# Vervorming in schakelende vermogensomzetters

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*20-06-2017*

TU/e Technische Universiteit Eindhoven University of Technology

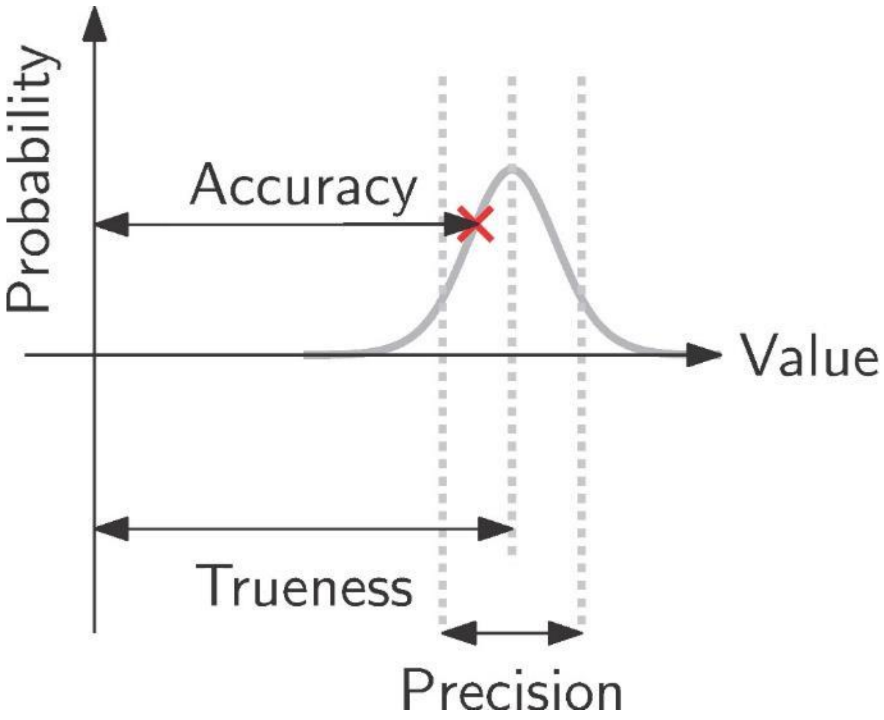
Where innovation starts

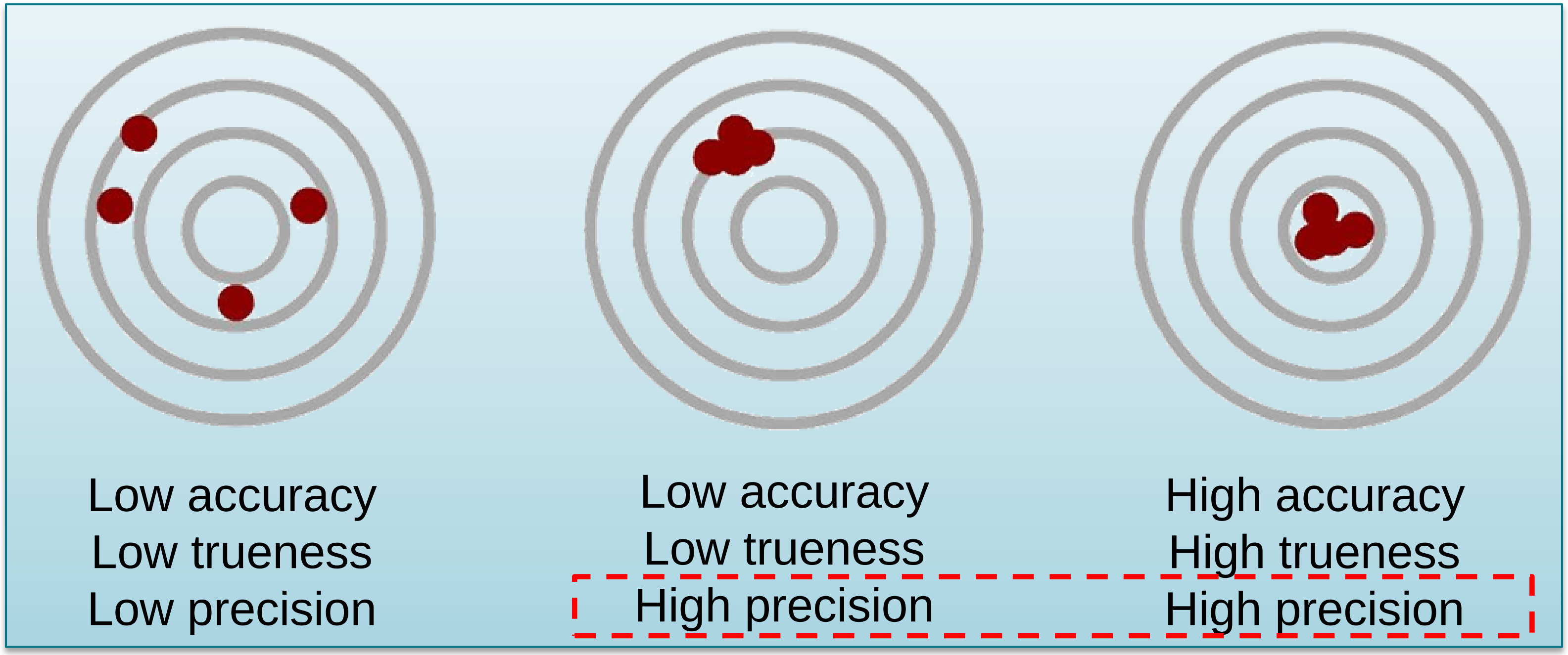
# The issue with precision

What you expect the output is doing

What the output of the converter is actually doing

# Accuracy, trueness and precision





Low accuracy
Low trueness
Low precision

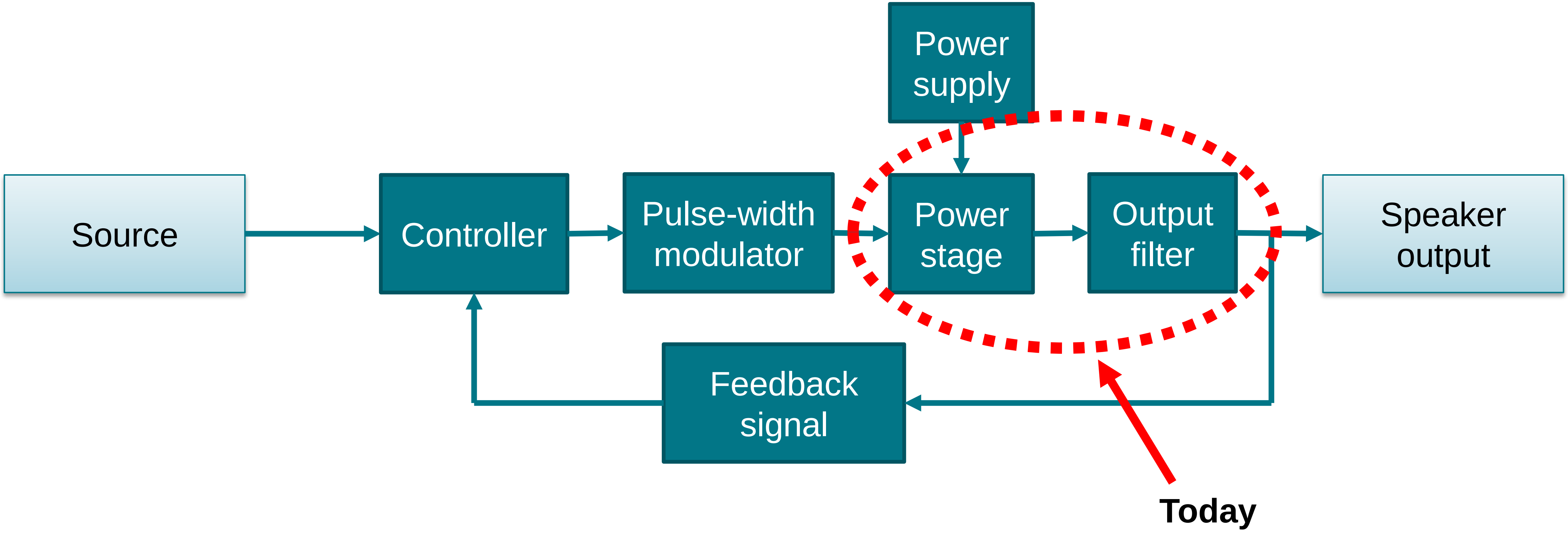
Low accuracy
Low trueness
High precision

High accuracy
High trueness
High precision

**High precision is a necessary condition for high accuracy**

# High-precision power converter

- Generic block diagram:



# Distortion sources in power stage + filter

- Power stage
  - Dead-time
  - Non-linear on-state resistance & on-state resistance mismatch
  - Non-linear parasitic capacitances
  - Soft vs hard-switching

- Inductors
  - Saturation
  - Resistance variation
  - Hysteresis

- Capacitors
  - Voltage dependency
  - Relaxation

# Contents

- Power stage
  - ○ Dead-time
  - ○ Non-linear on-state resistance

- Inductors
  - ○ Saturation
  - ○ Resistance variation

Today:

- Modeling techniques
- Results
- Conclusions

# Contents

- Power stage
  - Dead-time
  - Non-linear on-state resistance

- Inductors
  - Saturation
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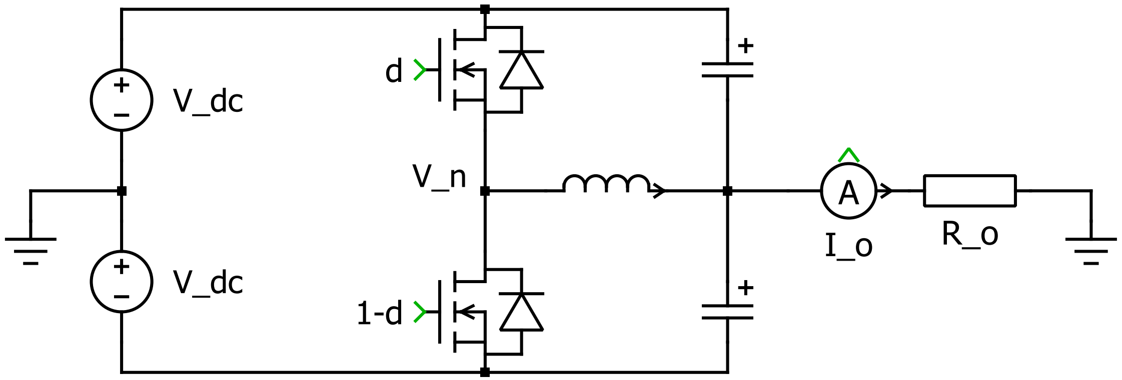
# Dead-time distortion

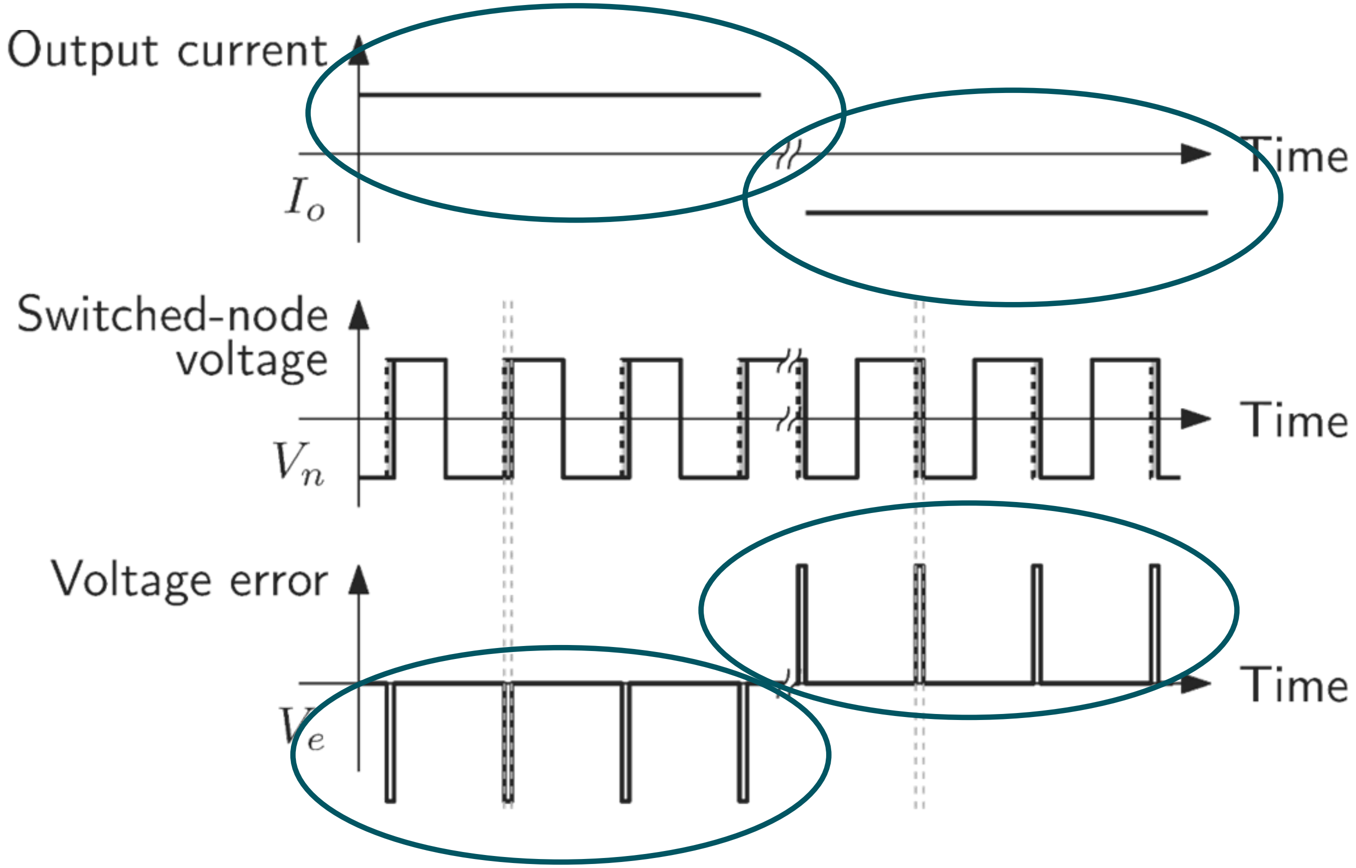
- Dead-time: period of time where both transistors are off to prevent shoot-through

- When both transistors are off, the switched-node voltage is not forced to equal PWM output
  - *Voltage error occurs!*

- *Influence of dead-time on output THD?*



# Average voltage error



Average voltage error per switching cycle:

$$\langle V_e \rangle = -\frac{2t_{dt}V_{dc}}{t_p}\,\mathrm{sign}(I_o)$$

with $t_{dt}$ the dead-time, and $t_p$ the period time.

# Fourier-series of output voltage

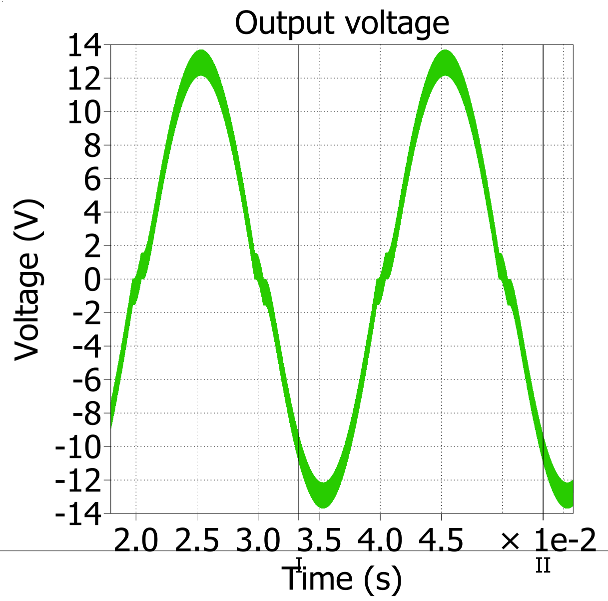
# Output voltage distortion

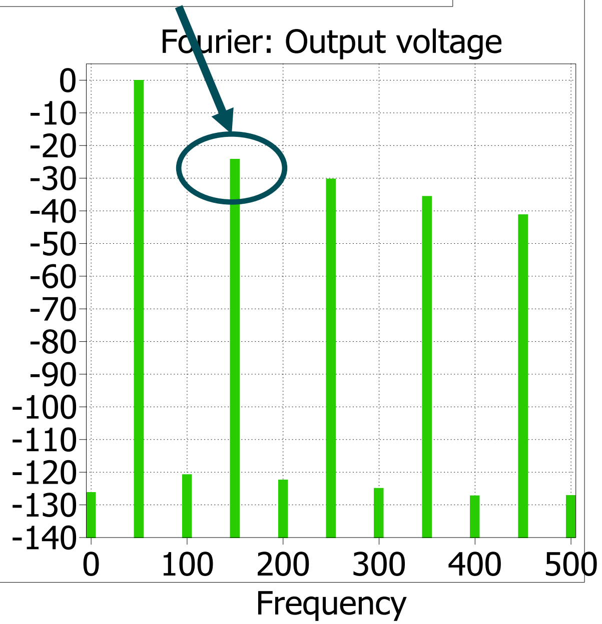
$$\boxed{\mathrm{THD}_3 = \frac{8t_{dt}}{3\pi t_p D - 24t_{dt}}}$$

# Results

## Calculation:

## Simulation:





# Contents

- Power stage
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  - Non-linear on-state resistance

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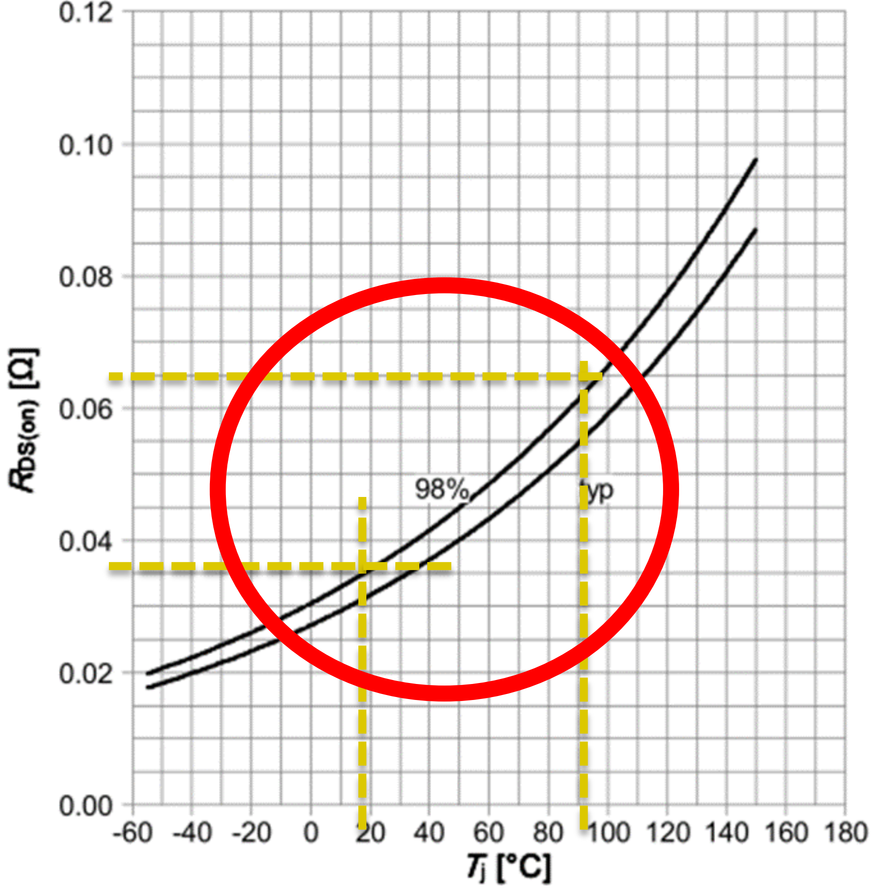
# Non-linear on-state of MOSFET

- MOSFET on-state resistance varies with temperature

- *Influence of non-linear resistance on output THD?*

Infineon IPW65R037C6

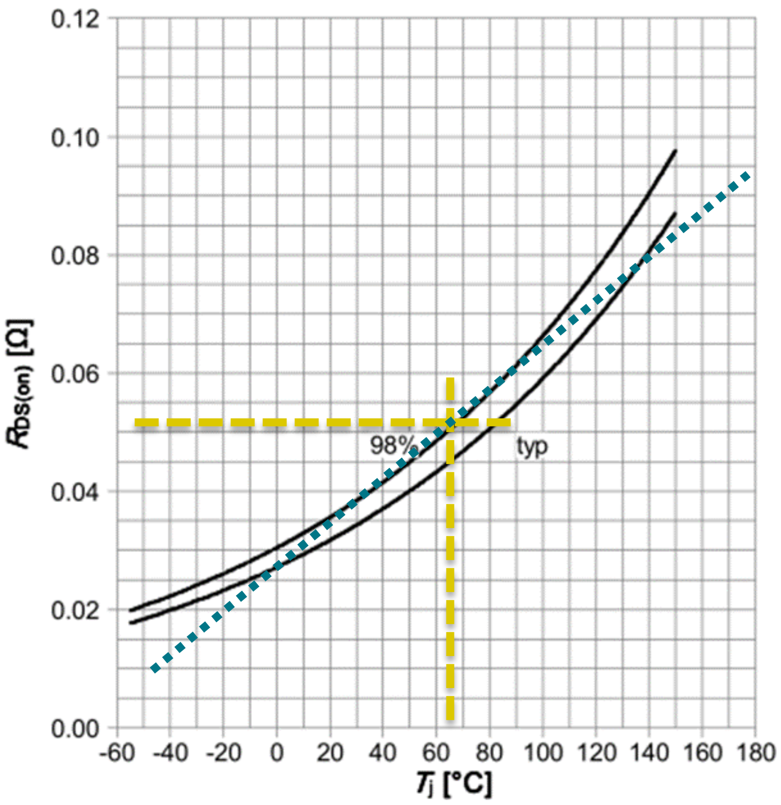


# Dissipated power (1)

- Determine first-order Taylor-approximation:
  - $R_{ds,\text{fit}}(\text{T}) = R_{ds}(T_{\text{heatsink}}) + \frac{\text{d}R_{ds}}{dT_j}(T - T_{\text{heatsink}})$

- Example:
  $T_{\text{heatsink}} = 60°\text{C}$ for Infineon IPW65R037C6 MOSFET, then:
  - $R_{ds}(T_{\text{heatsink}}) \approx 0.048\ \Omega$
  - $\frac{\text{d}R_{ds}}{dT_j} \approx 350 \cdot 10^{-6}\ \Omega/\text{K}$

Infineon IPW65R037C6



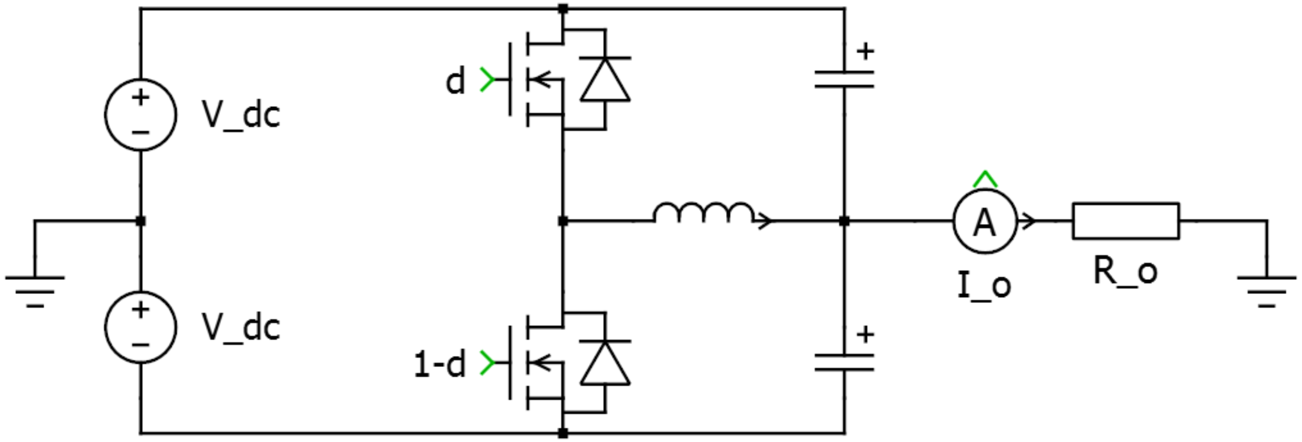
# Dissipated power (2)

- 
  - The top MOSFET junction dissipated power equals

$$P_{top,sw}(t) = I_{top,sw}^2(t)\ R_{ds} = \frac{D^2 V_{dc}^2 R_{ds}}{2(R_o + R_{ds})^2} \cos^2(\omega_0 t)\,(1 + D\cos(\omega_o t))$$

  - The **second harmonic ($2\omega_o$)** is dominant for small $D$, and equals

$$P_{top,sw,f2}(t) = \frac{D^2 V_{dc}^2 R_{ds}}{4(R_o + R_{ds})^2} \cos(2\omega_o t)$$

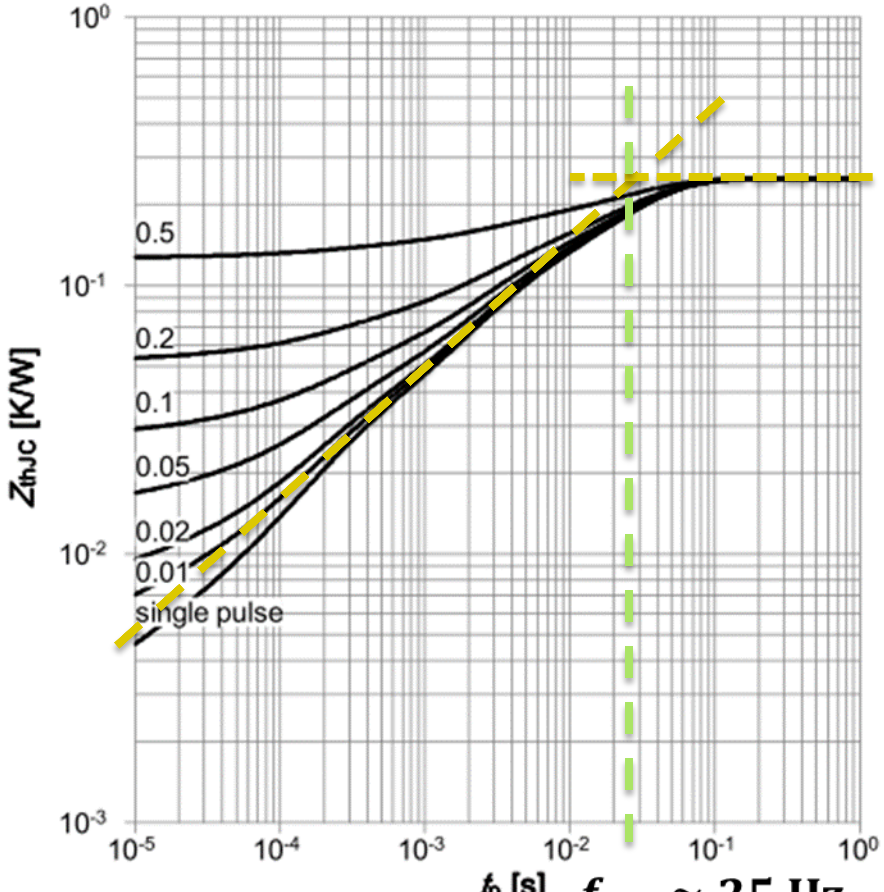


Half-bridge topology with output filter

# Transistor thermal model

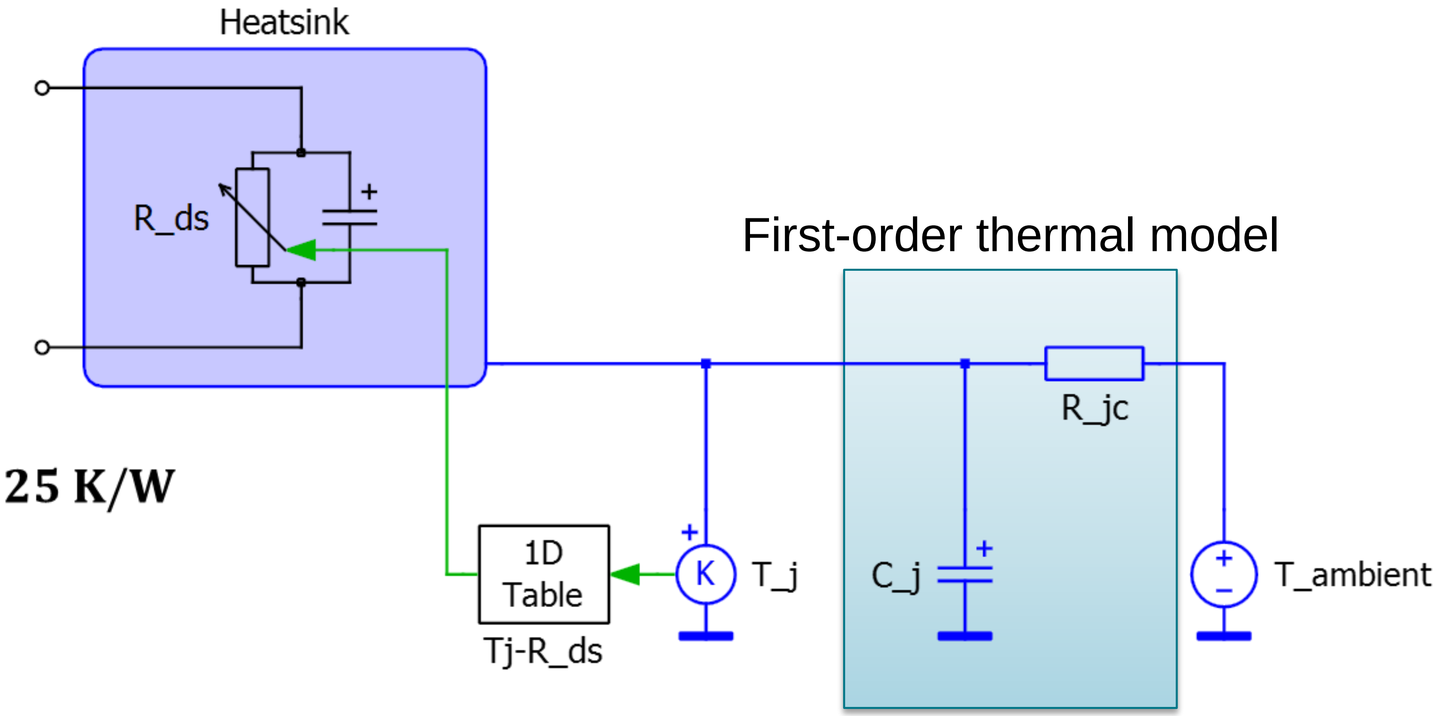
- Thermal model

Infineon IPW65R037C6



$\boldsymbol{R_{JC} \approx 0.25\ \mathrm{K/W}}$

$\boldsymbol{f_{bw} \approx 25\ \mathrm{Hz}}$



$$2\pi f_{bw} R_{JC} C_J = 1$$

Therefore it holds that

$$\boldsymbol{C_J = \frac{1}{2\pi f_{bw} R_{JC}}}$$

# Output voltage distortion

Het afbeeldingonderdeel met relatie-id rId2 is niet aangetroffen in het bestand.

Magnitude of harmonics (3rd and 1st)

From datasheet

From thermal model

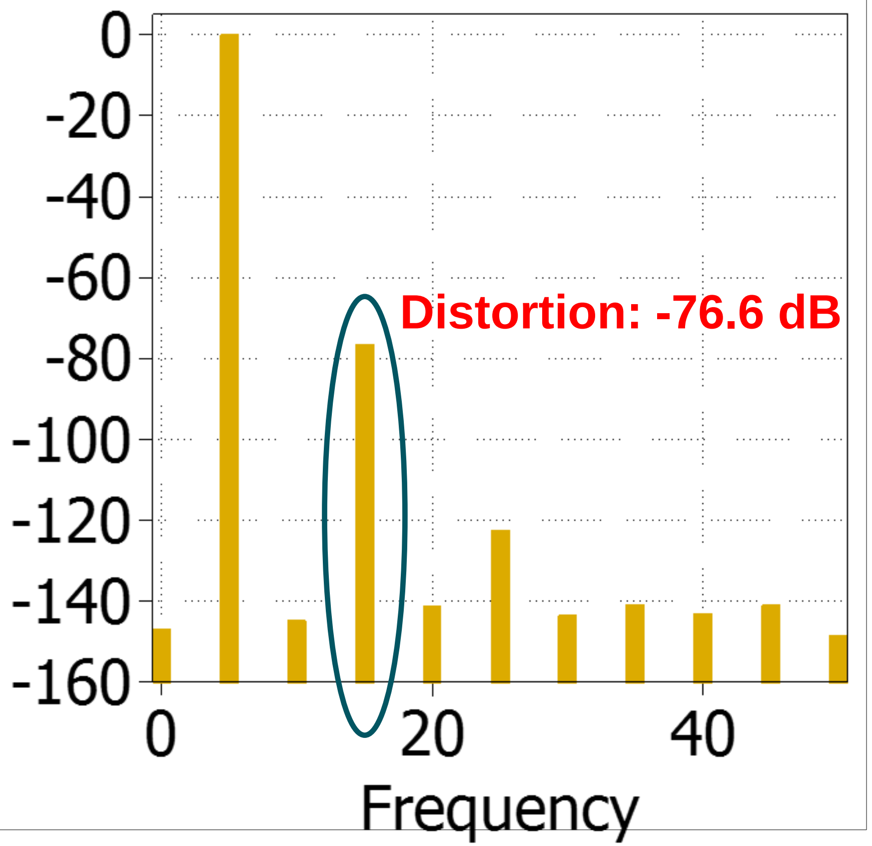
Output voltage
(linearized resistor divider)

# Results

- 5 Hz excitation in 1 Ohm load

**Calculation:**

**Simulation:**



Distortion: -76.6 dB

Note: fifth harmonic (-122 dB) can be found by using a second-order Taylor approximation at slide 16.

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Electromechanics & Power Electronics

# Contents

- Power stage
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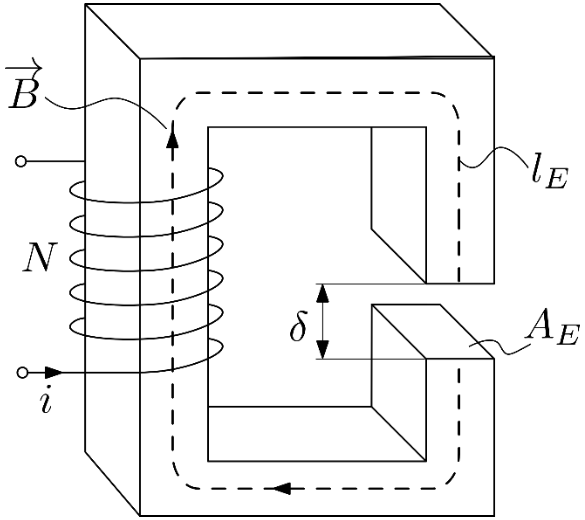
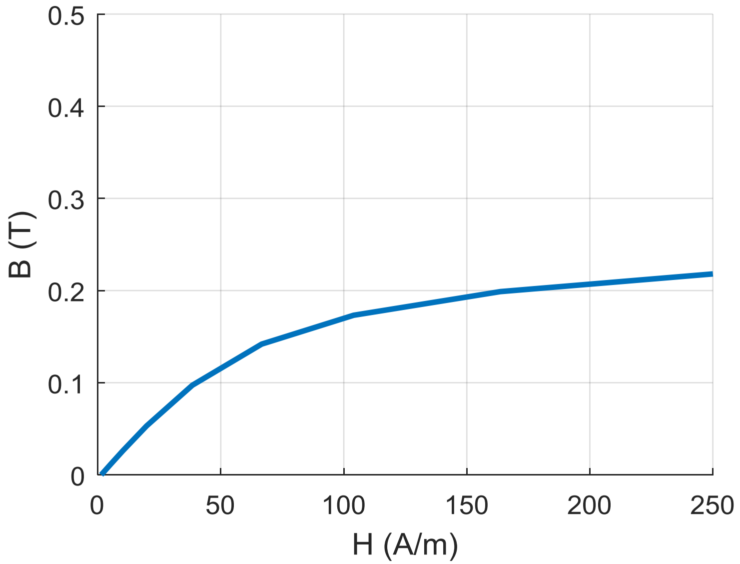
# Inductor saturation

- Core material is non-linear → distortion!





**Procedure steps:**

1. Determine swing of inductance
2. Find resulting voltage error
3. Calculate third harmonic magnitude

# Determining inductance swing (1)

- Sinusoidal excitation: determine inductance at $H = 0$ and $H = H_E$

1. Determine inductance with load line technique

$$\mathcal{F} = Ni = H_E l_E + H_\delta \delta$$

Core

Air gap

$$B_\delta = B_E$$

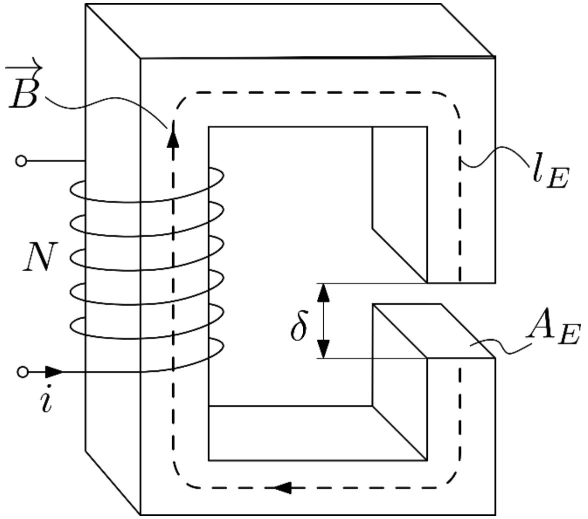
therefore

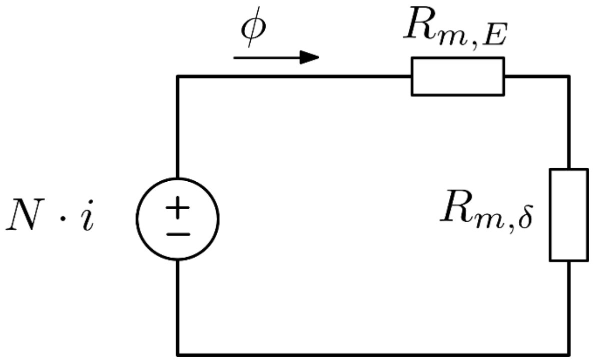
$$H_\delta = \frac{B}{\mu_0}$$

$$\boxed{H_E = -\frac{\delta}{\mu_0 l_E} B + \frac{Ni}{l_E}}$$

**N=number of turns**
**i=current**

Load line equation: all possible solutions for H as function of B with given geometry and operating current.





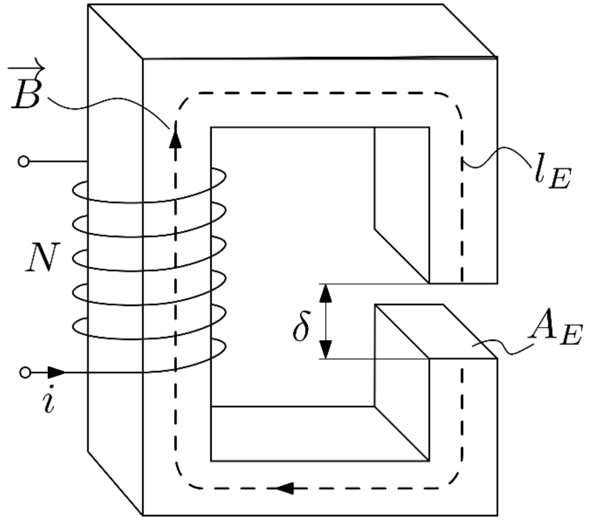
# Determining inductance swing (2)

2. Determine BH-curve of material using

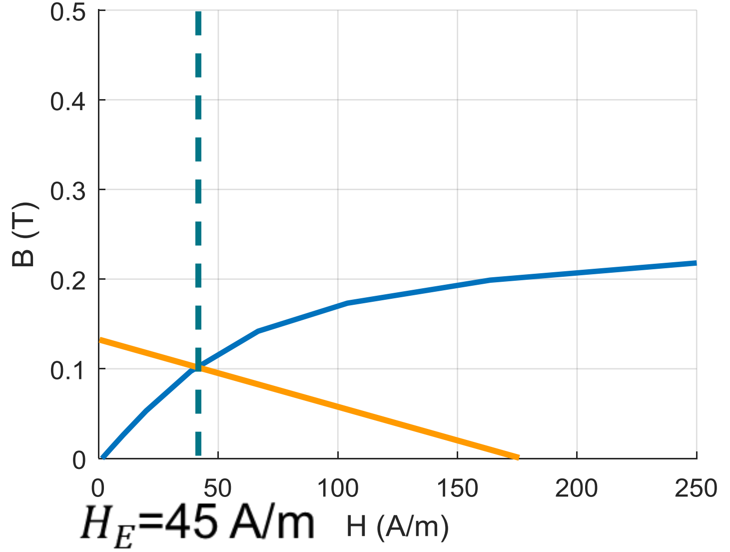
$$\int dB = \int \mu \, dH \Rightarrow \boxed{B = \int \mu_0 \mu_r \, dH}$$

3. Find intersection of load line with BH-curve

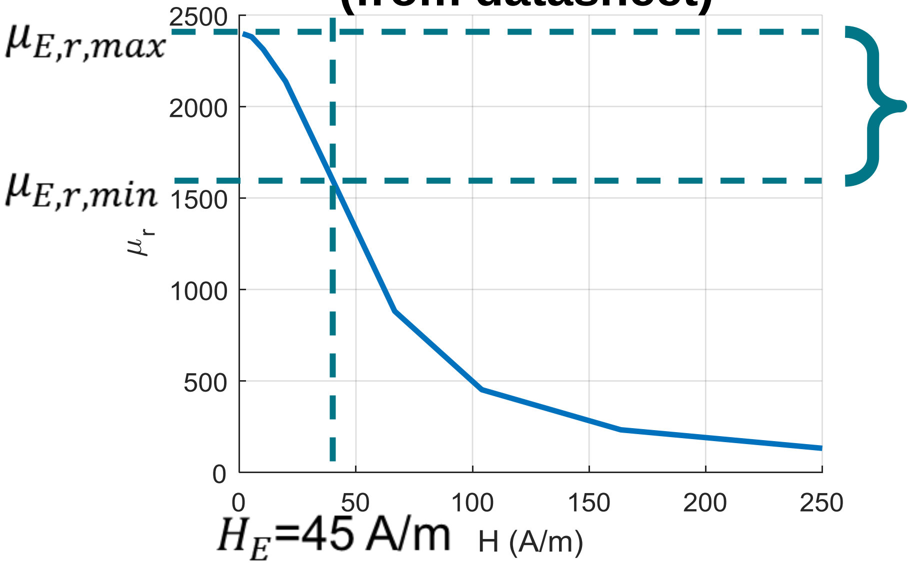
$$\boxed{H_E = -\frac{\delta}{\mu_0 l_E} B + \frac{Ni}{l_E}}$$



**3C90 BH-curve (calculated from saturation curve)**



**3C90 saturation curve (from datasheet)**



**$\mu_r$ swing → inductance swing**

# Voltage error

- Finding inductor harmonic distortion:
  - Output current:

$$i_o = I_o \sin(\omega_o t)$$

  - Voltage over inductor:

$$V_L = L\frac{di_o}{dt}$$

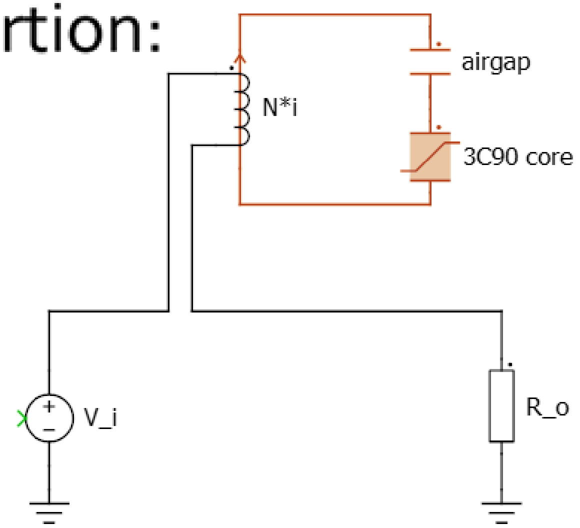
  - Distortion = difference from ideal inductor:

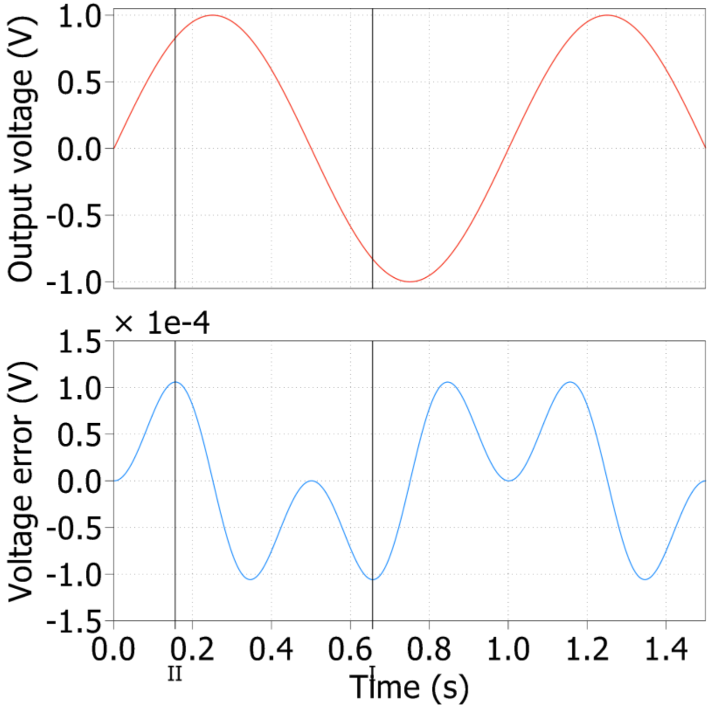
$$V_{\text{error}} = \Delta L \frac{di_o}{dt}$$

maximum at maximum current

maximum at zero current

  - Maximum of $V_{\text{error}}$ occurs at $i_o \approx 0.8 I_o$ (see graph)





# Harmonic distortion

- ○ Distortion equal to

$$V_{\text{error}} = \Delta L \frac{di_o}{dt}$$

$$\frac{di_o}{dt} = I_o \omega_o \cos\left(\omega_o t\right) \approx \frac{\omega_o V_i \cos(\omega_o t)}{R_o}$$

Note we assume resistive behavior here!

- ○ At $i_o = 0.8 I_o$:

$$\frac{di_o}{dt} = \frac{\omega_o V_i \cos(\arcsin(0.8))}{R_o} = \frac{0.6\omega_o V_i}{R_o}$$

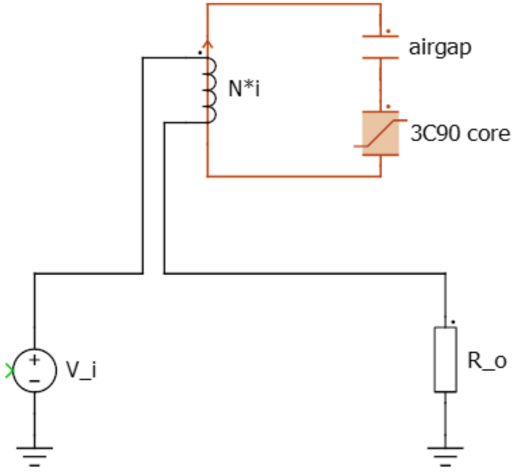
- ○ Maximum error therefore:

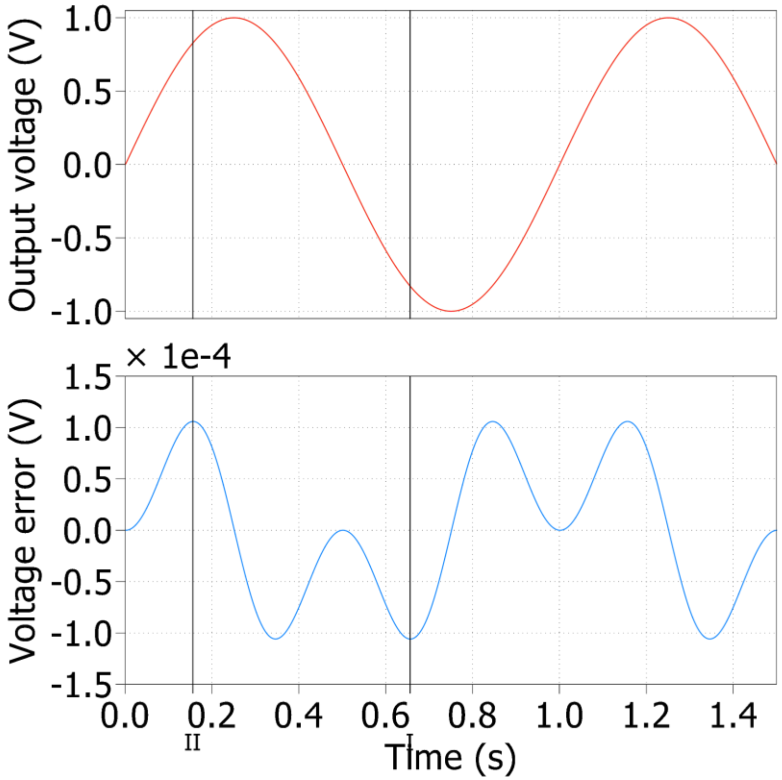
$$V_{\text{error}} = (L_{max} - L_{min}) \frac{0.6\omega_o V_i}{R_o}$$

- ○ Harmonic distortion using third harmonic magnitude:

$$\text{THD}_3 = \frac{3\sqrt{3}\text{V}_{\text{error}}}{8\text{V}_{\text{i}}}$$

First harmonic and third harmonic have equal magnitude. Ratio peak error and harmonic magnitude $\frac{8}{3\sqrt{3}}$.





# Results

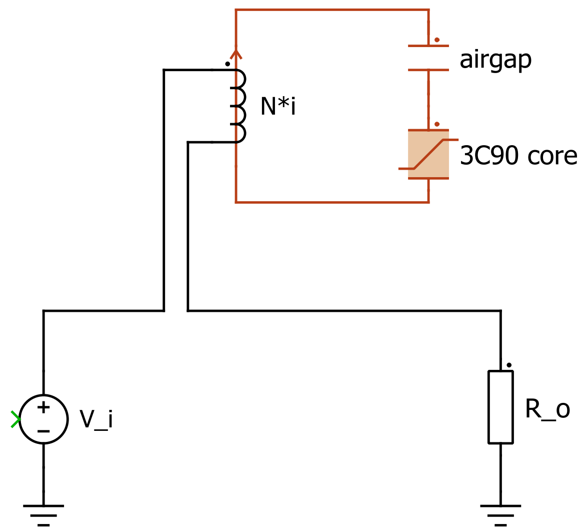
## Calculation result:

Result from calculations in previous slides:

Het afbeeldingonderdeel met relatie-id rId3 is niet aangetroffen in het bestand.

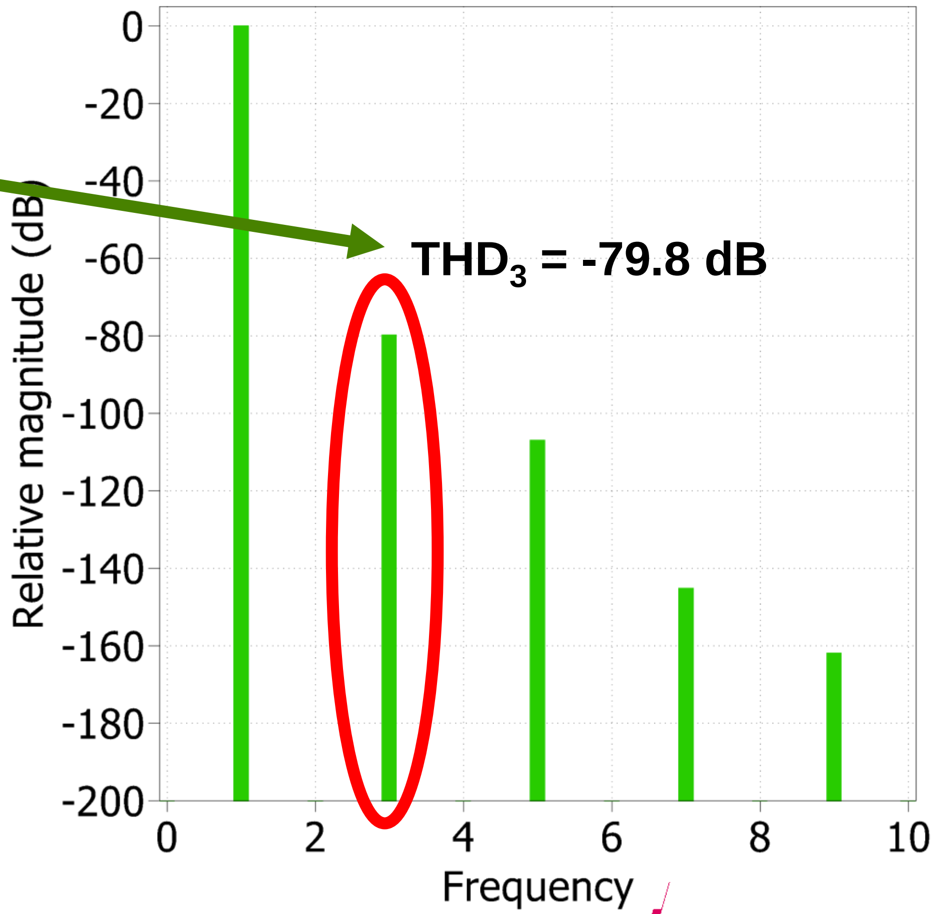
Accurate!

## Simulation diagram:



## Simulation result:

MATLAB Simulink + PLECS simulation



**$THD_3$ = -79.8 dB**

# Contents

- Power stage
  - Dead-time
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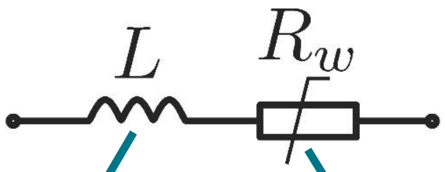
# Winding thermal model

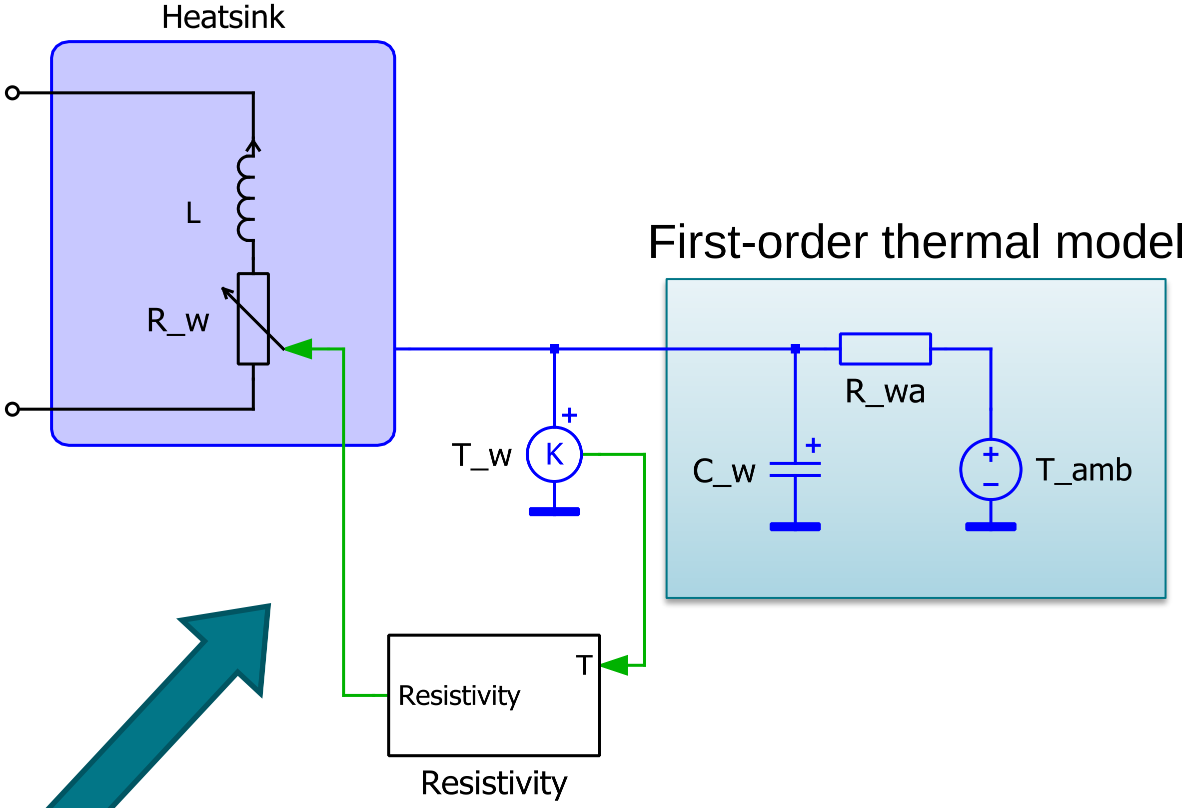
- Assume first-order thermal model



"Ideal" inductor

Parasitic electric resistance

**Copper mass → thermal capacity**
**Winding surface area → thermal resistance**
**Electrical resistance is temperature dependent!**



# Output voltage distortion

- The THD caused by non-linear resistance of winding equals

$$\boxed{\mathrm{THD}_3(t) = \frac{V_{o,f3}}{V_{o,f1}} = \frac{R_{\mathrm{w,swing}}}{2\left(R_o + R_{w_0}\right) - R_{\mathrm{w,swing}}}}$$

Magnitude of harmonics (3rd and 1st)

with

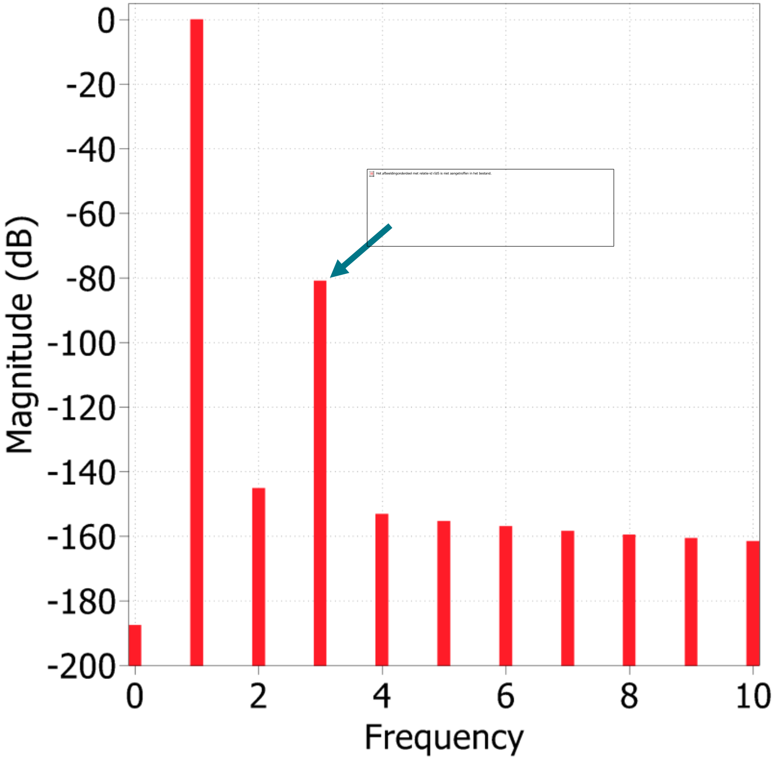
$$R_{w,\mathrm{swing}} = \alpha R_{w_0}\left(\frac{R_{wa}}{\sqrt{4\omega_o^2 C_w^2 R_w^2 + 1}}\right)\left(\frac{\hat{I}^2 R_{w_0}}{2}\right)$$

# Results

- **Calculation results:**

**Simulation results:**

Output voltage spectrum

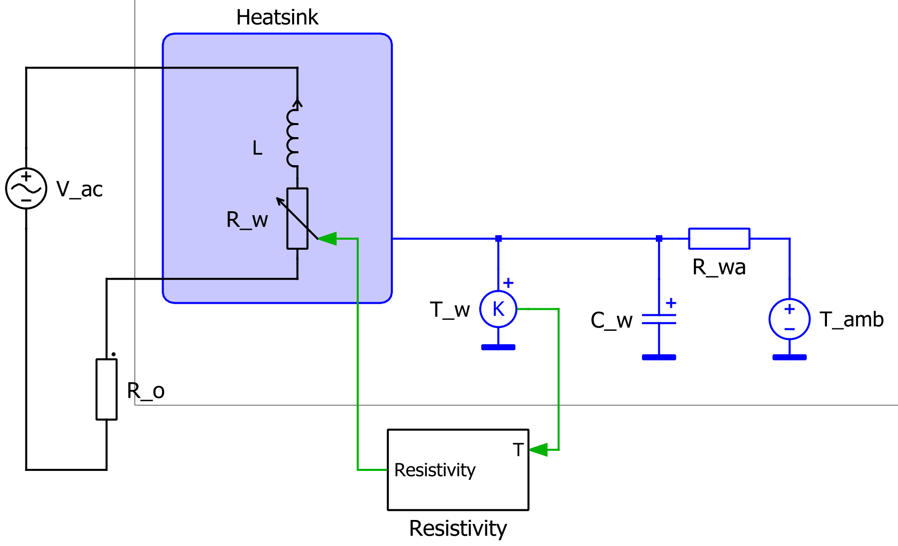


# Results

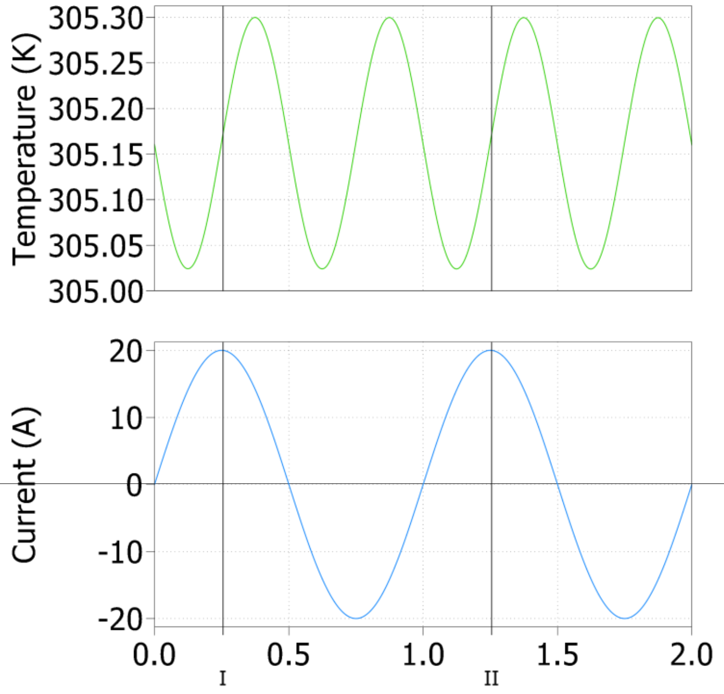
Het afbeeldingonderdeel met relatie-id rId3 is niet aangetroffen in het bestand.

High dissipation in inductor is required to reach significant distortion

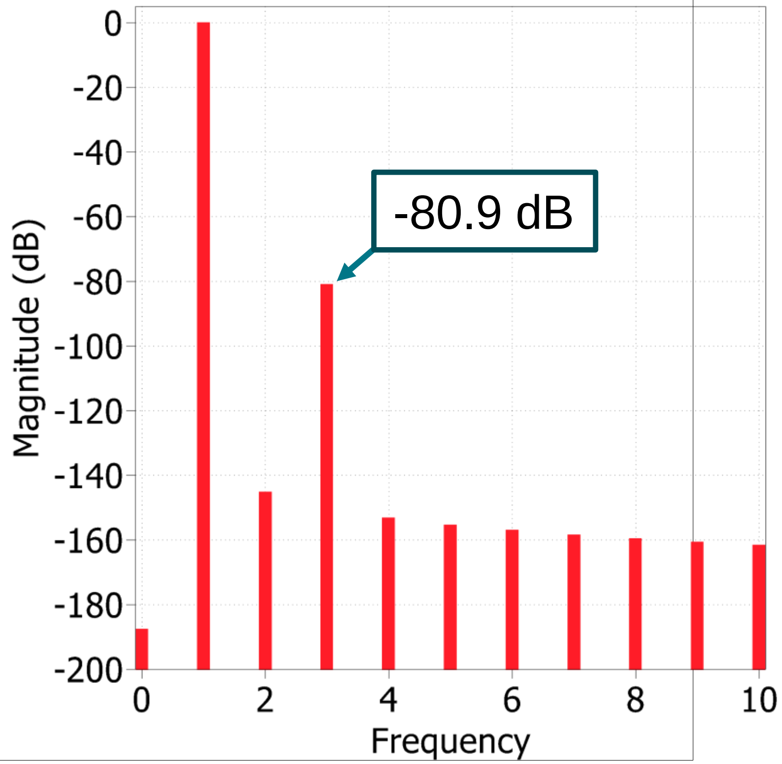
## Simulation model



## Results



## Output voltage spectrum



-80.9 dB

# Conclusions

- High-precision requires accurate models of all converter components
- Various non-linear effects modeled and validated with good results
- Most significant effect in most scenarios is dead-time
- Inductor core hysteresis is not covered

Any questions?