirement is down by a factor of 94!***

→ The new LUT easily fits inside an FPGA

→ No external memory hardware necessary

II. b) Indirect Methods – Least-Latency LS-Estimator

Ways to calculate the Pseudoinverse:

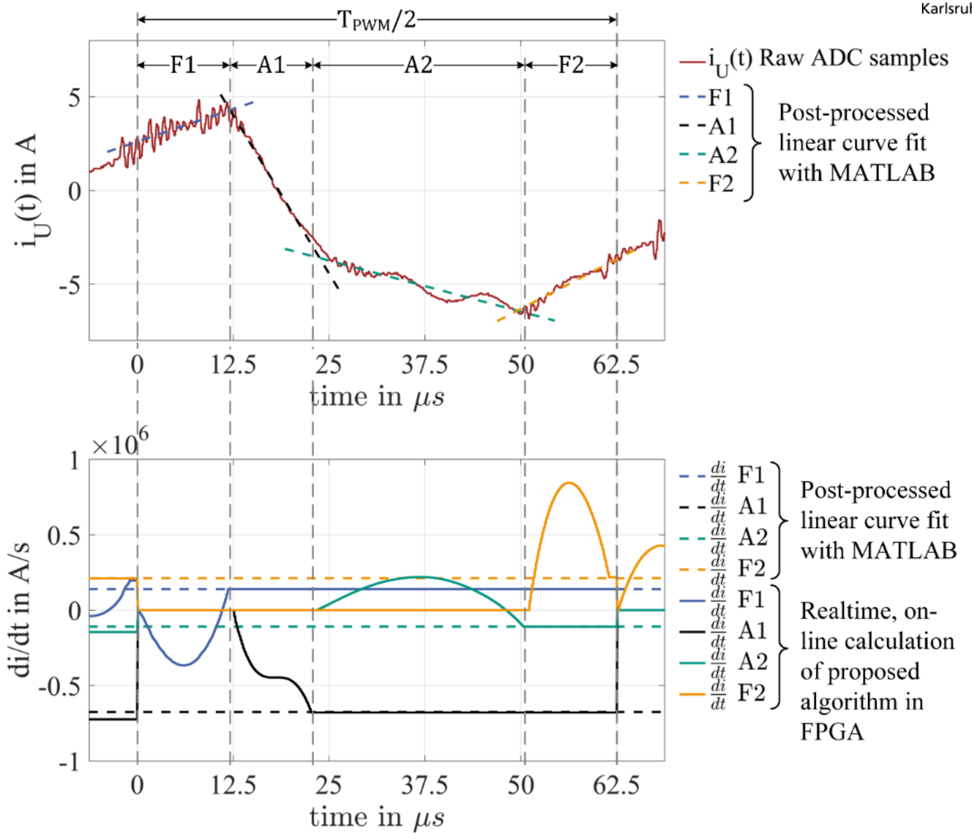
1. complete offline forecast
   → Storage of all constants in a lookup table
   → large memory requirement

2. partially online calculation with small lookup table
   → only start values and increments in small lookup-table
   → Very small memory footprint, very fast, hardly any computational overhead

II. b) Indirect Methods – Least-Latency LS-Estimator

Measurement results – current slopes:

$$f_{AD} = 6 \text{ MSps}$$
$$f_{PWM} = 8 \text{ kHz}$$



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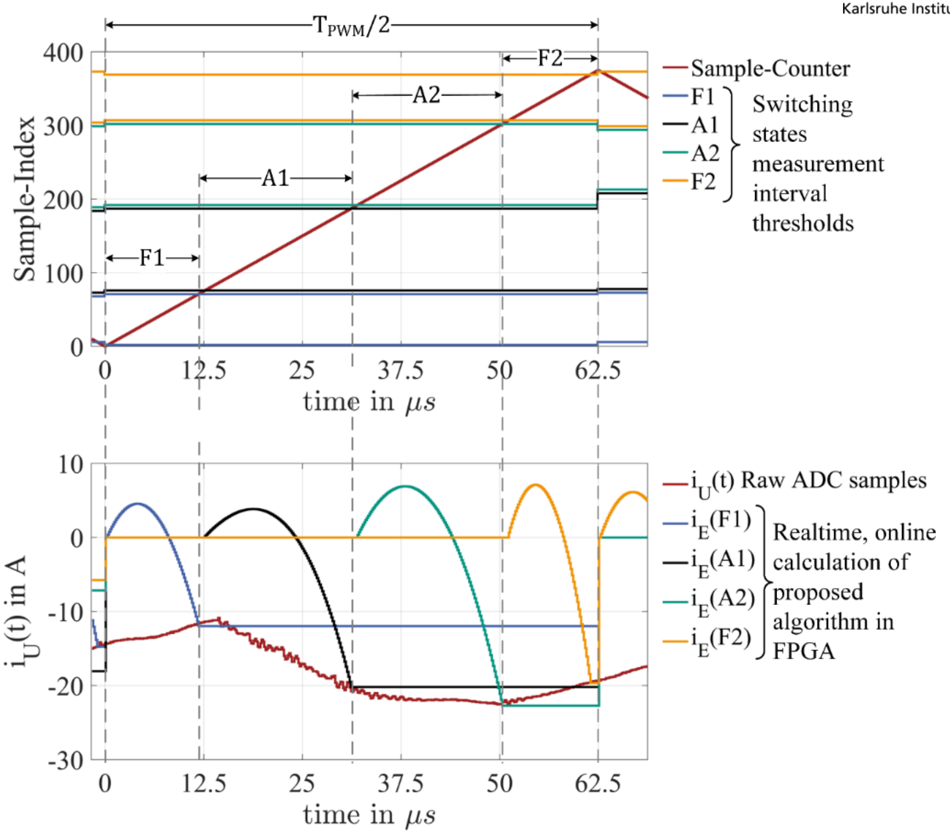
II. b) Indirect Methods – Least-Latency LS-Estimator

Measurement results – absolute values:

$$f_{AD} = 6 \text{ MSps}$$
$$f_{PWM} = 8 \text{ kHz}$$



Agenda

I. **Motivation**

II. Methods to identify the current slopes

   I. Direct methods

      1. Dedicated di/dt-sensors

      2. Analog Differentiation

      3. PCB-integrated planar Rogowski-coil

II. **Indirect methods**

      I. Oversampling – Least Latency Least-Squares-Estimator

      II. **Sub-Sampling – „Easy Current Slope Detection“**

III. Conclusion

II. b) Indirect Methods – Easy Current Slope Detection

Challenges with fast switching DC-DC-Converters:

- Low power
- very high switching frequency up to MHz-range
- Small mechanical footprint
- Low cost demand

Oversampling or dedicated di/dt-sensor?

↓

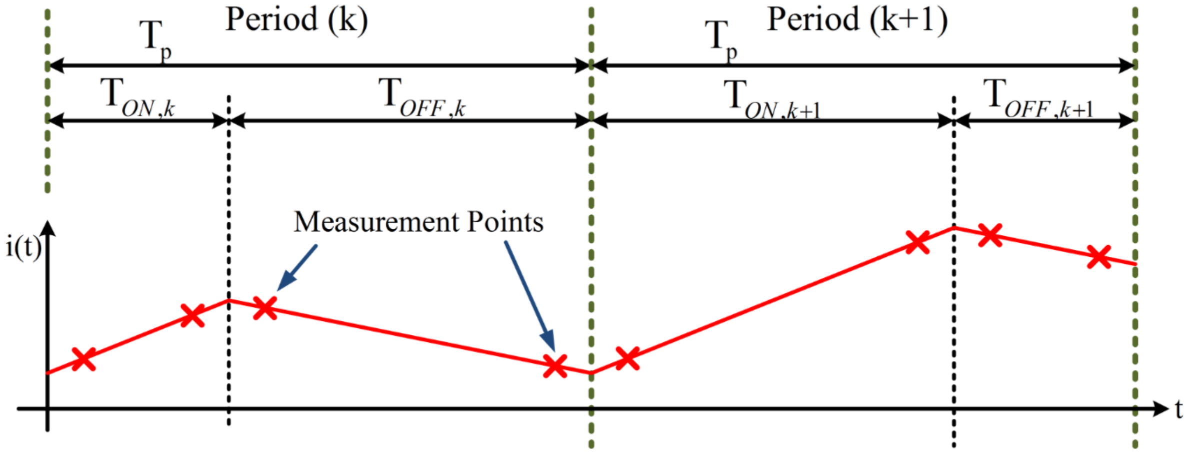
impossible or too expensive

How can the $\frac{di}{dt}$ be measured with already existing hardware?

- State-of-the-art microcontrollers
- „usual“ current sensing

II. b) Indirect Methods – Easy Current Slope Detection

„Two-point-method“:

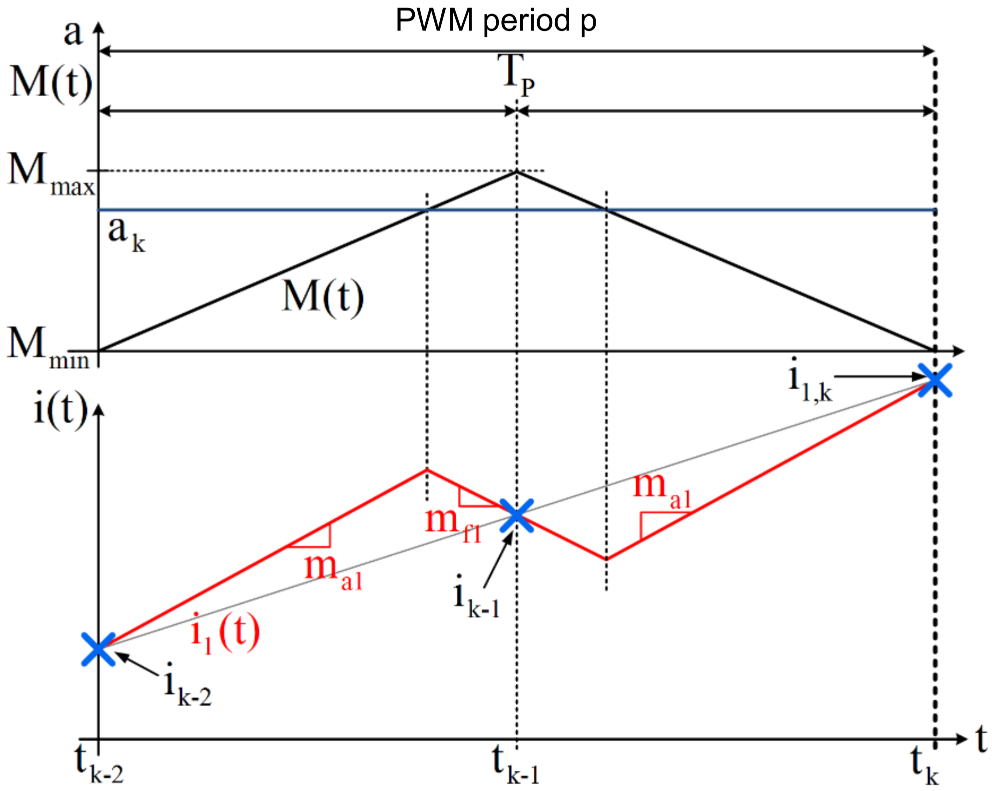


- ✓ Simple
- ✗ very sensitive to noise
- ✗ difficult with small duty cycles / high switching frequency
- ✗ Special trigger necessary

II. b) Indirect Methods – Easy Current Slope Detection

- Standard sampling times in microcontrollers:
  - M(t) = 0
  - M(t) = max

- Sampling times „farthest away“ from duty cycle transitions



„a“ → active
„f“ → freewheeling

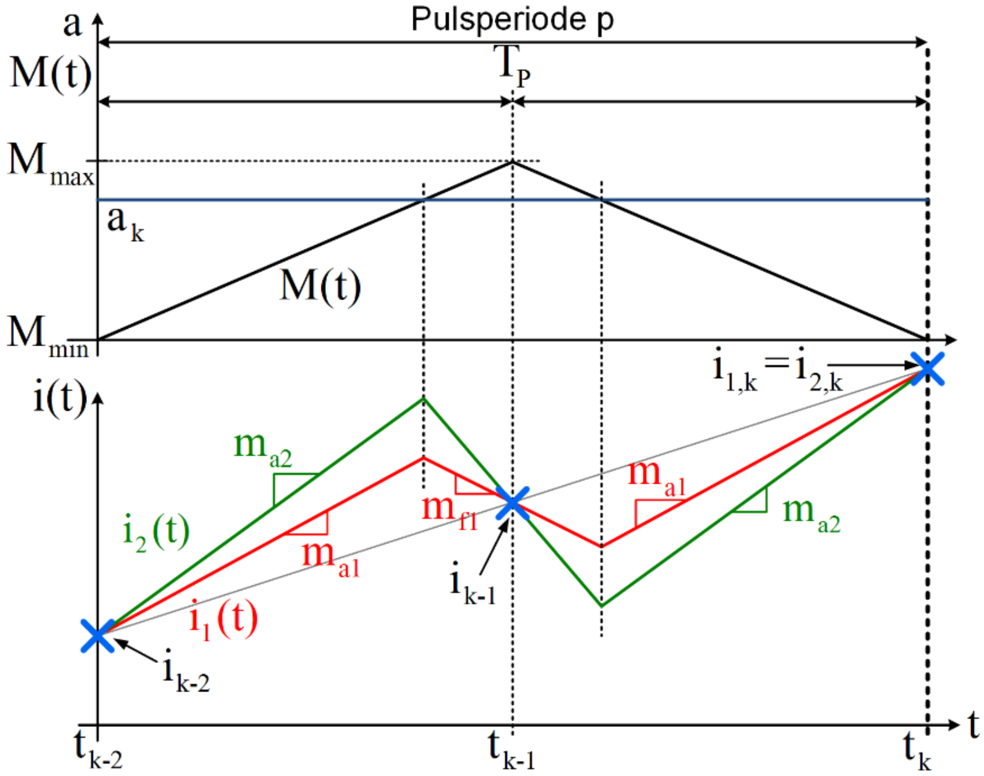
II. b) Indirect Methods – Easy Current Slope Detection

- Standard sampling times in microcontrollers :
  - M(t) = 0
  - M(t) = max

- Sampling times „farthest away“ from duty cycle transitions

- Different control paths
  - different current slopes
  - Identical measurement values

→ **Current slopes not detectable!**

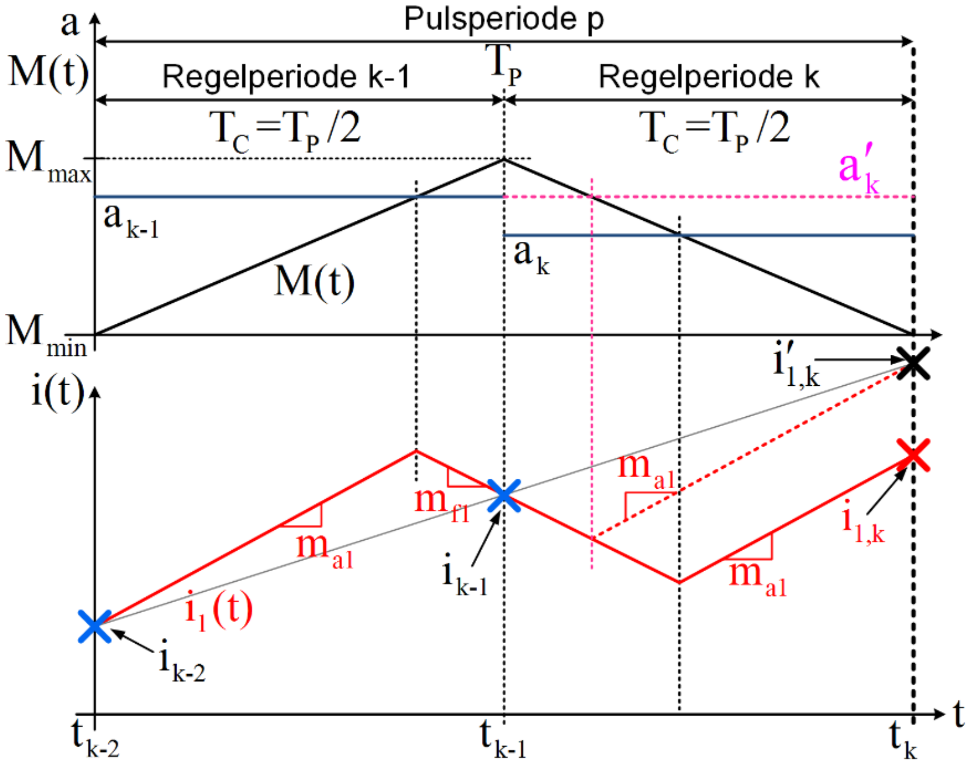


II. b) Indirect Methods – Easy Current Slope Detection

Trick:

Variation of subsequent duty-cycles (Jitter)

$$a_{k-1} \neq a_k$$



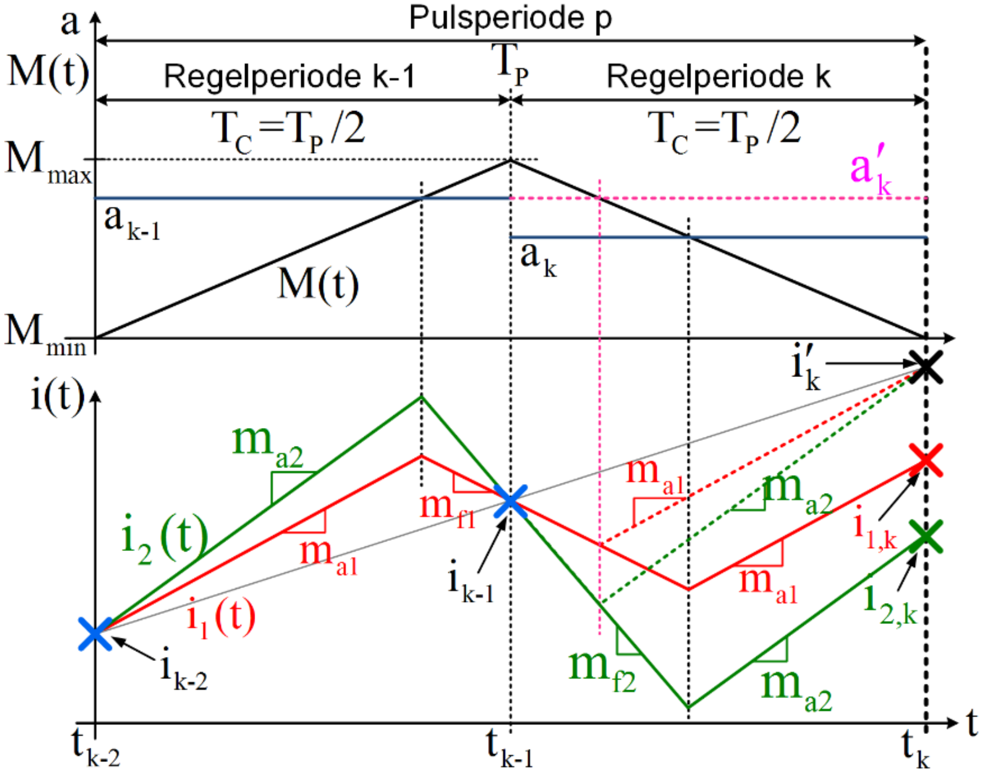
II. b) Indirect Methods – Easy Current Slope Detection

Trick:
Variation of subsequent duty-cycles (Jitter)

$$a_{k-1} \neq a_k$$

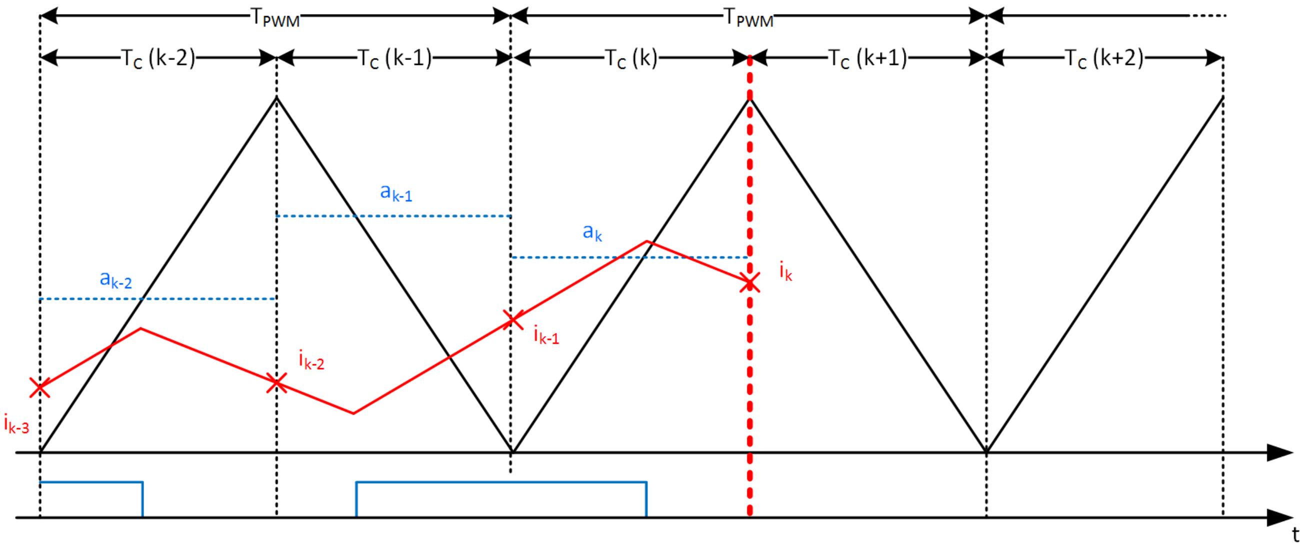
Different control paths
→ different current slopes
→ ***Different measurement values***

→ **Current slopes can be identified!**



II. b) Indirect Methods – Easy Current Slope Detection

Derivation of the ECSD-Algorithm



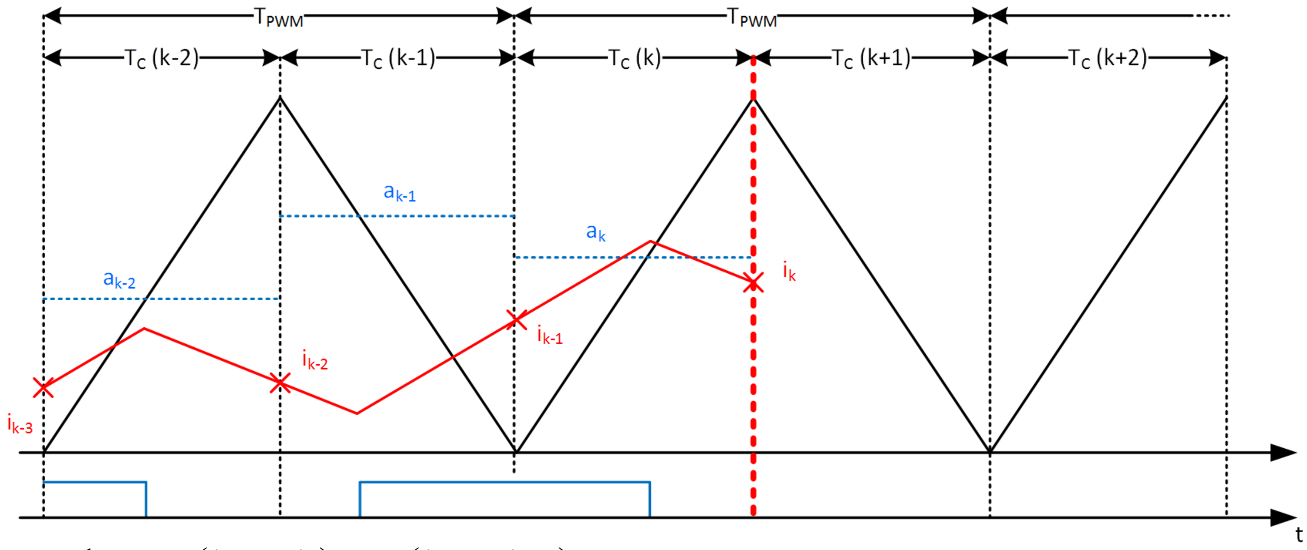
$$i_k = i_{k-1} + a_k \cdot T_C m_a + \left(1 - a_k\right) \cdot T_C m_f$$

$$i_{k-1} = i_{k-2} + a_{k-1} \cdot T_C m_a + \left(1 - a_{k-1}\right) \cdot T_C m_f$$

2 equations
2 unknowns

II. b) Indirect Methods – Easy Current Slope Detection

Derivation of the ECSD-Algorithm

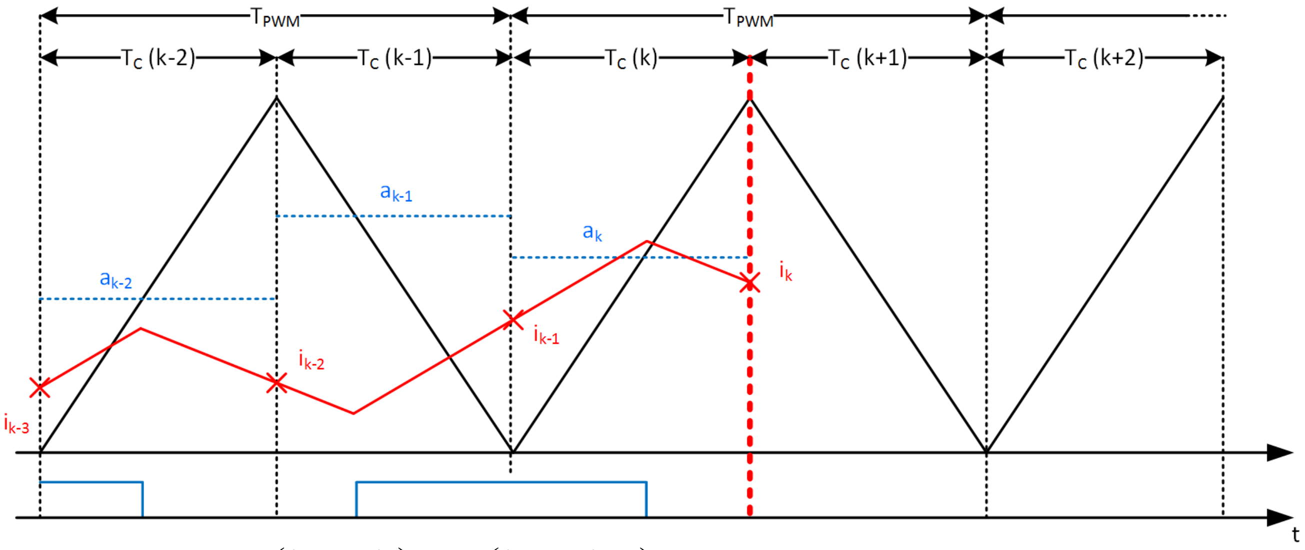


$$m_f = \frac{1}{T_C} \cdot \frac{a_{k-1}(i_{k-1} - i_k) + a_k(i_{k-1} - i_{k-2})}{a_k - a_{k-1}}$$

$$m_a = m_f + \frac{1}{T_C} \cdot \frac{i_{k-2} - 2i_{k-1} + i_k}{a_k - a_{k-1}}$$

II. b) Indirect Methods – Easy Current Slope Detection

Derivation of the ECSD-Algorithm



$$\Delta i_f = T_C m_f = \frac{a_{k-1}(i_{k-1} - i_k) + a_k(i_{k-1} - i_{k-2})}{a_k - a_{k-1}}$$

$$\Delta i_a = T_C m_a = \Delta i_f + \frac{i_{k-2} - 2i_{k-1} + i_k}{a_k - a_{k-1}}$$

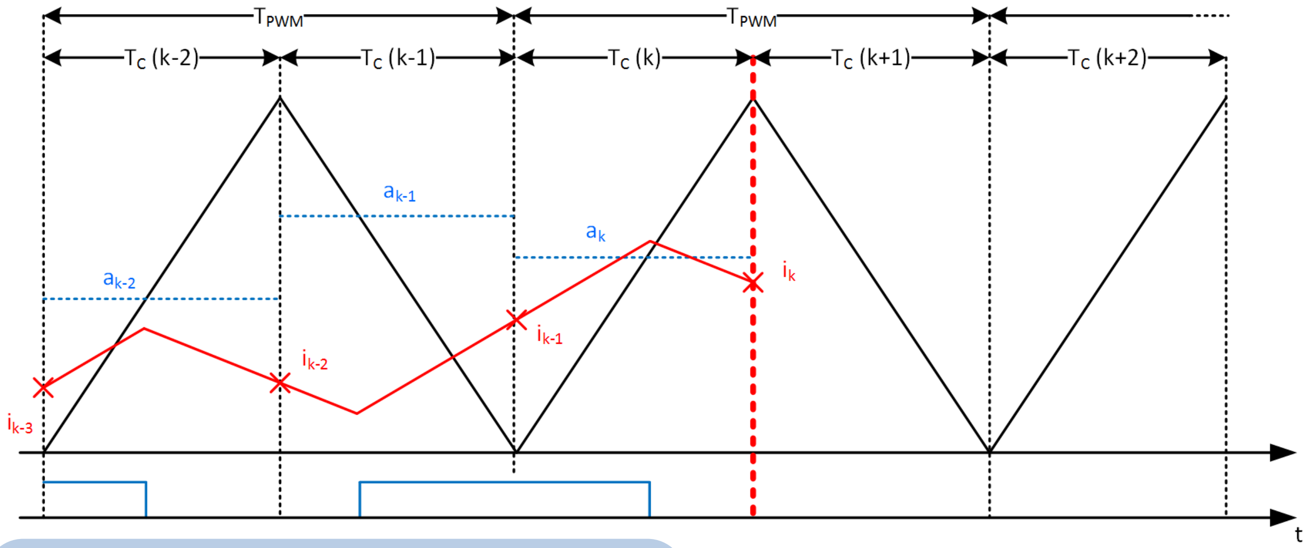
„Current Gradients“:

$$\Delta i_f = T_C \cdot m_f$$

$$\Delta i_a = T_C \cdot m_a$$

II. b) Indirect Methods – Easy Current Slope Detection

Derivation of the ECSD-Algorithm



$$\Delta i_f = T_C m_f = \frac{a_{k-1}(i_{k-1} - i_k) + a_k(i_{k-1} - i_{k-2})}{a_k - a_{k-1}}$$

$$\Delta i_a = T_C m_a = \Delta i_f + \frac{i_{k-2} - 2i_{k-1} + i_k}{a_k - a_{k-1}}$$

„Easy Current Slope Detection“

II. b) Indirect Methods – Easy Current Slope Detection

Using the Current Gradients for Direct Adaptive Current Control

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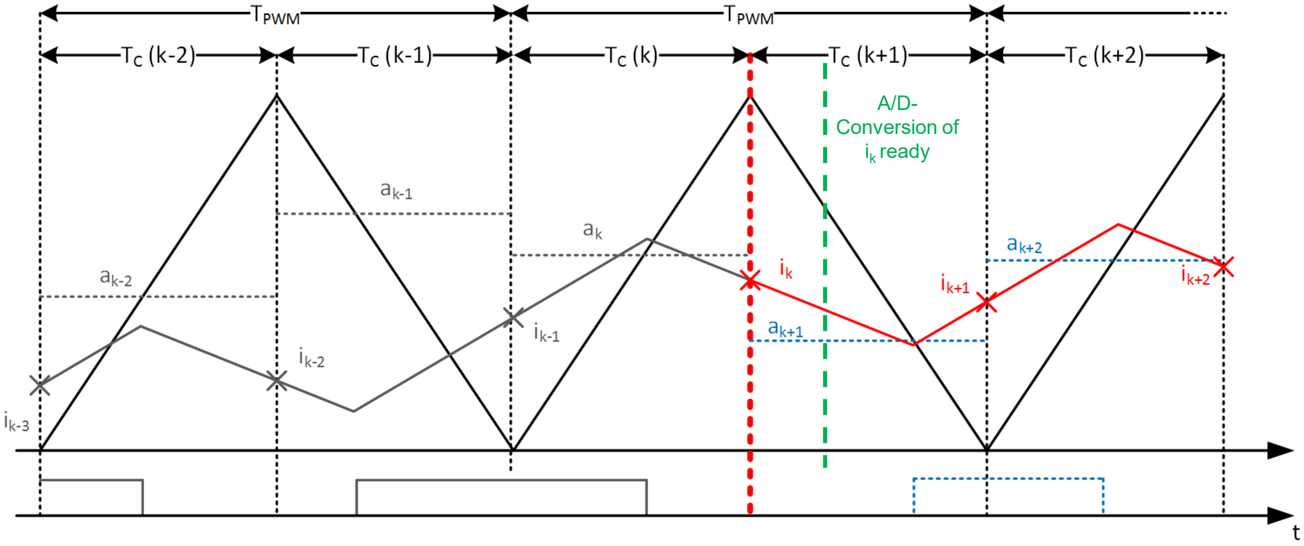

$$i_{k+1} = i_k + a_{k+1} \cdot \Delta i_a + \left(1 - a_{k+1}\right) \cdot \Delta i_f$$

$$i_{k+2} = i_{k+1} + a_{k+2} \cdot \Delta i_a + \left(1 - a_{k+2}\right) \cdot \Delta i_f$$

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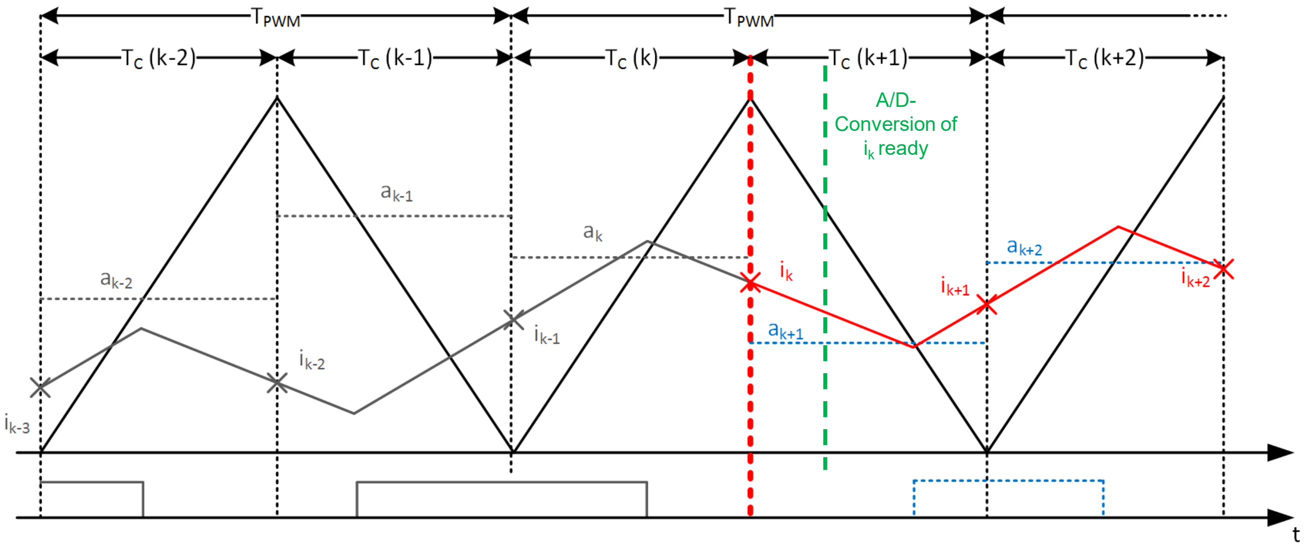
II. b) Indirect Methods – Easy Current Slope Detection

Using the Current Gradients for Direct Adaptive Current Control

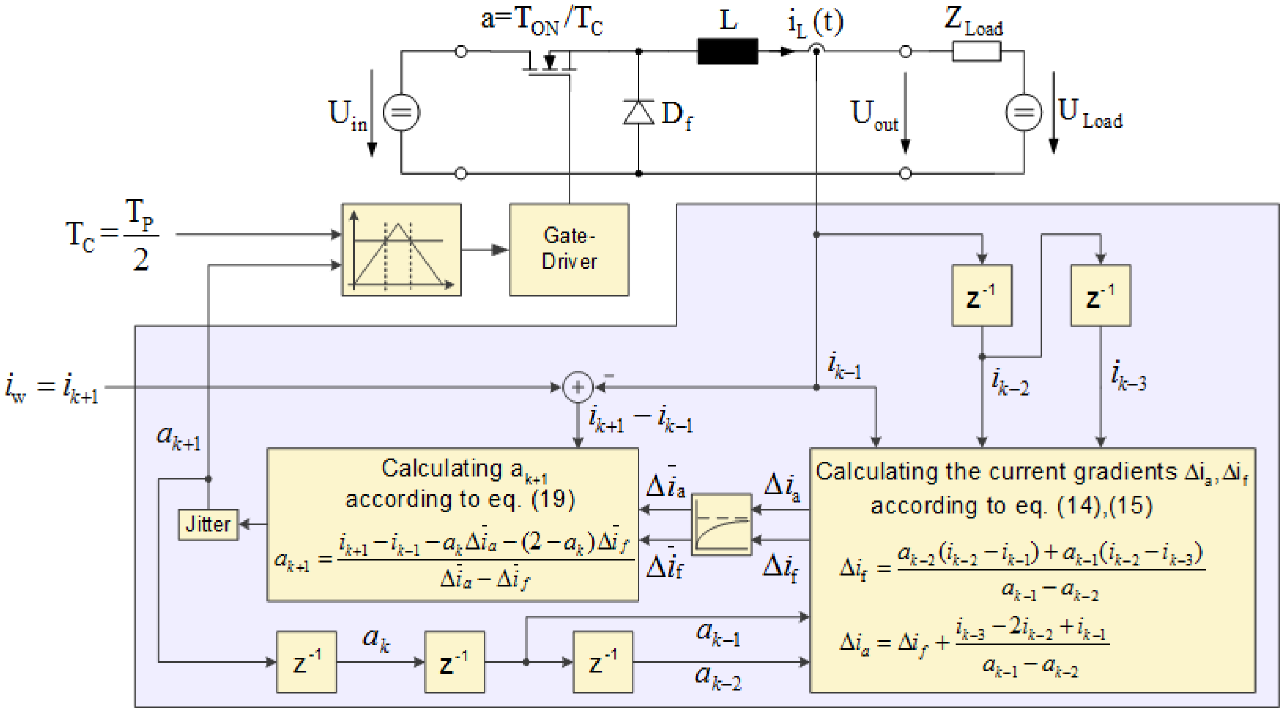


$$a_{k+2} = \frac{i_{k+2} - i_k - a_{k+1} \cdot \Delta i_a - \left(2 - a_{k+1}\right) \Delta i_f}{\Delta i_a - \Delta i_f}$$

Direct Adaptive Current Control
for
DC/DC-Converters

II. b) Indirect Methods – Easy Current Slope Detection

Using the Current Gradients for Direct Adaptive Current Control



DACC for DC/DC-Converters with easy identification of the current slopes

II. b) Indirect Methods – Easy Current Slope Detection

noise & sensitivity

Sensitivity

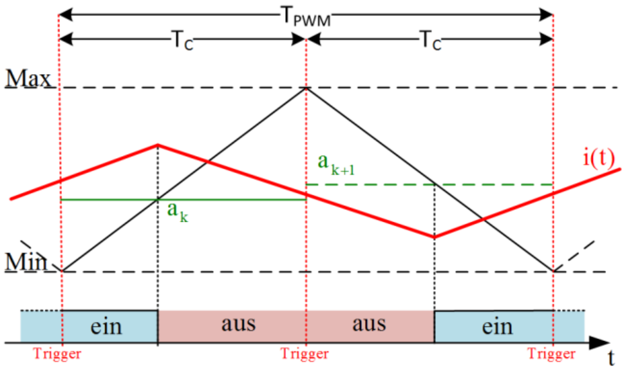
- In steady state operation:

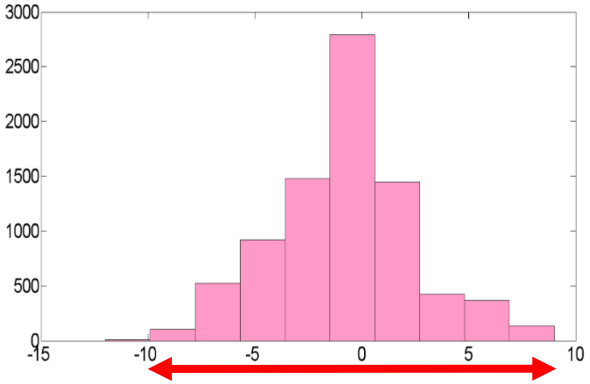
  Almost identical current samples

  → Difference $i_k - i_{k-1}$ is very small compared to the measuring range

- Critical:
  - Noise of the current signal
  - Noise of the AD-Converter

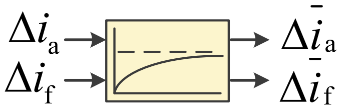
Original idea of controlling the current with the current slopes, calculated from period to period only did not work due to noise.

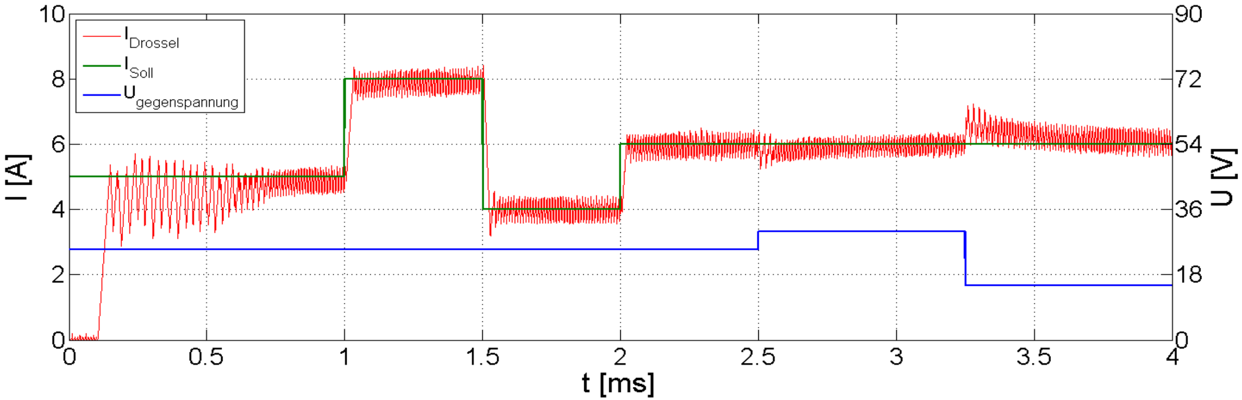




II. b) Indirect Methods – Easy Current Slope Detection

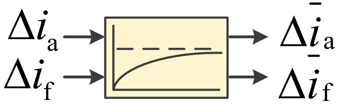
DACC with filtered current gradients (DACC-F)

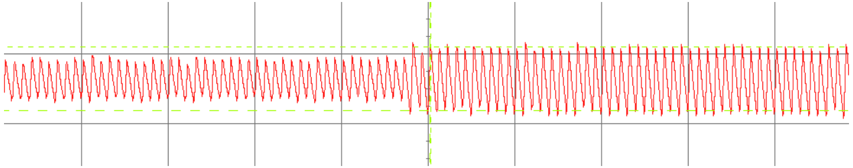




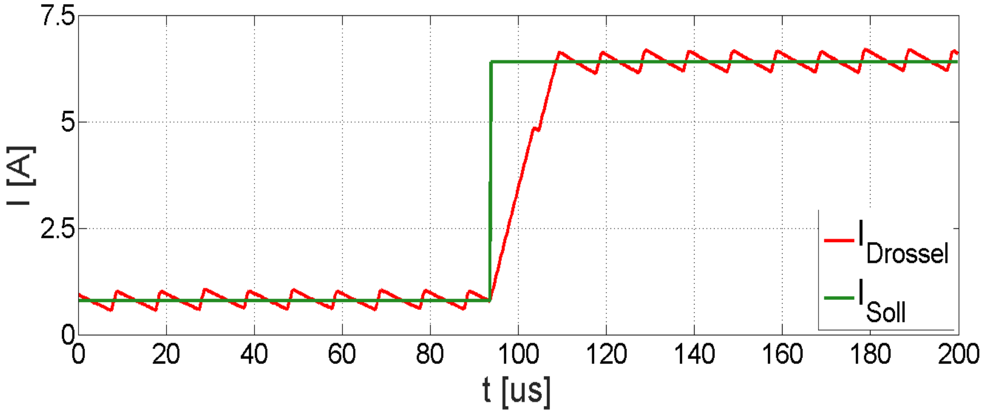
- ✓ only current measurement necessary
- ✓ self-parametrizing
- ✓ dead-beat-characteristics for setpoint steps
- ✗ without voltage feed-forward slow disturbance reaction

II. b) Indirect Methods – Easy Current Slope Detection
DACC with filtered current gradients (DACC-F) – with low-cost microcontroller

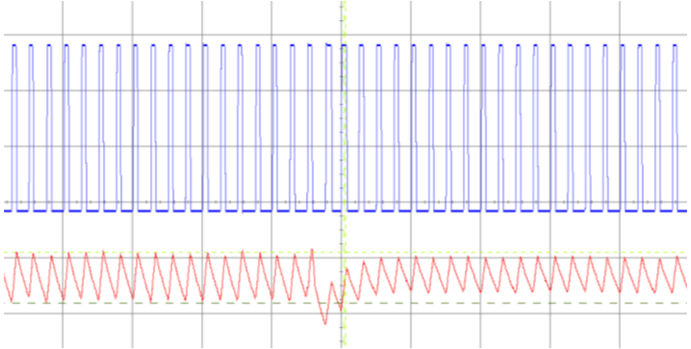




Load step: 800nH → 500nH



Setpoint Step 1A to 6A



Load step: 600nH →800nH

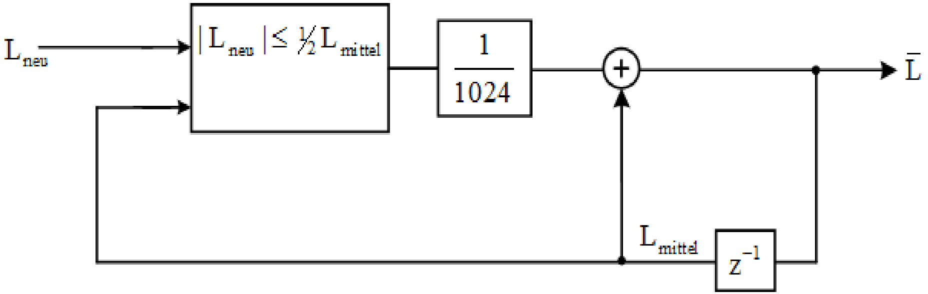
II. b) Indirect Methods – Easy Current Slope Detection

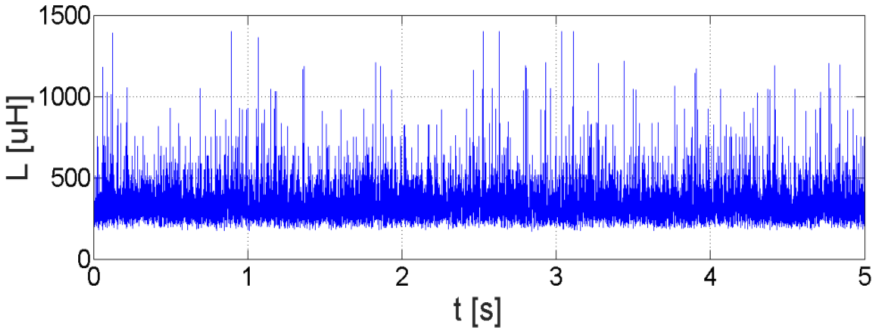
Using the ECSD to calculate L

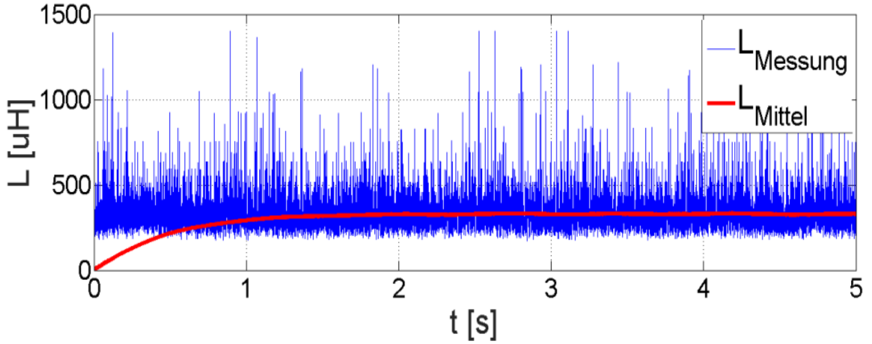
$$L = \frac{-U_a \cdot (a_k - a_{k-1})}{a_{k-1} \cdot (i_{k-1} - i_k) + a_k \cdot (i_{k-1} - i_{k-2})}$$

Filtering L:

- Noise is one-sided
- Special Filter

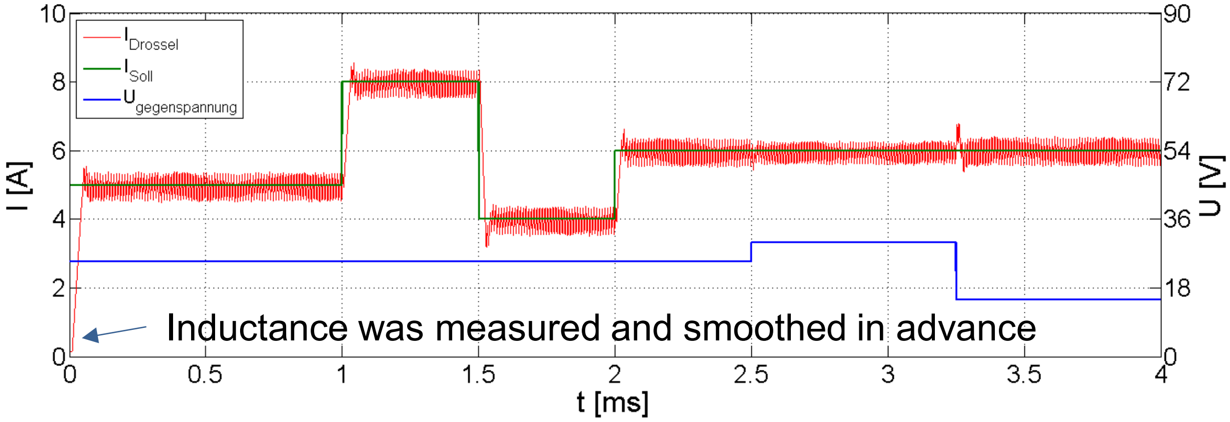






II. b) Indirect Methods – Easy Current Slope Detection

MPC with filtered L (DACC-MPC)



✓ Excellent control quality and good disturbance reaction

✘ Additional voltage-measurement necessary

✘ Smoothing out L takes relatively long (~1s)

Agenda

I. Motivation

II. Methods to identify the current slopes

   I. Direct methods

      1. Dedicated di/dt-sensors
      2. Analog Differentiation
      3. PCB-integrated planar Rogowski-coil

II. Indirect methods

      I. Oversampling – Least Latency Least-Squares-Estimator
      II. Sub-Sampling – „Easy Current Slope Detection“

III. Conclusion

III. Conclusion

Measurement of inverter induced current slopes…

…shows high potential

- Online Parameter Identification
- Direct Adaptive Control Schemes
- Adaptive Control
- …

…can be done by many different methods

- direct methods:
  - ✗ dedicated special hardware necessary
  - ✓ Conventional sampling, A/D-conversion and filtering
- indirect methods:
  - ✓ Conventional current sensing / measurement hardware
  - ✗ oversampling & filtering necessary

…is not trivial, but manageable

- Measurement results of the tested methods are good

Thank you for your attention!

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