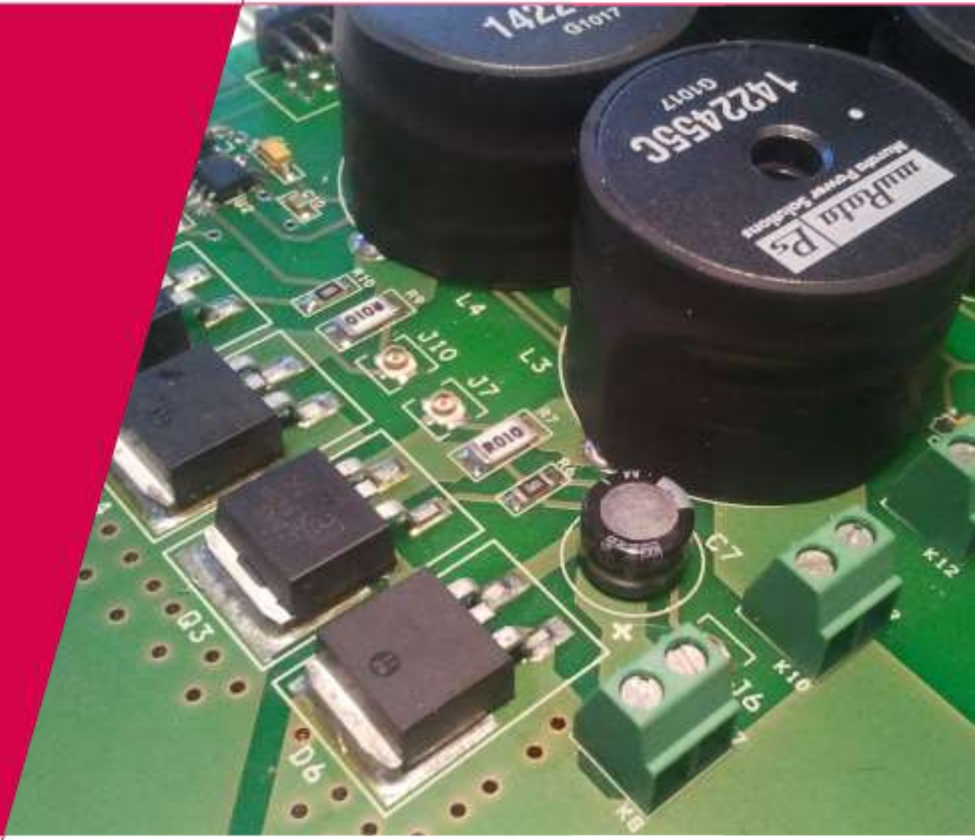
14 juni 2018
1931 Congrescentrum Den Bosch

POWER ELECTRONICS 2018

Soft-switching multi-level power amplifier for High Voltage



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TU/e Technische Universiteit Eindhoven University of Technology

ASML PRODRIVE TECHNOLOGIES NWO Applied and Engineering Sciences

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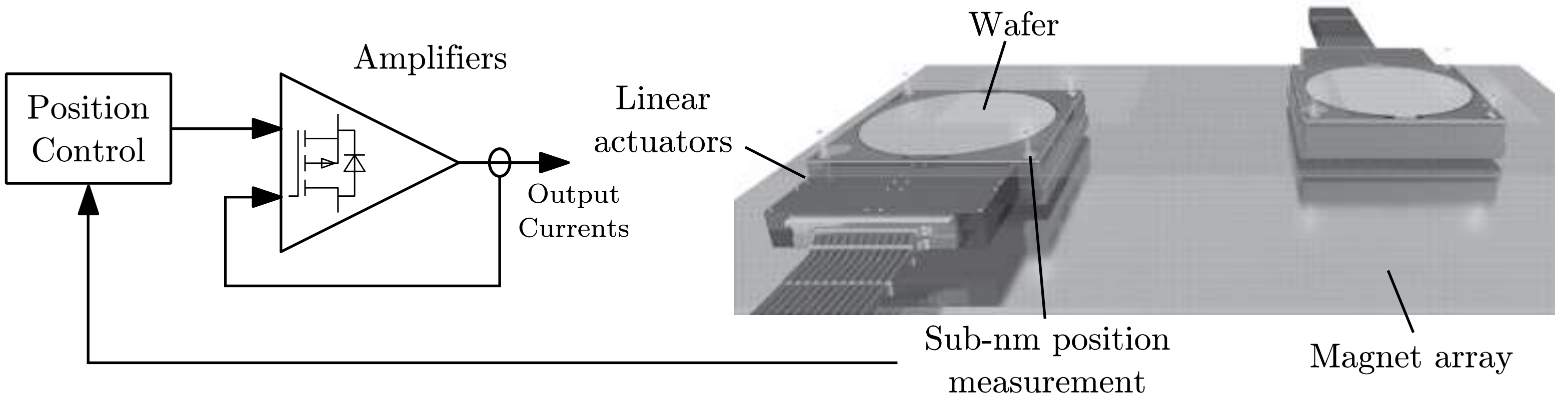
1. Introduction

- Amplifier in high precision motion control system
- Performance indicators
  - Position error
  - Throughput

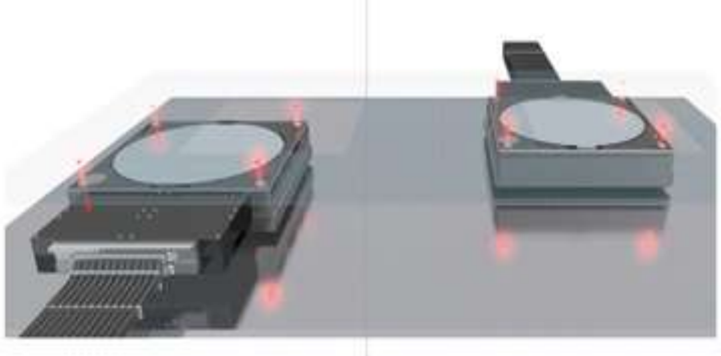
→ Main challenge: high output power and high accuracy



1. Introduction

- High output power → increase voltage instead of current
  - Bus voltage: $2\ kV$
  - Output current: $30\ A_{rms}$, $85\ A_{pk}$
- High accuracy → increase switching frequency
  - Switching frequency: $\geq 100\ kHz$
  - Reduced size of filter components

→ No fast HV switches available



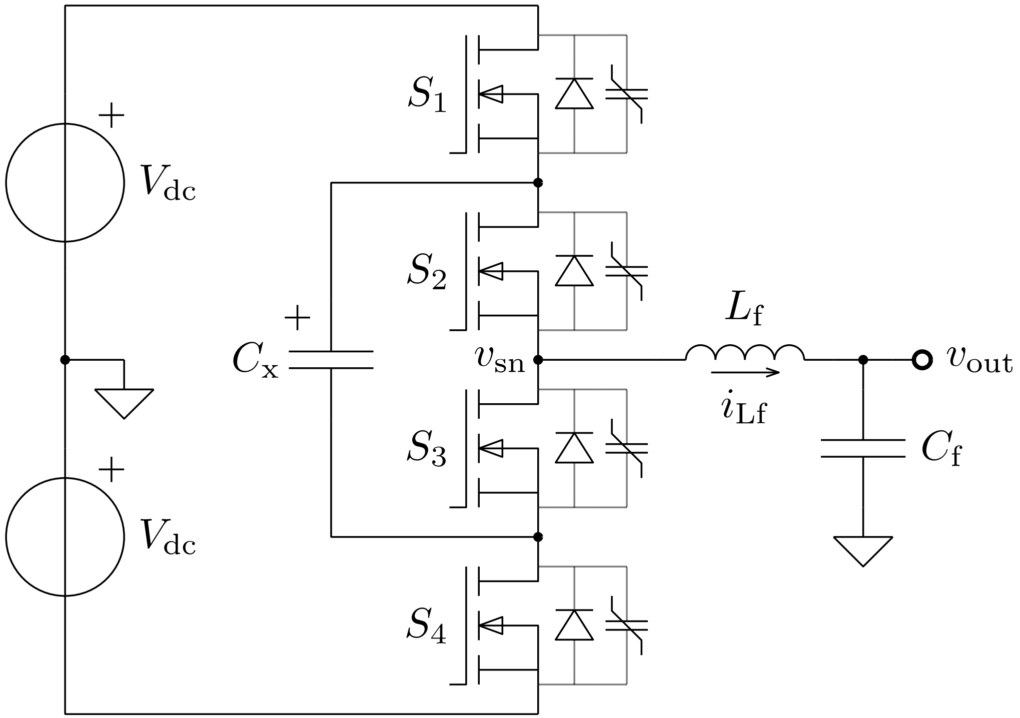
2. Flying capacitor resonant pole inverter

- 4 switches connected in series
- Redundant switching states
  - ➢ V_{Cx} regulated to V_{dc}
- Voltage across switches limited to V_{dc}

→ Use fast switches with lower voltage rating
  - 1200V SiC MOSFETs
  - Increased output voltage: $V_{dc} = 1\ kV$
  - High switching frequency: $f_{sw} \geq 100\ kHz$

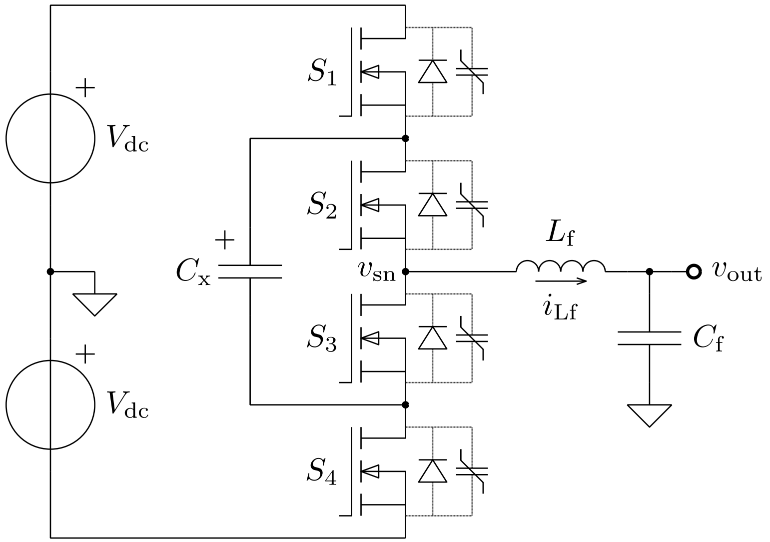
- 3-level switch-node voltage

→ Trapezoidal filter current

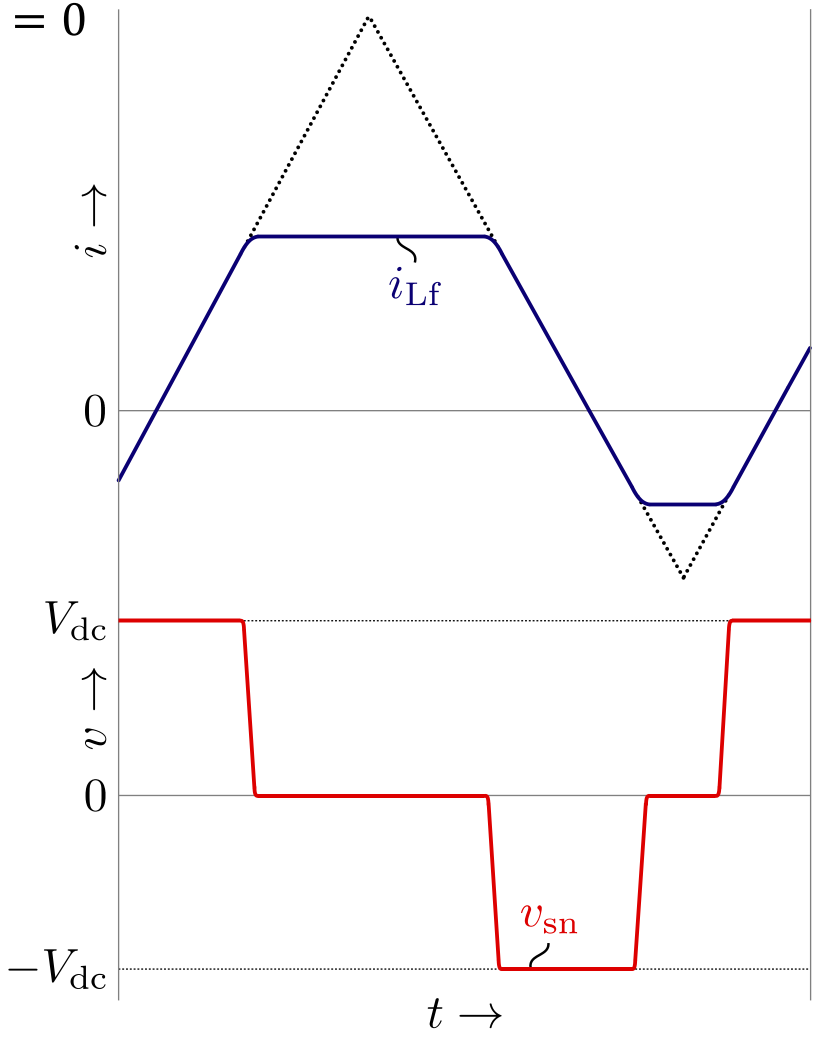


2. FC RPI – Trapezoidal filter current

- 3 voltage levels available
  - $v_{sn} = \{V_{dc}, 0, -V_{dc}\}$
  - Trapezoidal filter current i_{Lf}
- Decreased peak and rms value of the current

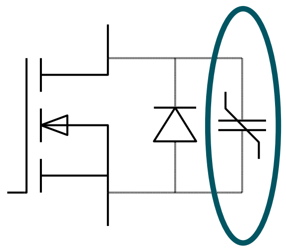


$i_{avg} > 0$, $v_{out} = 0$

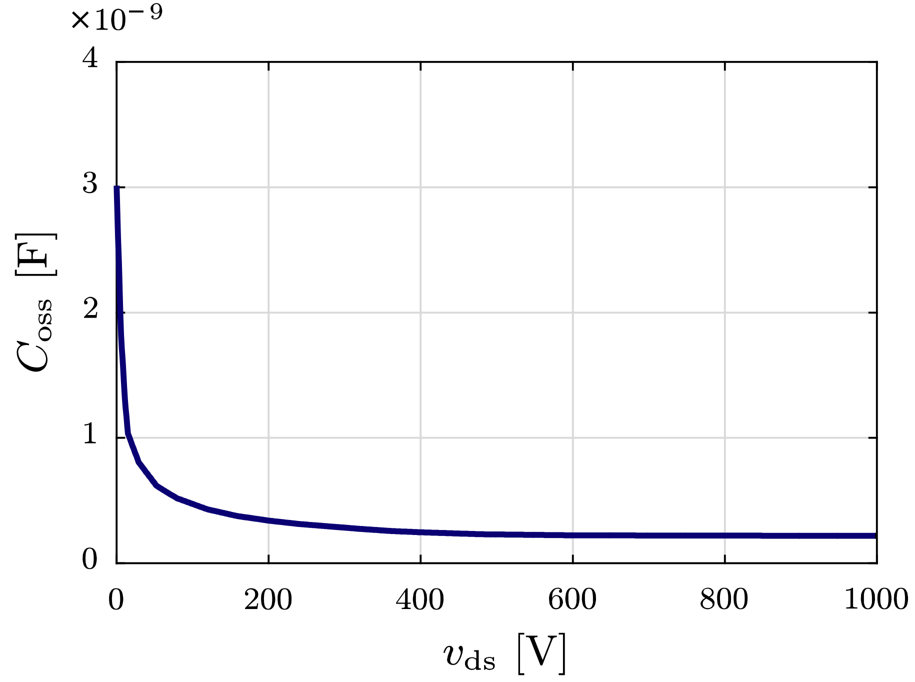


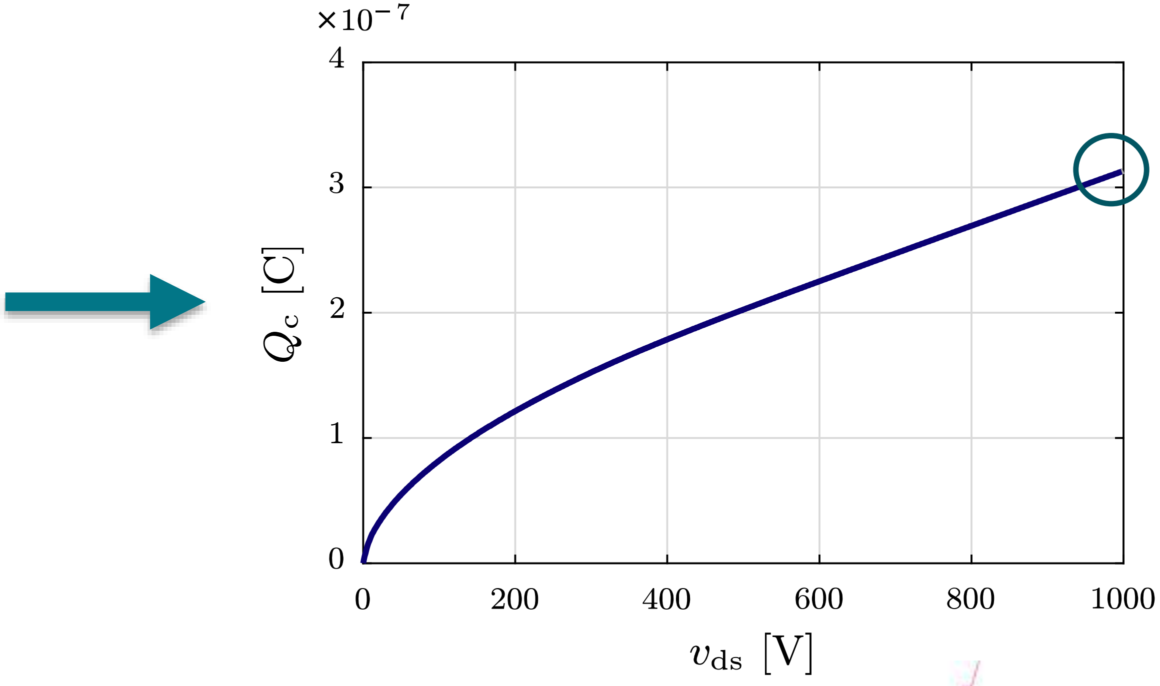
3. Charge-based ZVS

- Guarantee ZVS
  - Non-linear output capacitance of switch
  - Minimum required commutation charge Q_c
  - Piece-wise linear approximation of i_{Lf}



- From datasheet of Cree C2M0025120D:





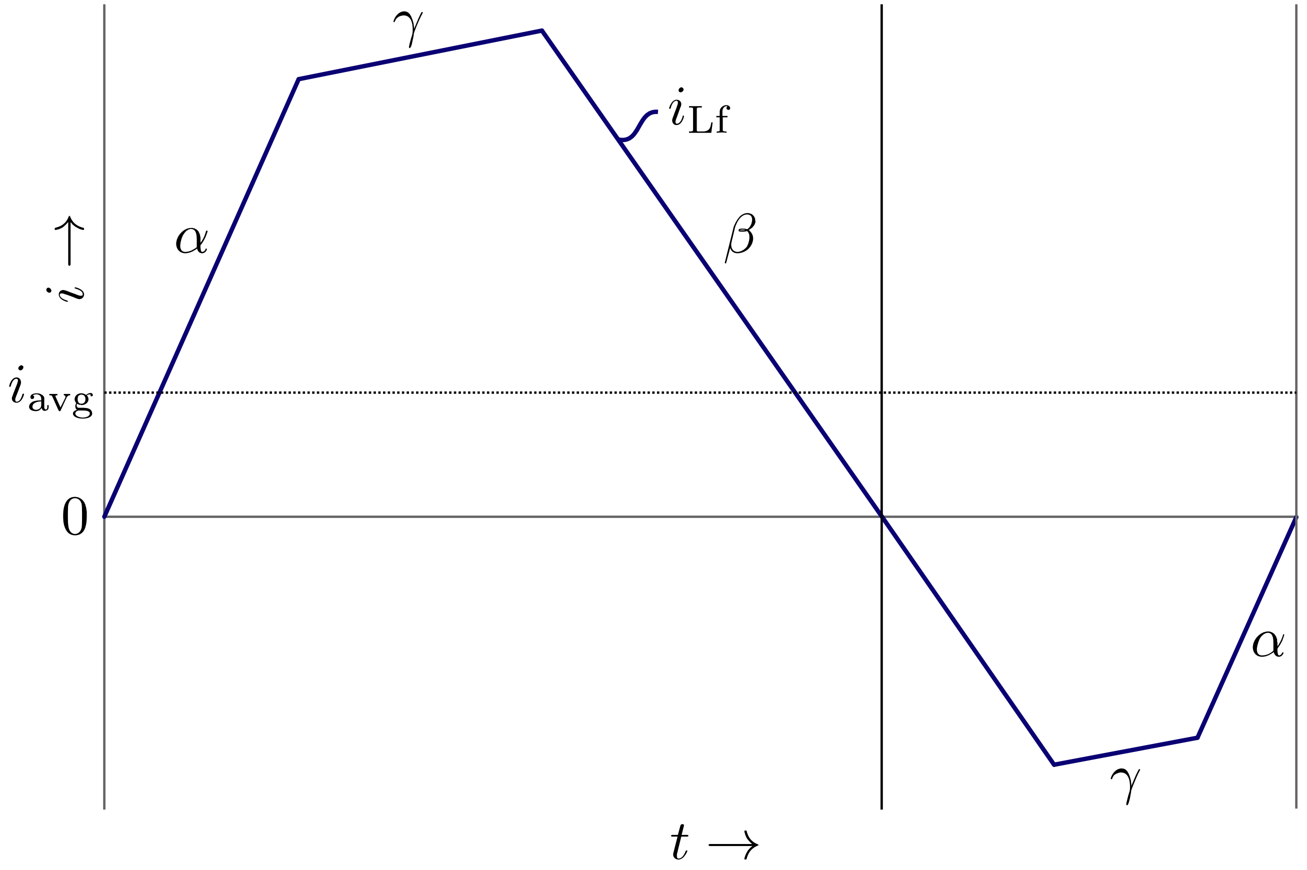
Trapezoidal filter current with ZVS

- **Case:** $i_{avg} > 0$ **and** $v_{out} < 0$

$$\alpha = \frac{V_{\mathrm{dc}} - v_{\mathrm{out}}}{L_{\mathrm{f}}}$$

$$\beta = \frac{-V_{\mathrm{dc}} - v_{\mathrm{out}}}{L_{\mathrm{f}}}$$

$$\gamma = \frac{0 - v_{\mathrm{out}}}{L_{\mathrm{f}}}$$



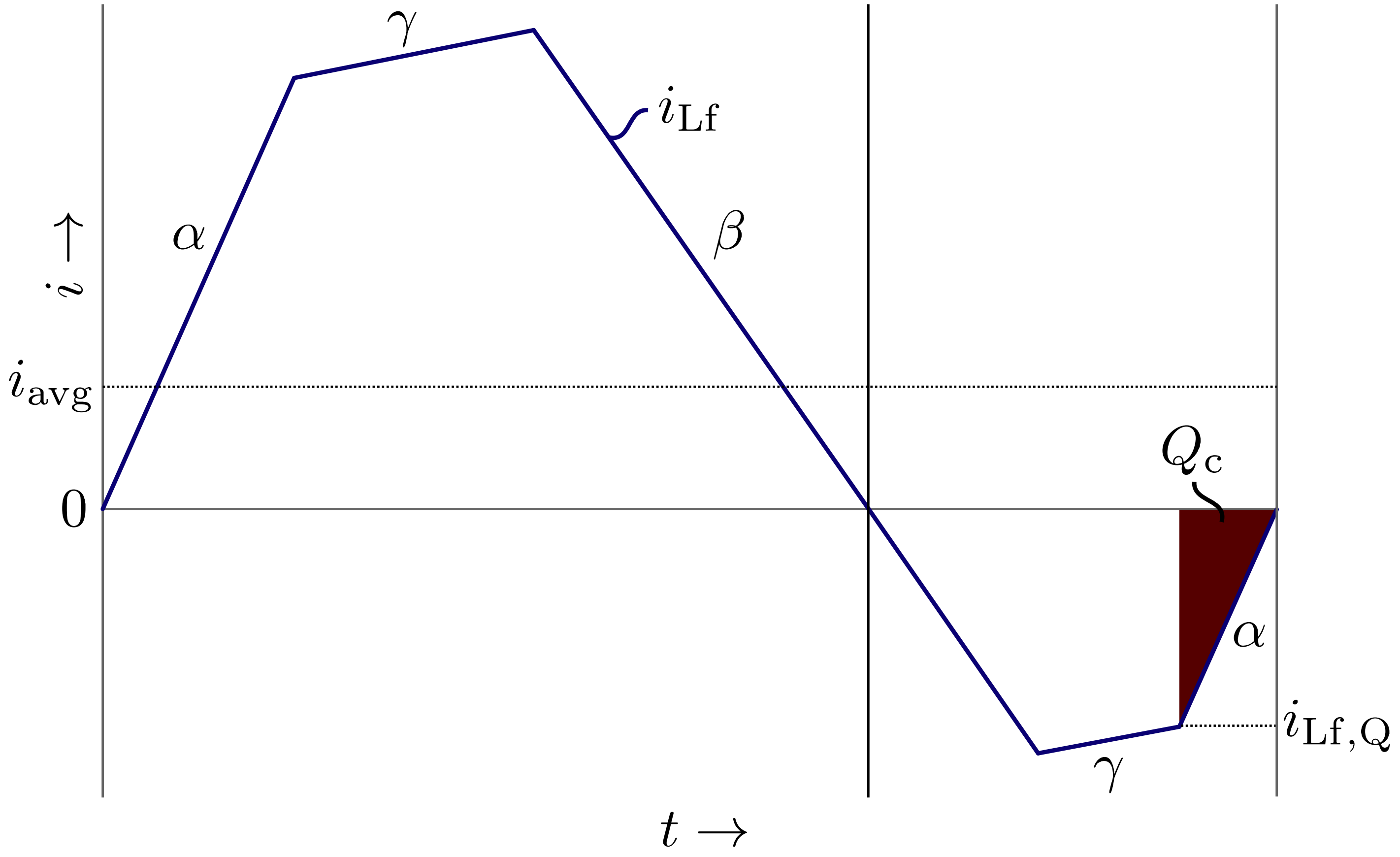
Trapezoidal filter current with ZVS

- Case: $i_{avg} > 0$ and $v_{out} < 0$

- $\boldsymbol{i_{Lf,Q}}$

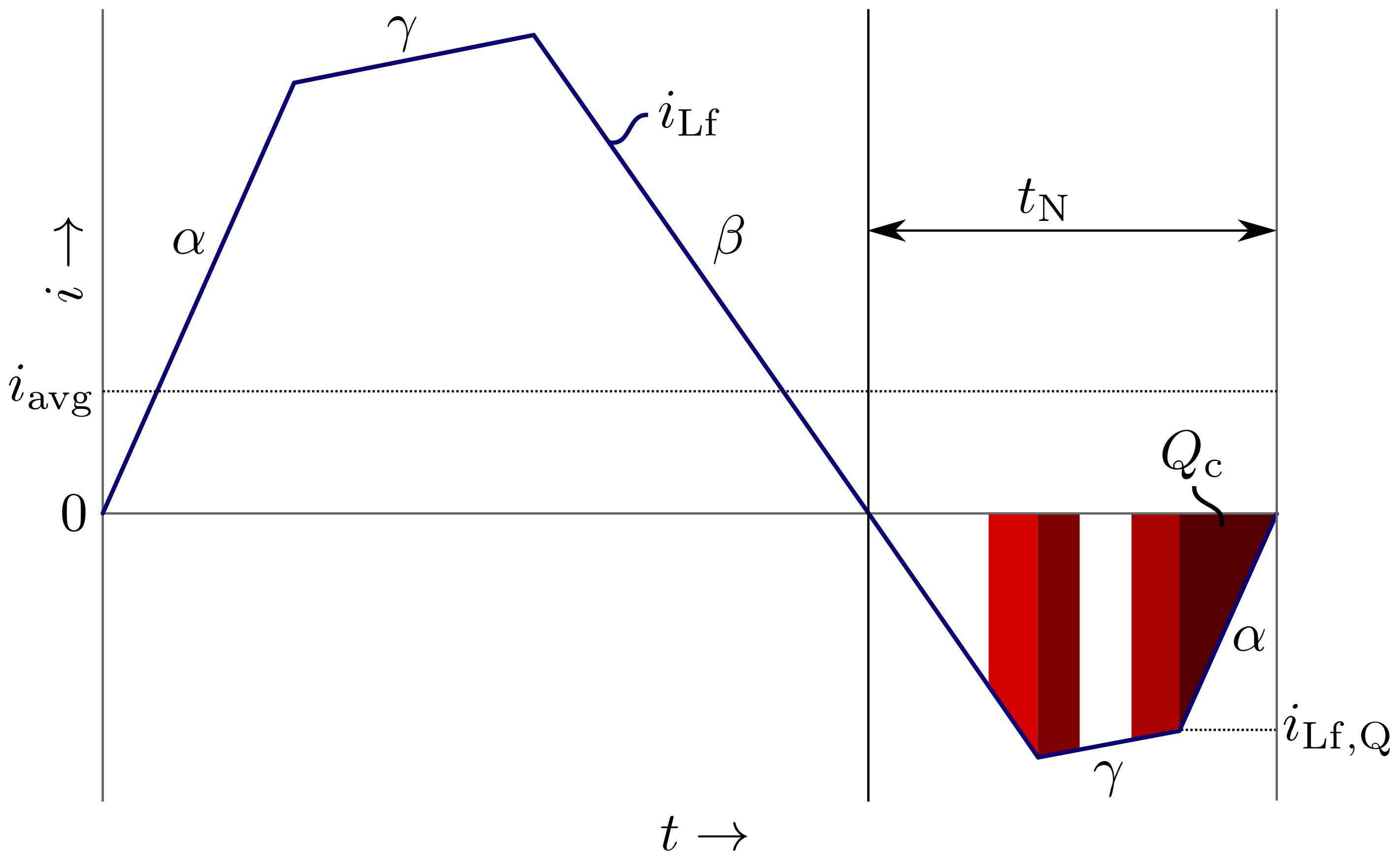
$$i_{\mathrm{Lf,Q}} = -\sqrt{2 \cdot Q_{\mathrm{c}} \cdot \alpha}$$

$$\alpha = \frac{V_{\mathrm{dc}} - v_{\mathrm{out}}}{L_{\mathrm{f}}}$$



Trapezoidal filter current with ZVS

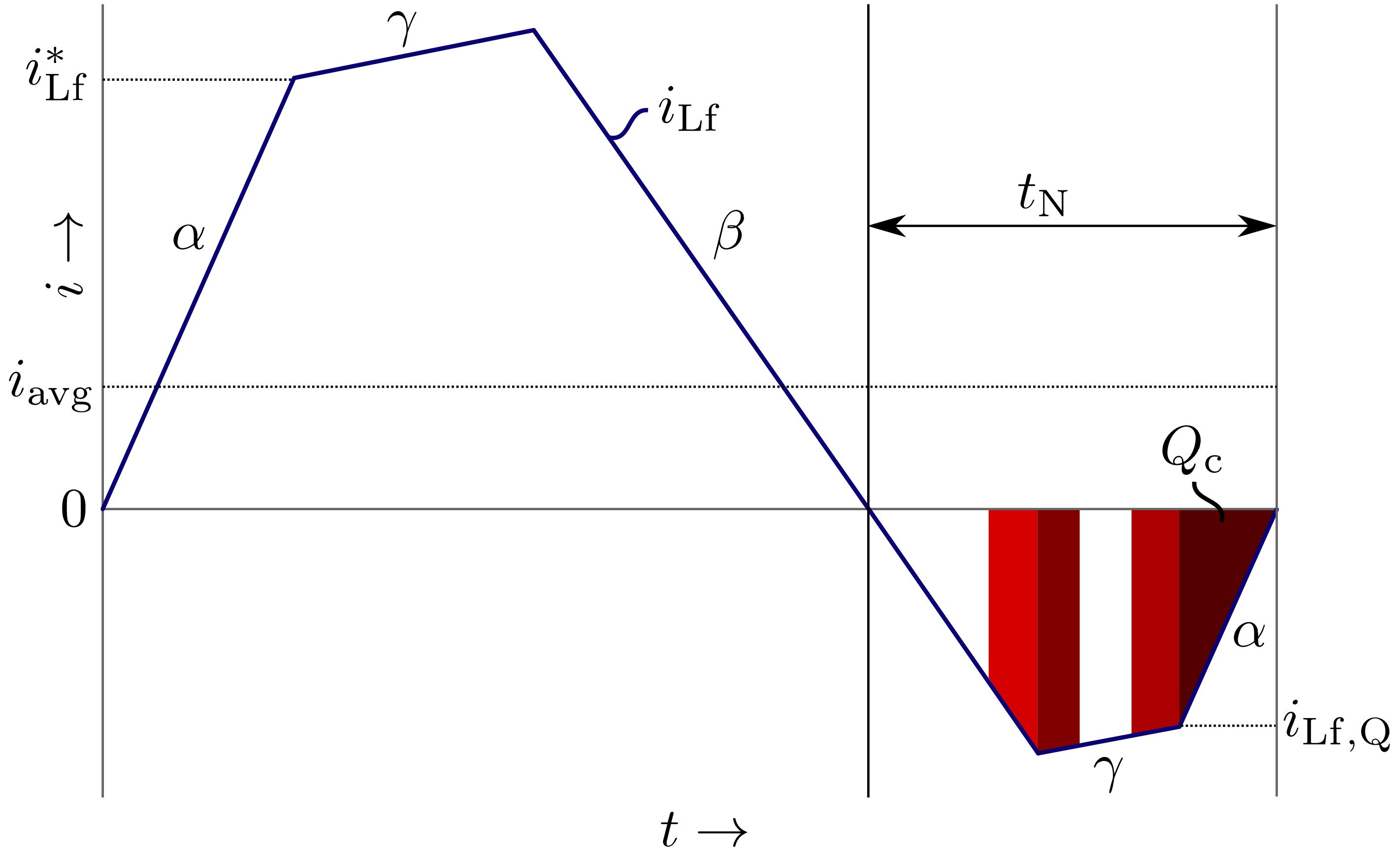
- Case: $i_{avg} > 0$ and $v_{out} < 0$
- $i_{Lf,Q}$
- **A_N and t_N**



Trapezoidal filter current with ZVS

- Case: $i_{avg} > 0$ and $v_{out} < 0$
- $i_{Lf,Q}$
- A_N and t_N
- **$i_{Lf}*$**

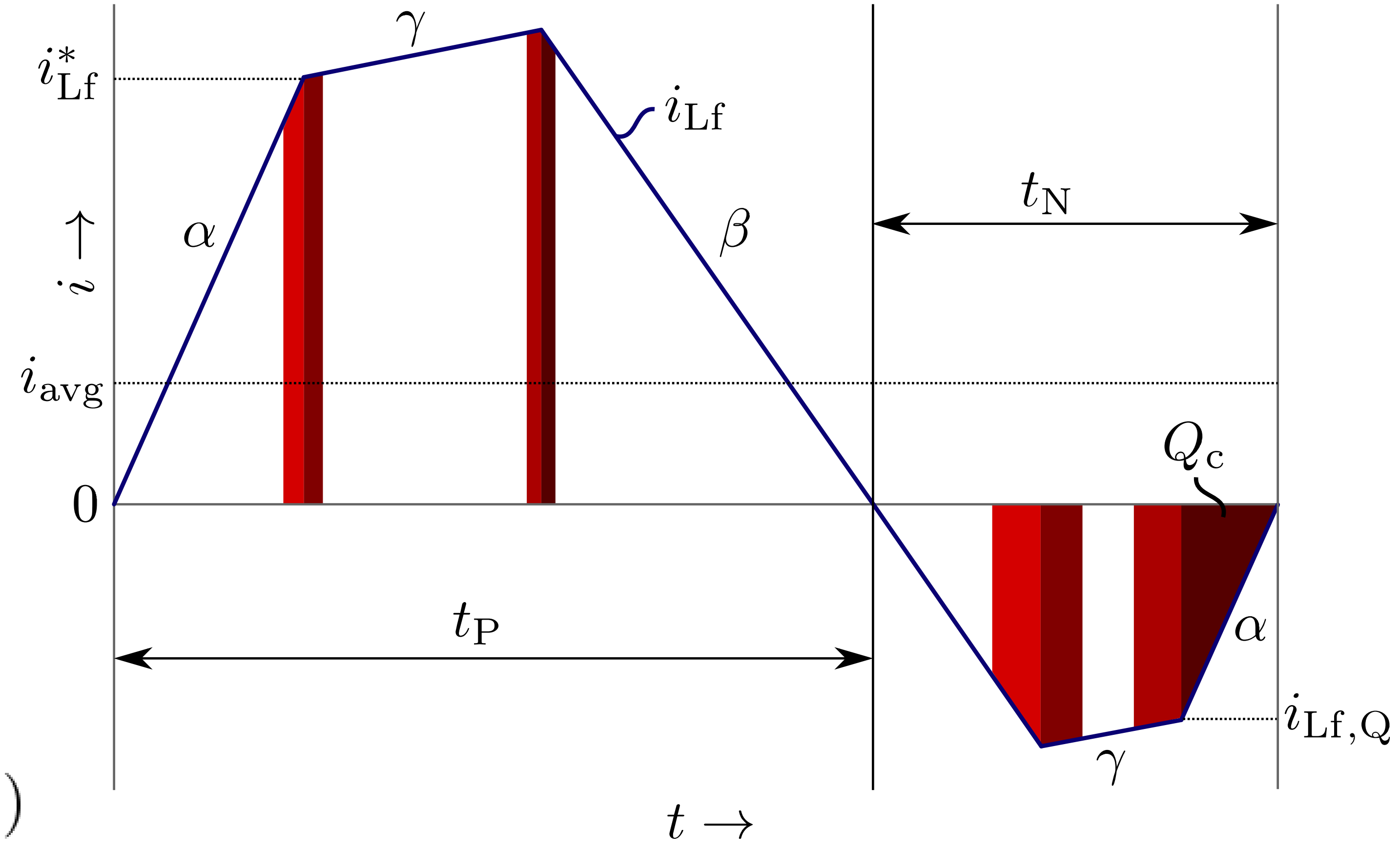
$$i^*_{\mathrm{Lf}} = -i_{\mathrm{Lf,Q}} + 2 \cdot i_{\mathrm{avg}}$$



Trapezoidal filter current with ZVS

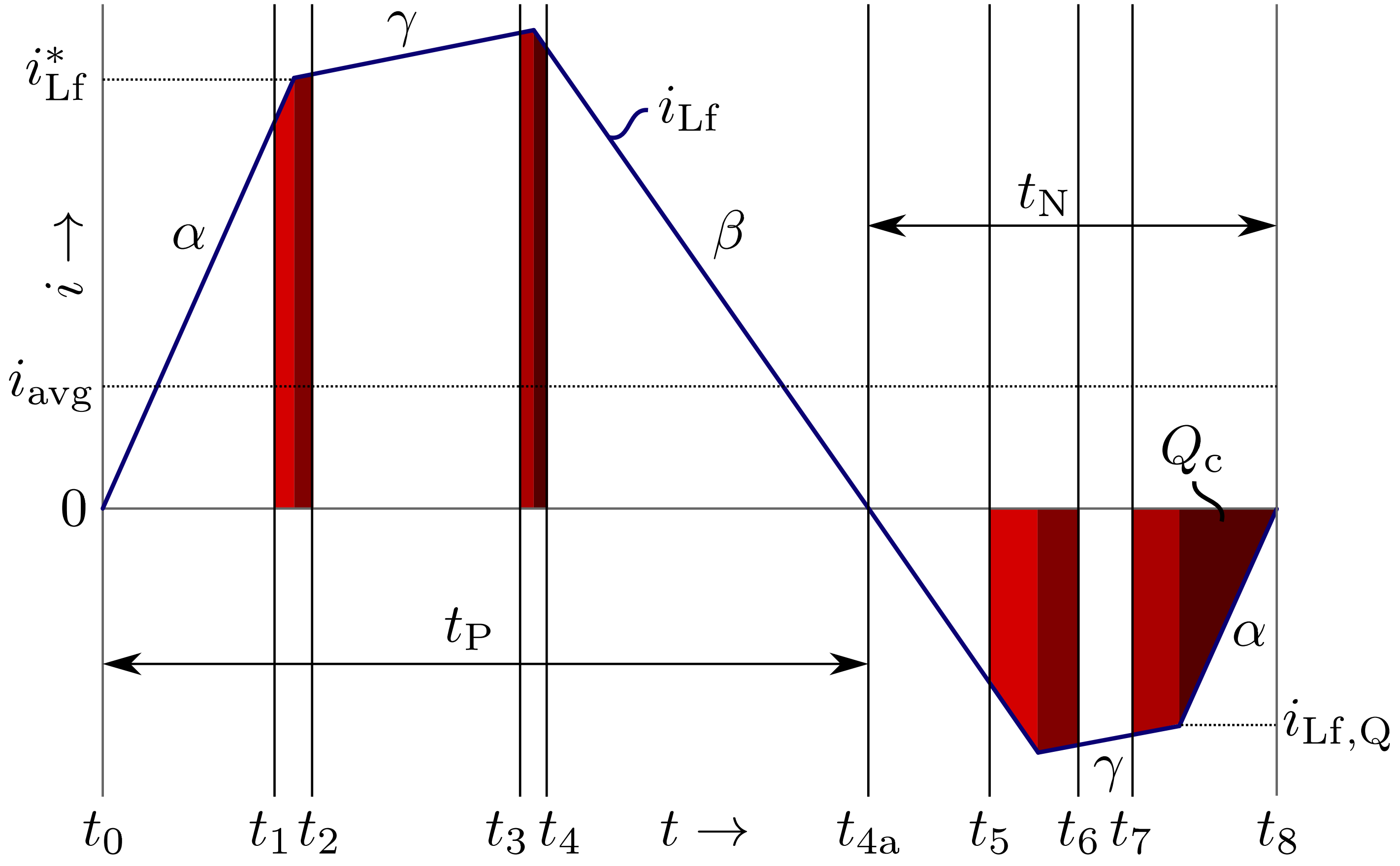
- Case: $i_{avg} > 0$ and $v_{out} < 0$
- $i_{Lf,Q}$
- A_N and t_N
- $i_{Lf}*$
- $\boldsymbol{A_P}$ **and** $\boldsymbol{t_P}$

$$A_{\mathrm{P}} = A_{\mathrm{N}} + i_{\mathrm{avg}}\left(t_{\mathrm{N}} + t_{\mathrm{P}}\right)$$



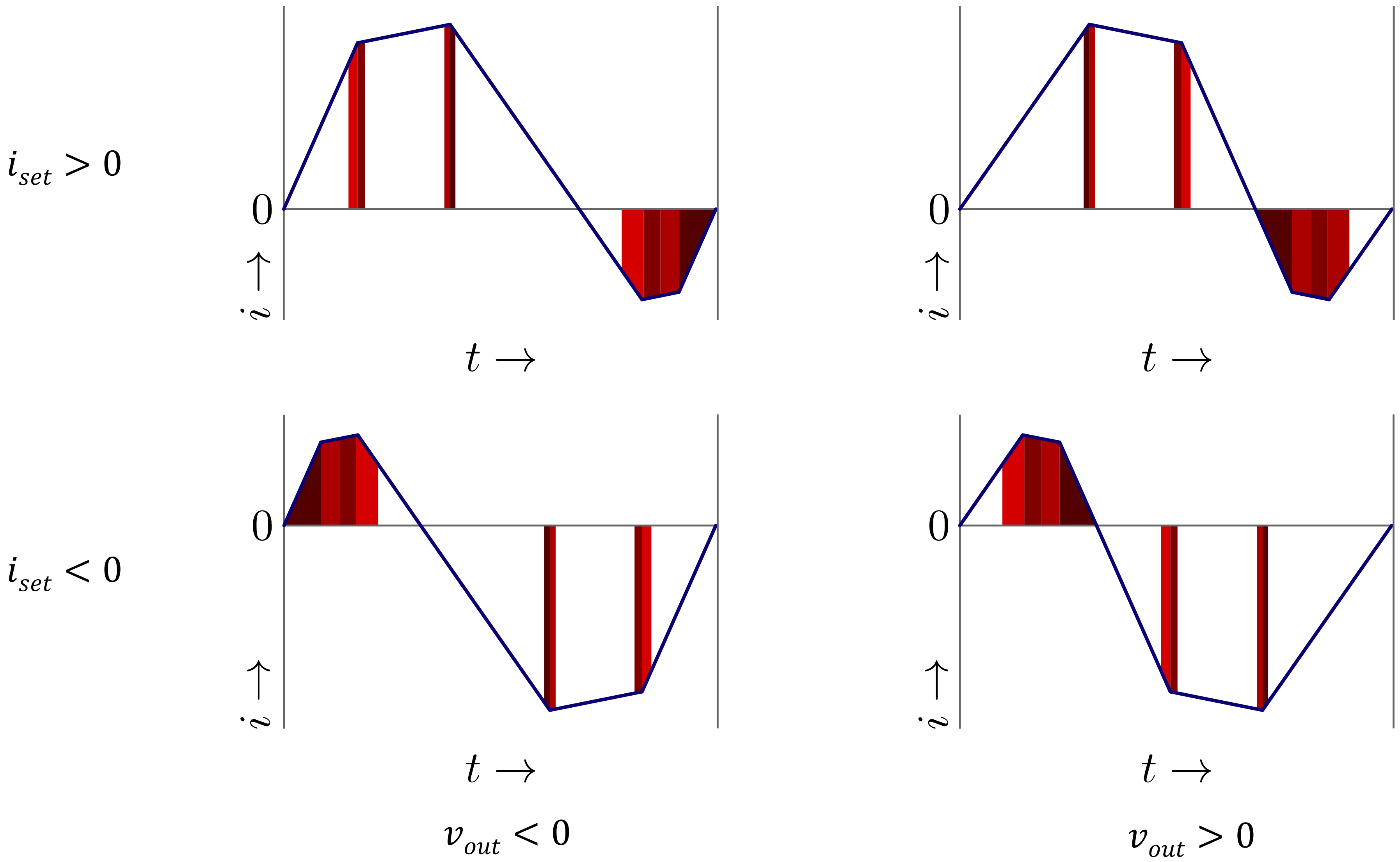
Trapezoidal filter current with ZVS

- Case: $i_{avg} > 0$ and $v_{out} < 0$
- $i_{Lf,Q}$
- A_N and t_N
- $i_{Lf}*$
- A_P and t_P



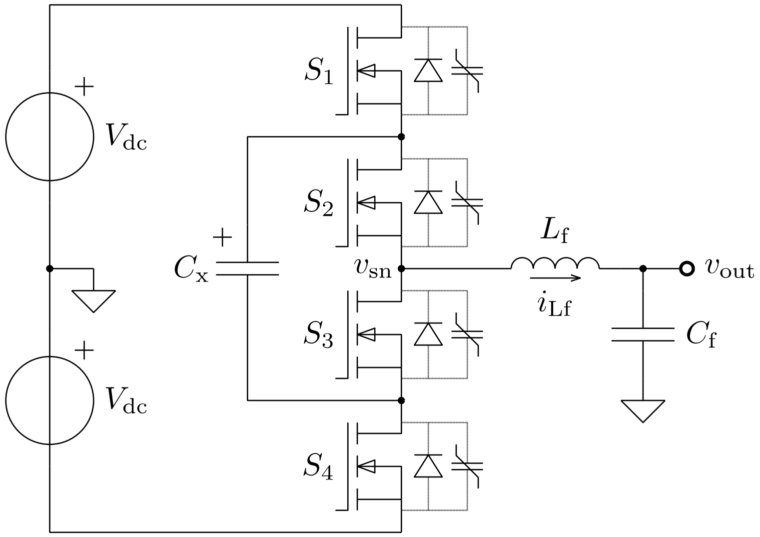
4-quadrant operation

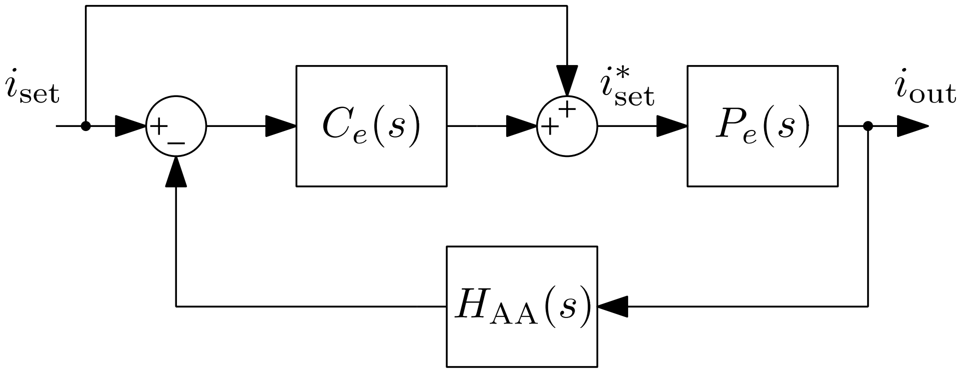
- Analysis similar for all 4 quadrants



4. Simulation results

- Complete simulation framework constructed
- PLECS blockset
  - Electrical circuit
  - Load: series connection of R_o and L_o
- Matlab Simulink
  - Charge-based ZVS modulation
  - Trapezoidal filter current
  - Output current control
    - Open-loop bandwidth: 10 kHz

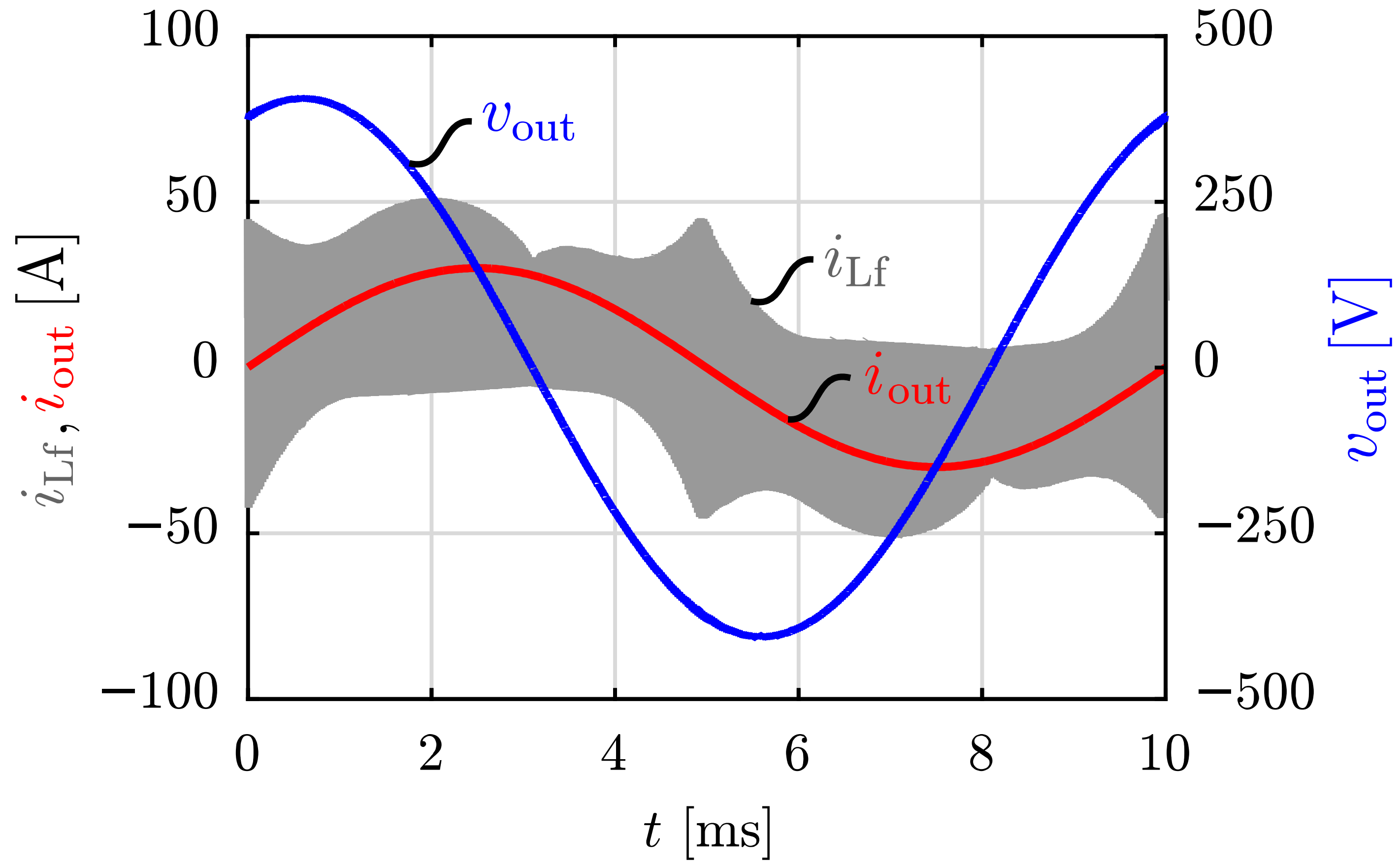




Parameter	Value	Unit	Parameter	Value	Unit
V_{dc}	1	kV	R_o	5	Ω
C_x	100	μF	L_o	20	mH
L_f	20	μH	$f_{i,set}$	100	Hz
C_f	10	μF	$\|i_{set}\|$	30	A

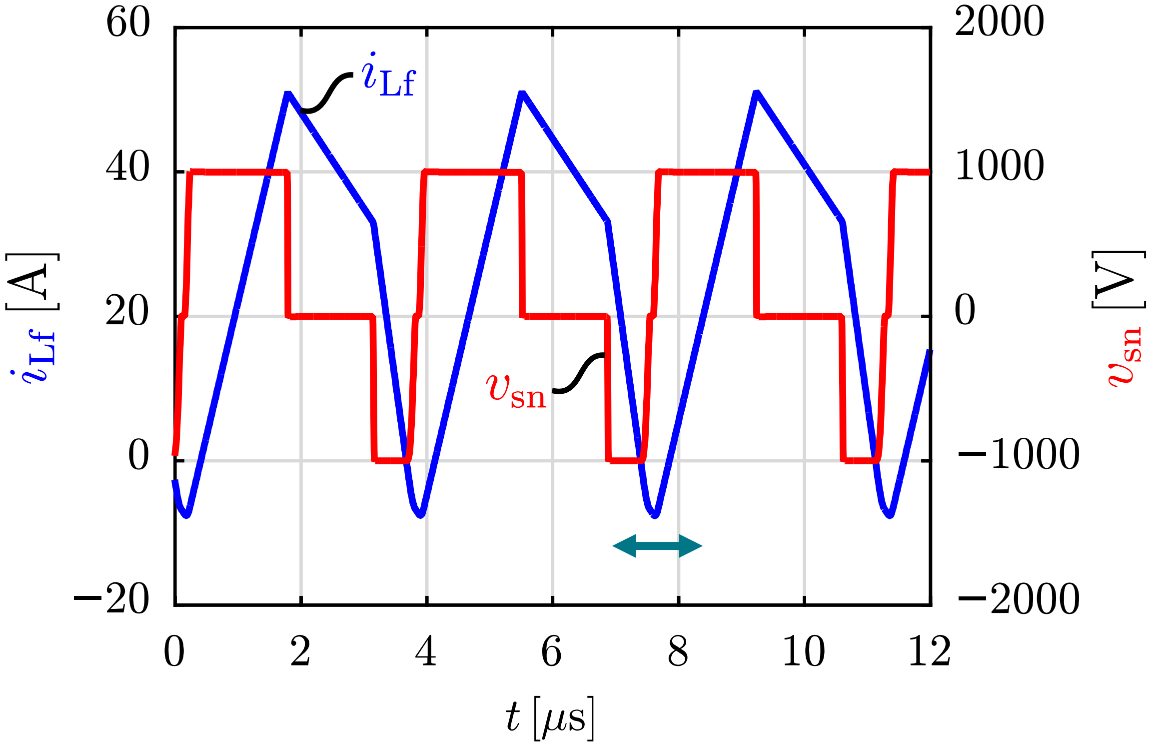
4. Simulation results – Time domain

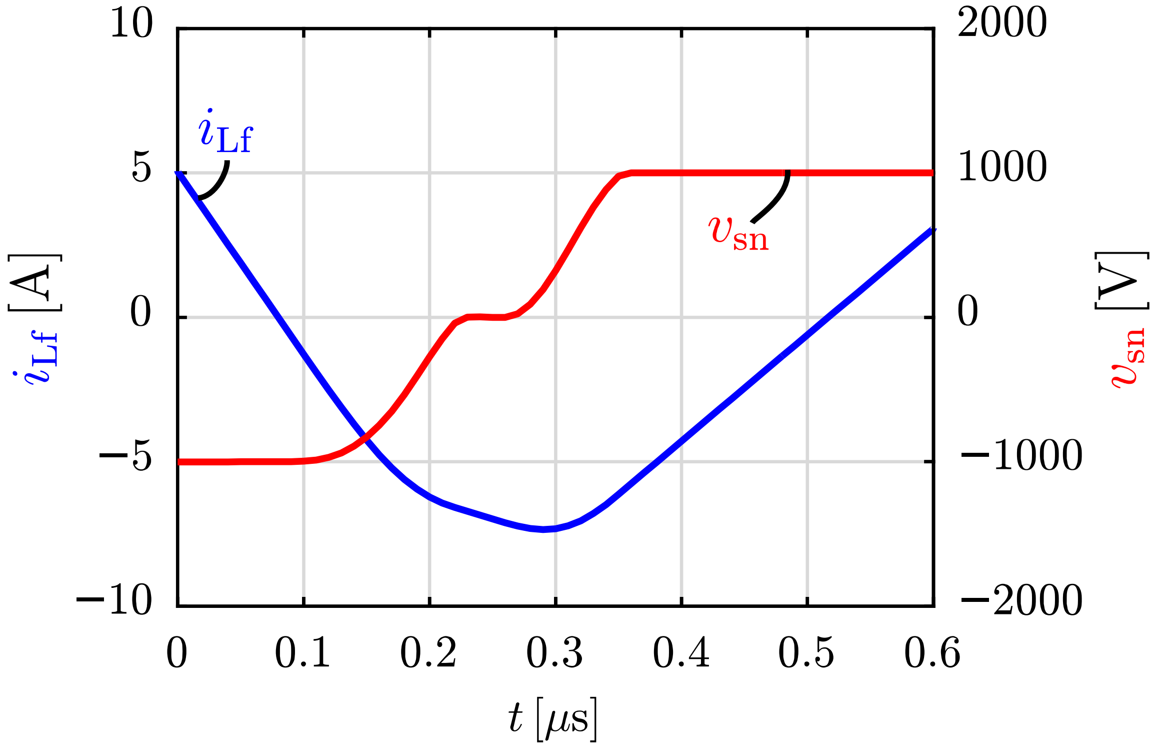
- 1 period of 100 Hz sinewave
- Phase difference between i_{out} and v_{out} due to inductive load
- Shape of i_{Lf} depending on i_{out} and v_{out}



4. Simulation results – Time domain

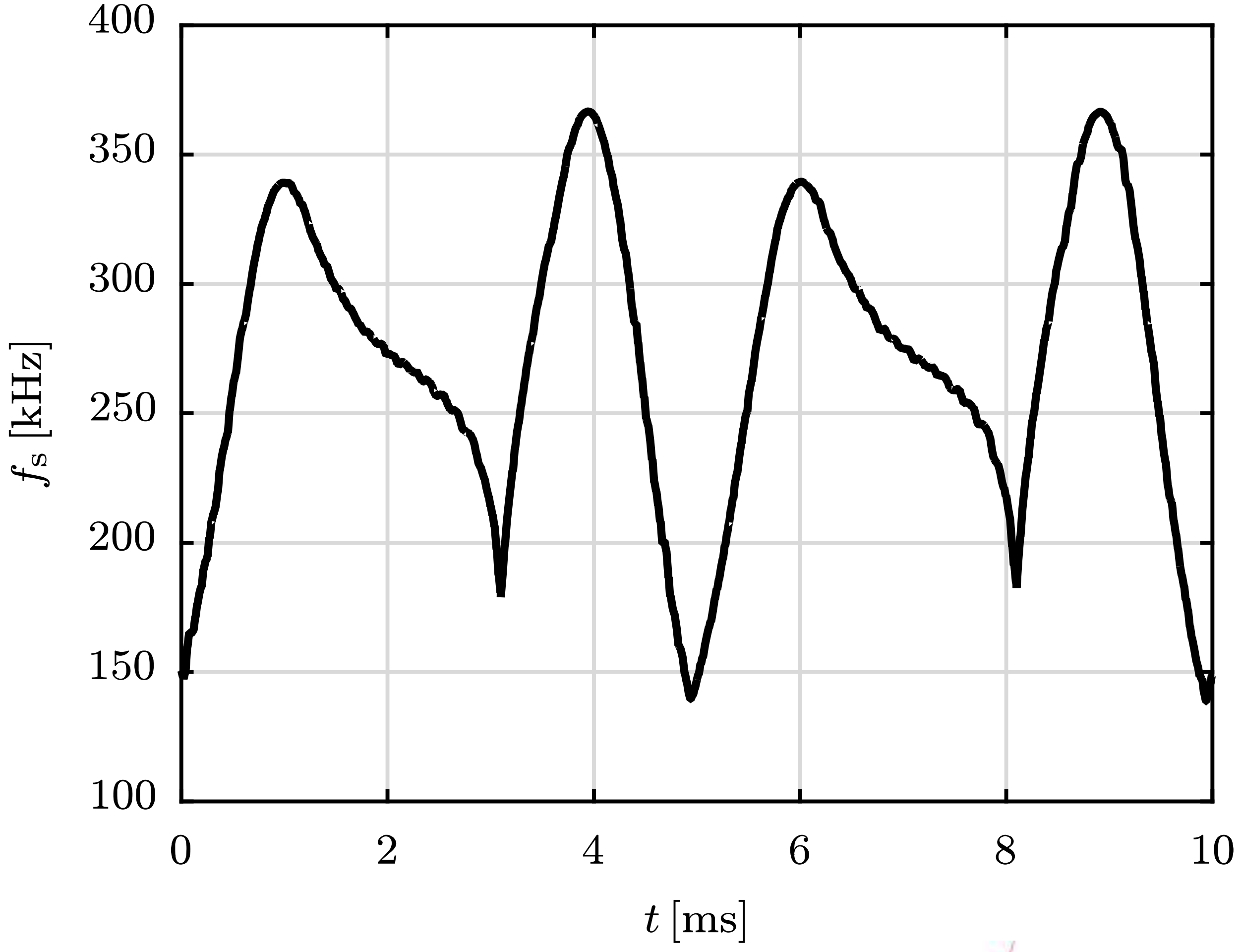
- Zoom-in at peak of i_{out}
- Proper commutation of v_{sn}





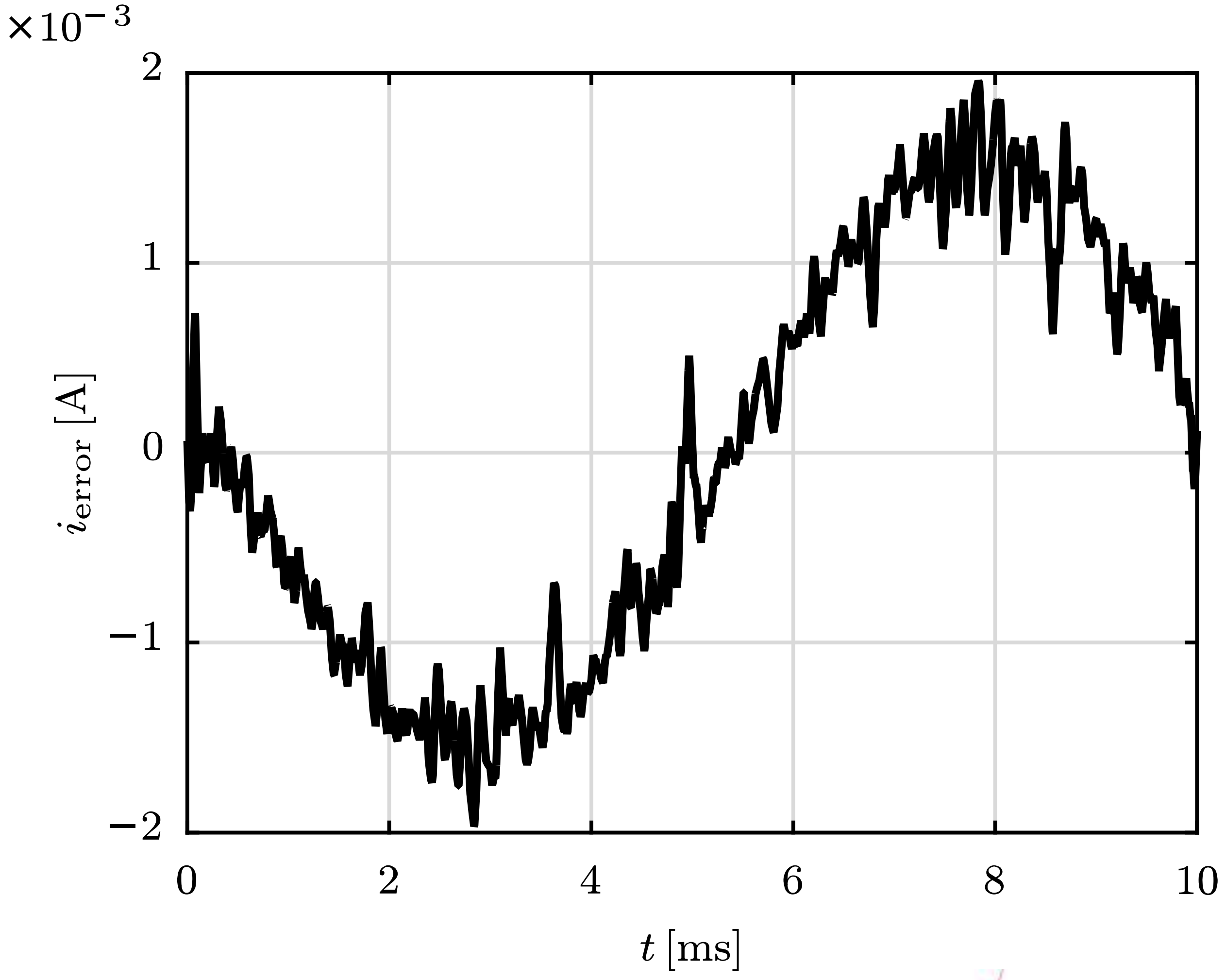
4. Simulation results – Switching frequency

- 1 period of $100\ Hz$ sinewave
- Range: $140 - 370\ kHz$
- Depending on i_{out} and v_{out}



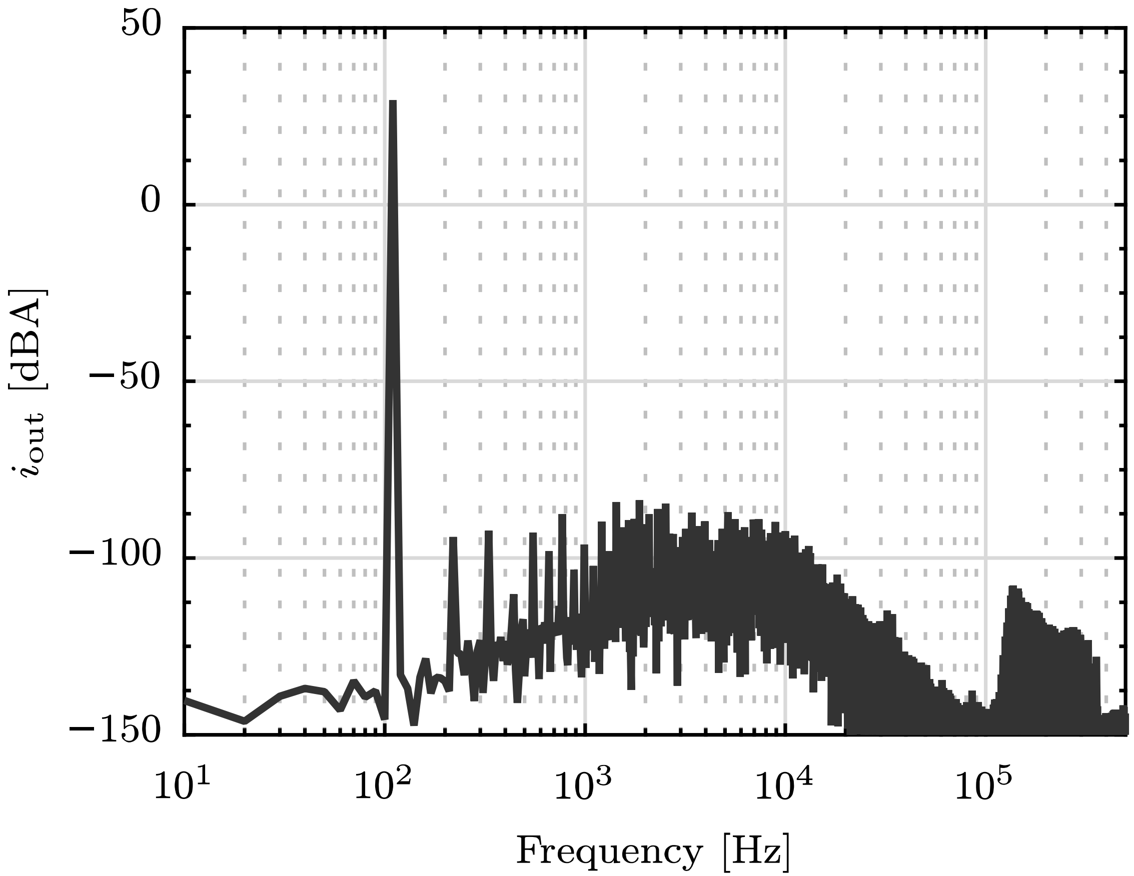
4. Simulation results – Current error

- 1 period of 100 Hz sinewave
- Maximum error: 2 mA
- Depending on i_{out} and v_{out}



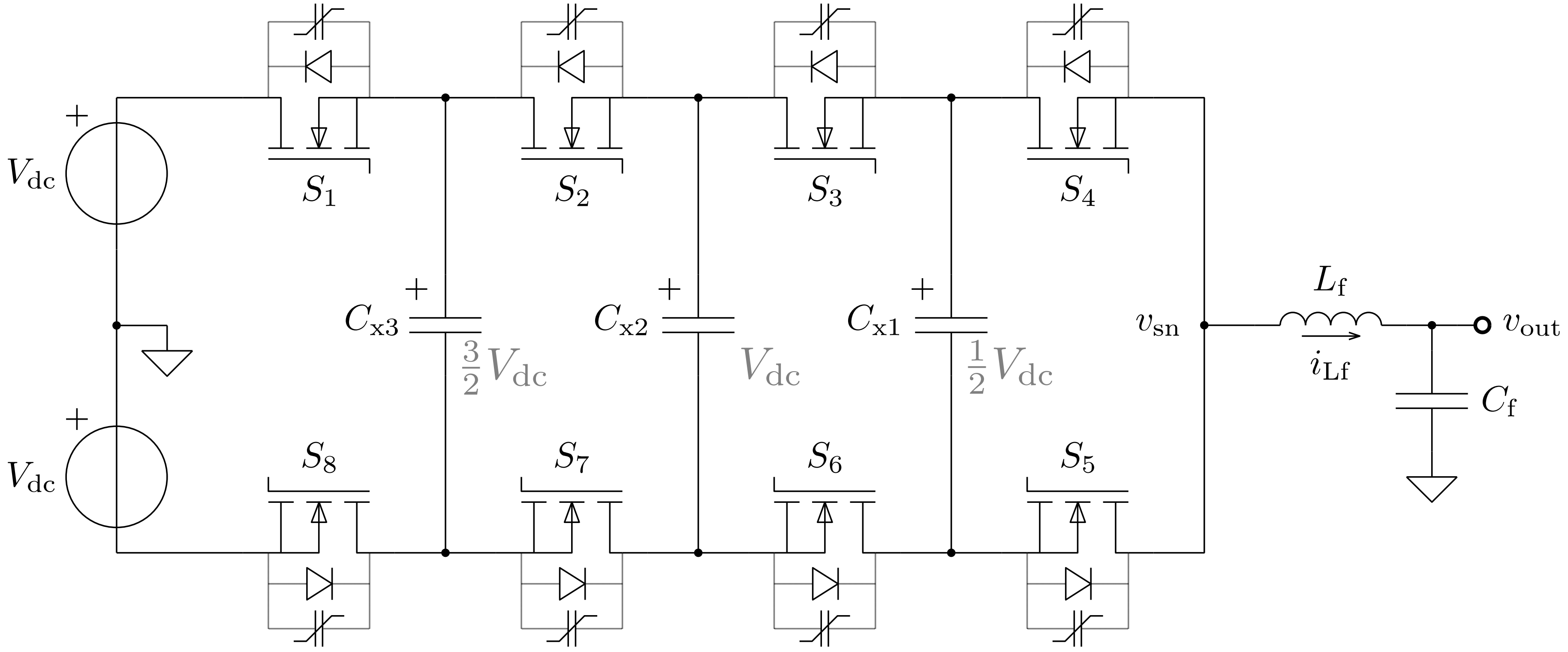
4. Simulation results – Spectral analysis

- Simulation settings
  - $f_{i,set} = 110\ Hz$
  - $|i_{set}| = 30\ A$
  - $n = 11\ periods$
- SFDR: $113.2\ dB$
- THD: $-101{,}9\ dB$



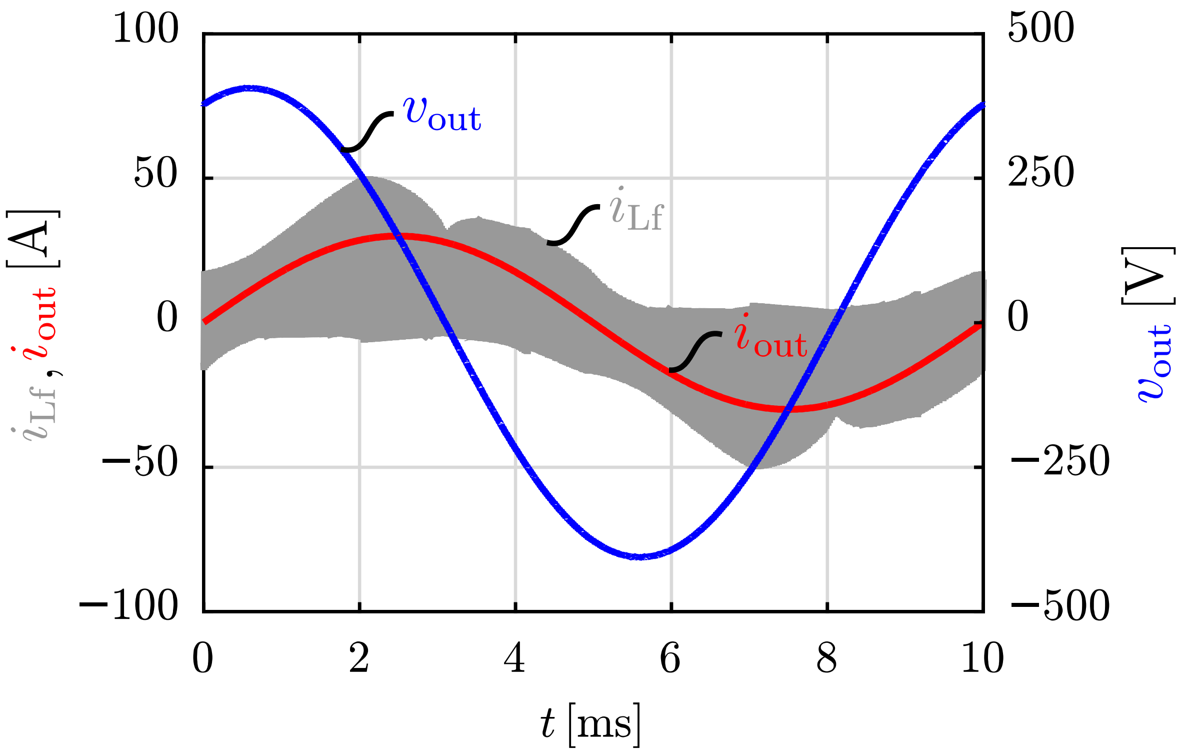
5. Increased number of levels

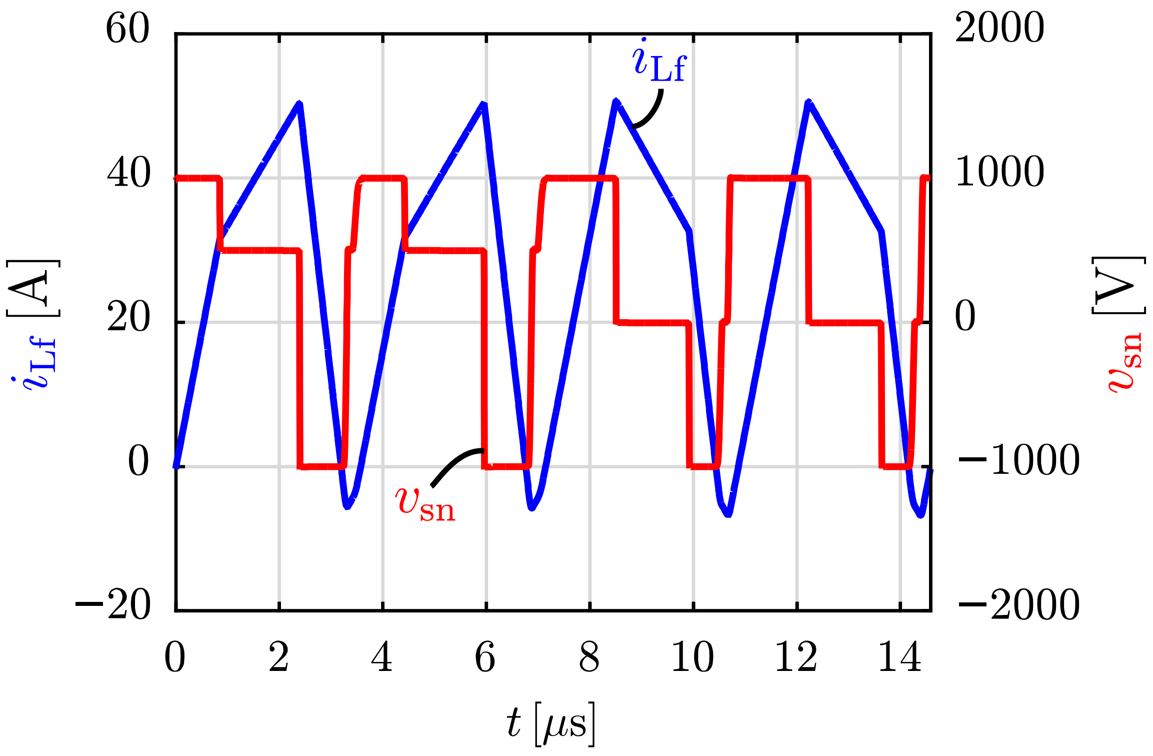
- 5-level Flying Capacitor Resonant Pole Inverter
  - 3 flying capacitors



5. Increased number of levels

- Choose middle voltage level closest to v_{out}
- Increase V_{dc}
- Decrease rms and peak values of i_{Lf}





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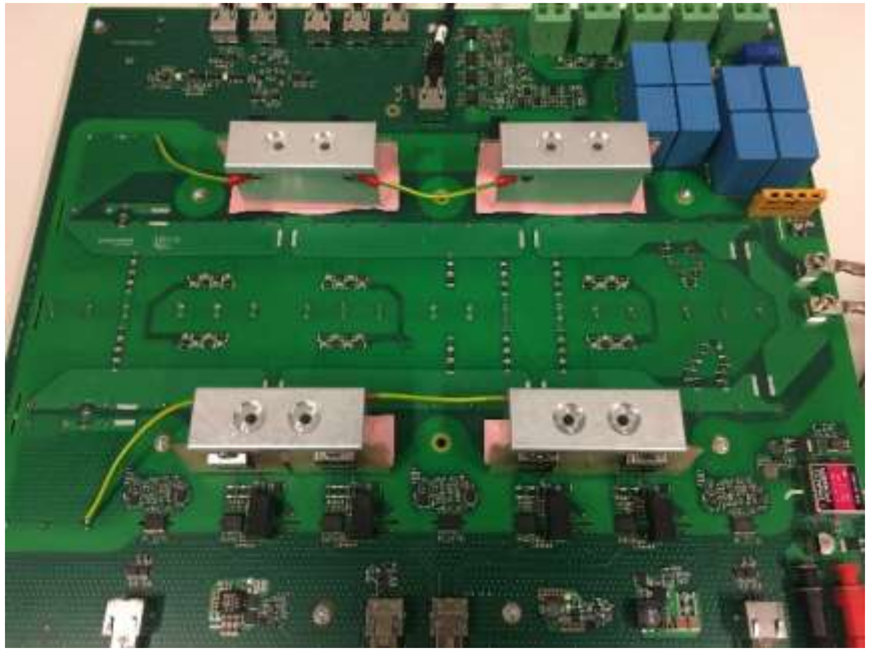
5. Conclusions

- Presented converter configuration
  - Multi-level converter for fast switching of HV
  - Flying Capacitor Resonant Pole Inverter
  - Charge-based Zero-Voltage Switching

- Performance verified with simulation framework
  - High switching frequency
  - High accuracy

- Future work
  - Hardware verification (see TU/e demo stand)



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Thank you for your attention

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Backup

Output current control

- Bode of tranfers