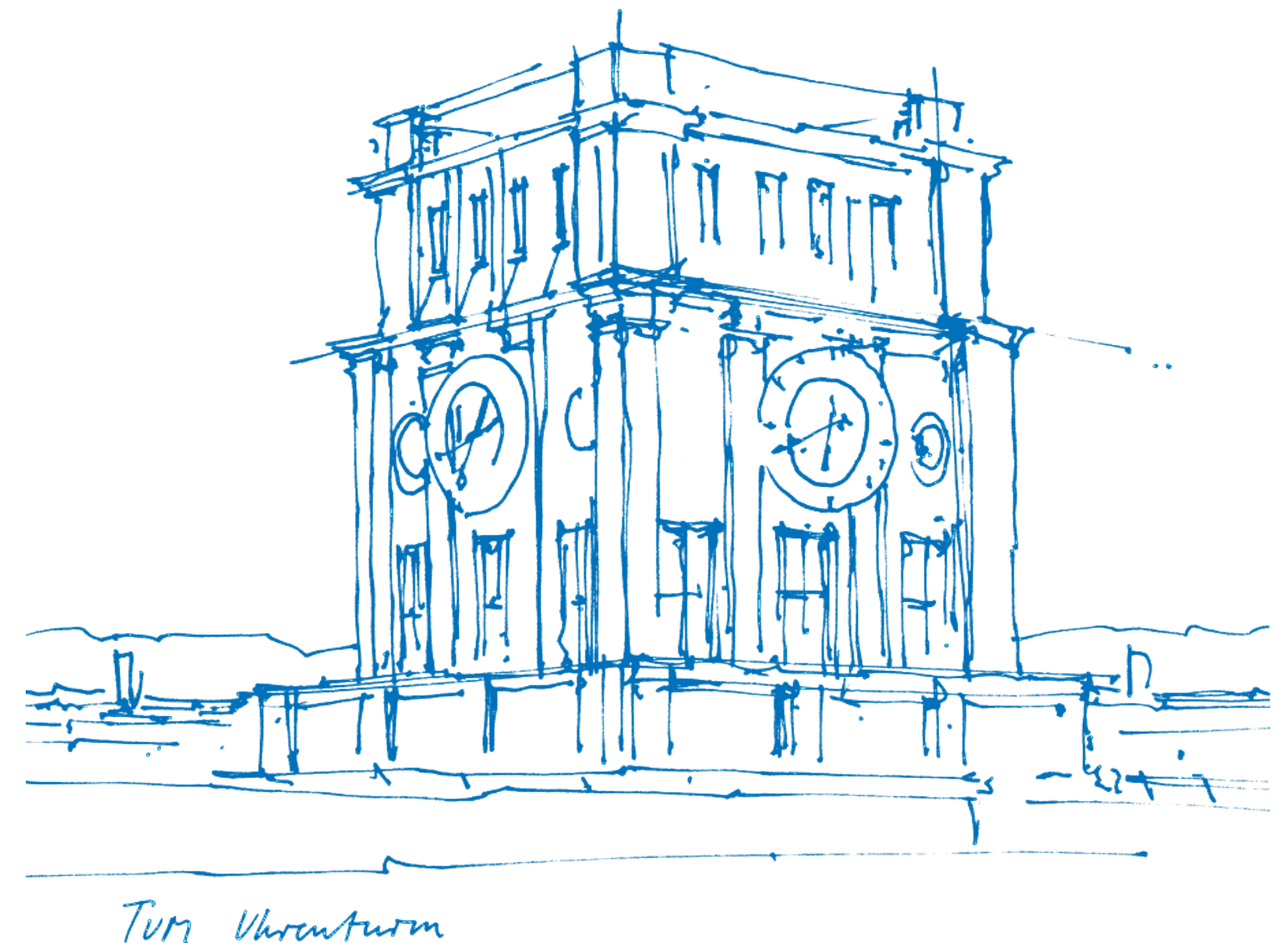


# New Concepts for Reaching 99% Efficiency in Compact Power Converters for Regenerative Variable Speed Drives

Christos Leontaris, Gean Jacques Maia de Sousa, Lou Scholtissek, Marcelo Lobo Heldwein (*presenter*)

13 November 2025

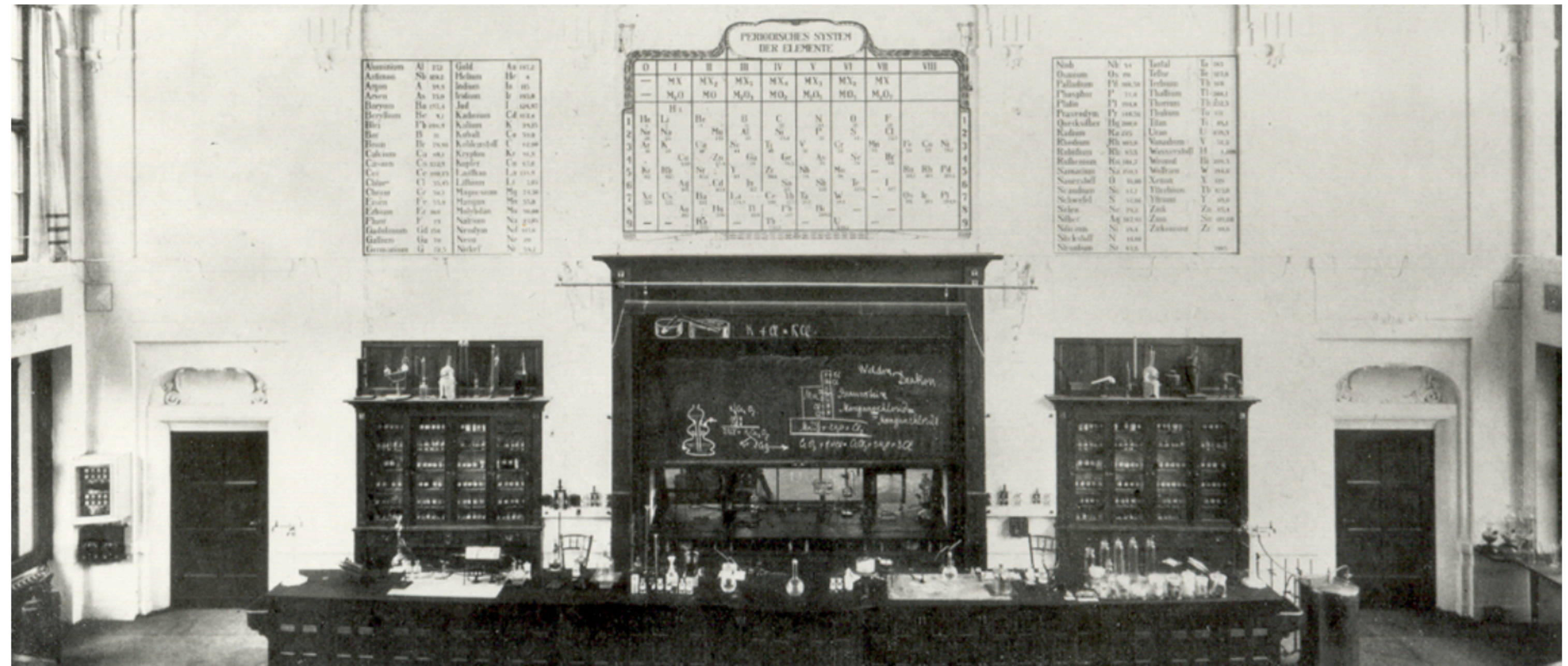
Presentation at the Webinar 2025 - SOBRAEP / PELS





# Brief history of the Technical University of Munich (TUM)

Ever since it was founded in **1868**, the Technical University of Munich has seen itself as the servant of an increasingly technical society. Then as now, TUM researchers are looking for solutions to the great challenges of the future. The newly founded university was intended to place technical education in Bavaria on the foundation of natural sciences. In doing so, it made a decisive contribution to technological progress worldwide - and produced several Nobel Prize winners and important inventions.



Hörsaal im ehemaligen Chemischen Institut (1909)

Bild: TUM.Archiv



# TUM (a few numbers)

## 50.484 Students

are enrolled at our university in the winter semester 2022/23. Of them, 36% are female students, 41% have come from abroad for their education at TUM.

## 643 Professors

research and teach at TUM. We have appointed 209 professors from universities abroad (as of 2006–2020).

## 8 Schools and departments

form the academic foundation of our university, connected by 6 integrative research institutes at the interfaces between disciplines.

## 9,676 Publications

by TUM academics appeared in 2022 in international journals (peer-reviewed articles, conference papers, reviews; source: Scopus 2023).

## 1,109 Doctorates

were awarded by TUM in the academic year 2020/21. Modernized doctoral degree regulations were published in 2012.

## 430.4 mio. Euros third-party funding

for research and teaching was secured in accounting year 2021 making TUM one of German's top- ranked universities.

## 18 Nobel Prizes

have been awarded to TUM professors and alumni since 1927, e.g. to Rudolf Mößbauer (Physics) and Ernst Otto Fischer (Chemistry).

## 24 Leibniz Prizes

have been awarded to TUM scientists since 1987 (as of: 2023). Our long-serving President Wolfgang A. Herrmann received it in 1987.

## 8 Humboldt Professors

have joined the TUM ranks (as of: 2022) – a major success in this competition for top international talent.

## 78 Start-up companies

were founded at TUM in 2022.

## 73 Patents

for inventions from TUM researchers were submitted to Patent Offices 2020.

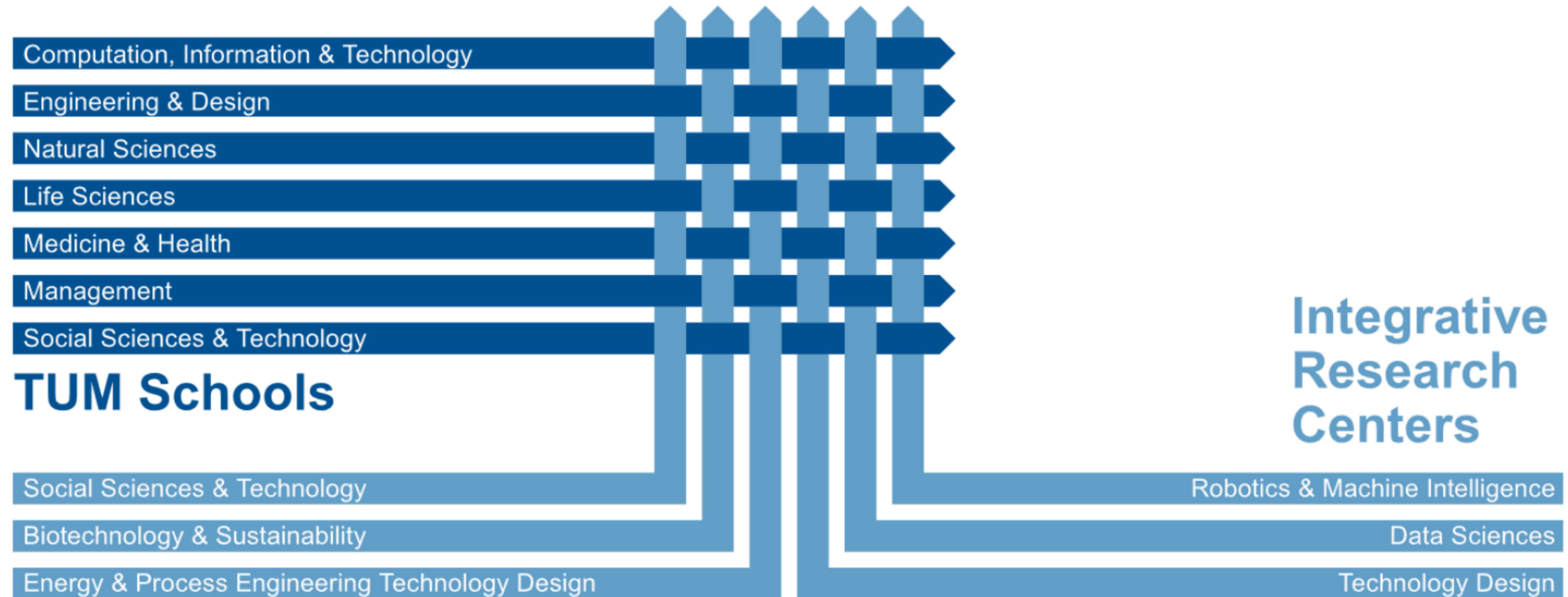
## > 6,000 Cooperation agreements

were concluded with companies or other partners for research projects since 2013.



## TUM structure

# Bridges to Innovation



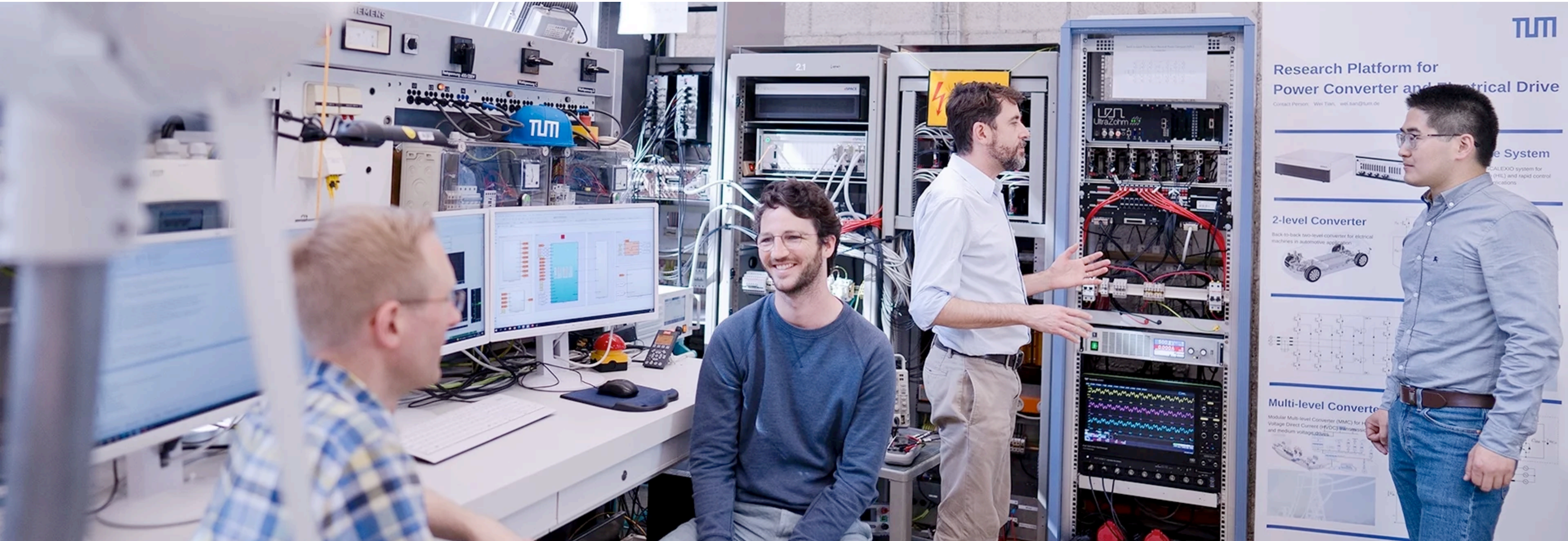


# Munich



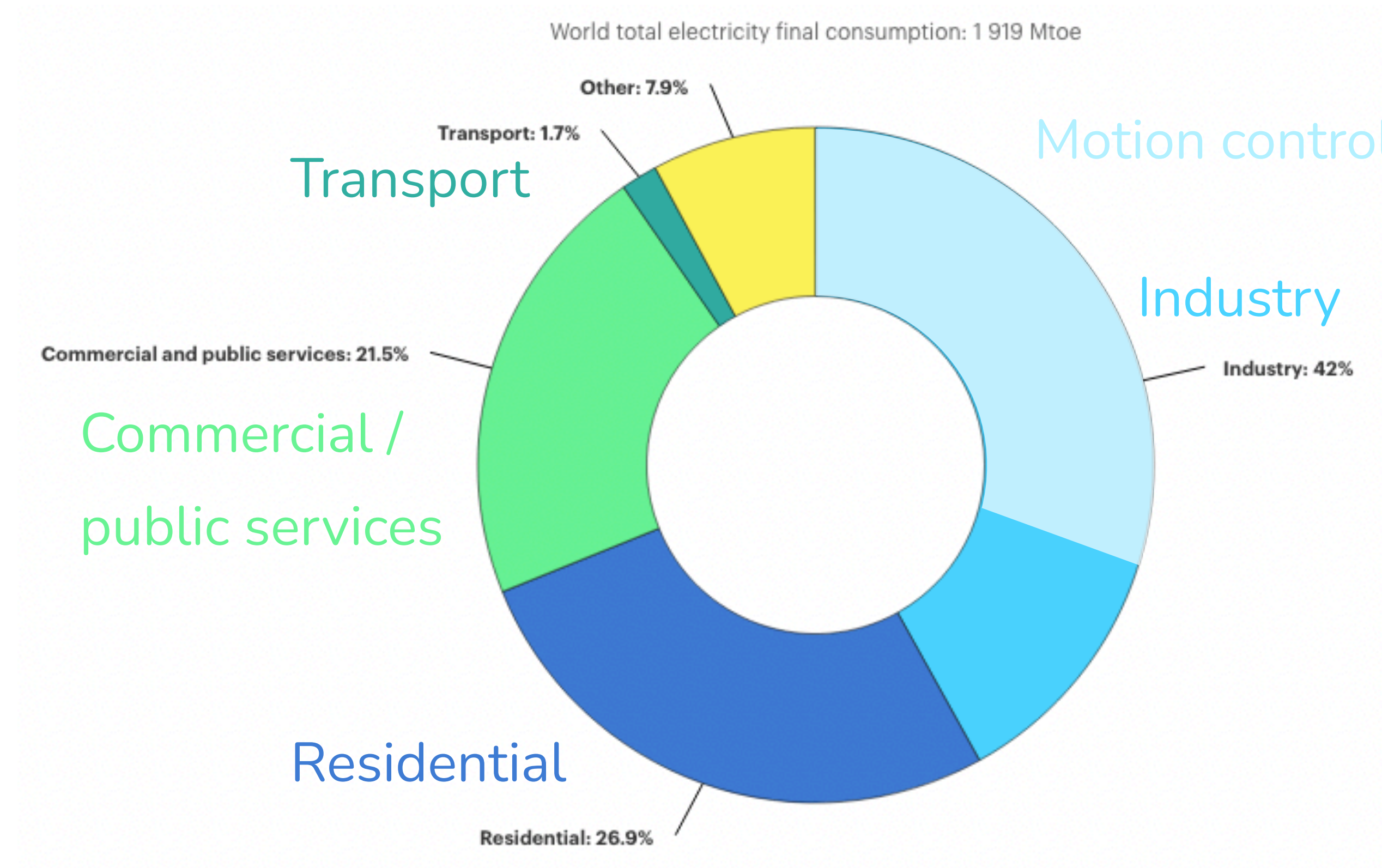


# A part of our labs



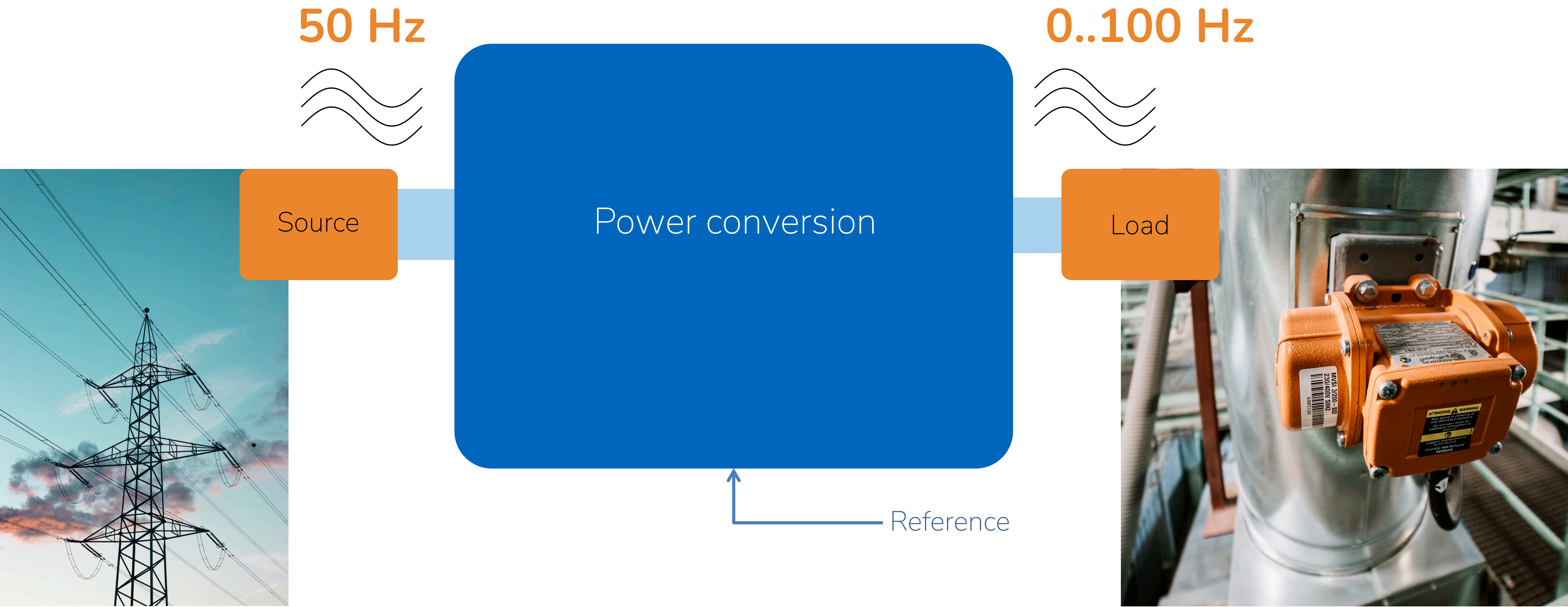


# Path to net zero emissions by 2050





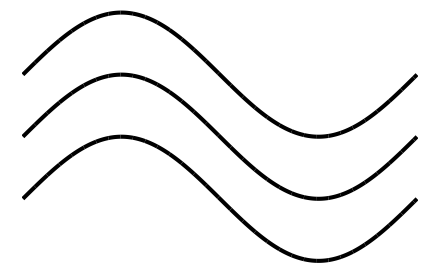
# Bidirectional motor drive applications (Industrial motor drives)





# Bidirectional motor drive applications (Industrial motor drives)

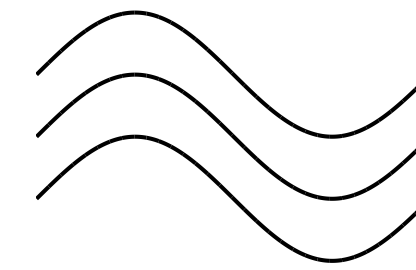
0..100 Hz



Source

Power conversion

50 Hz



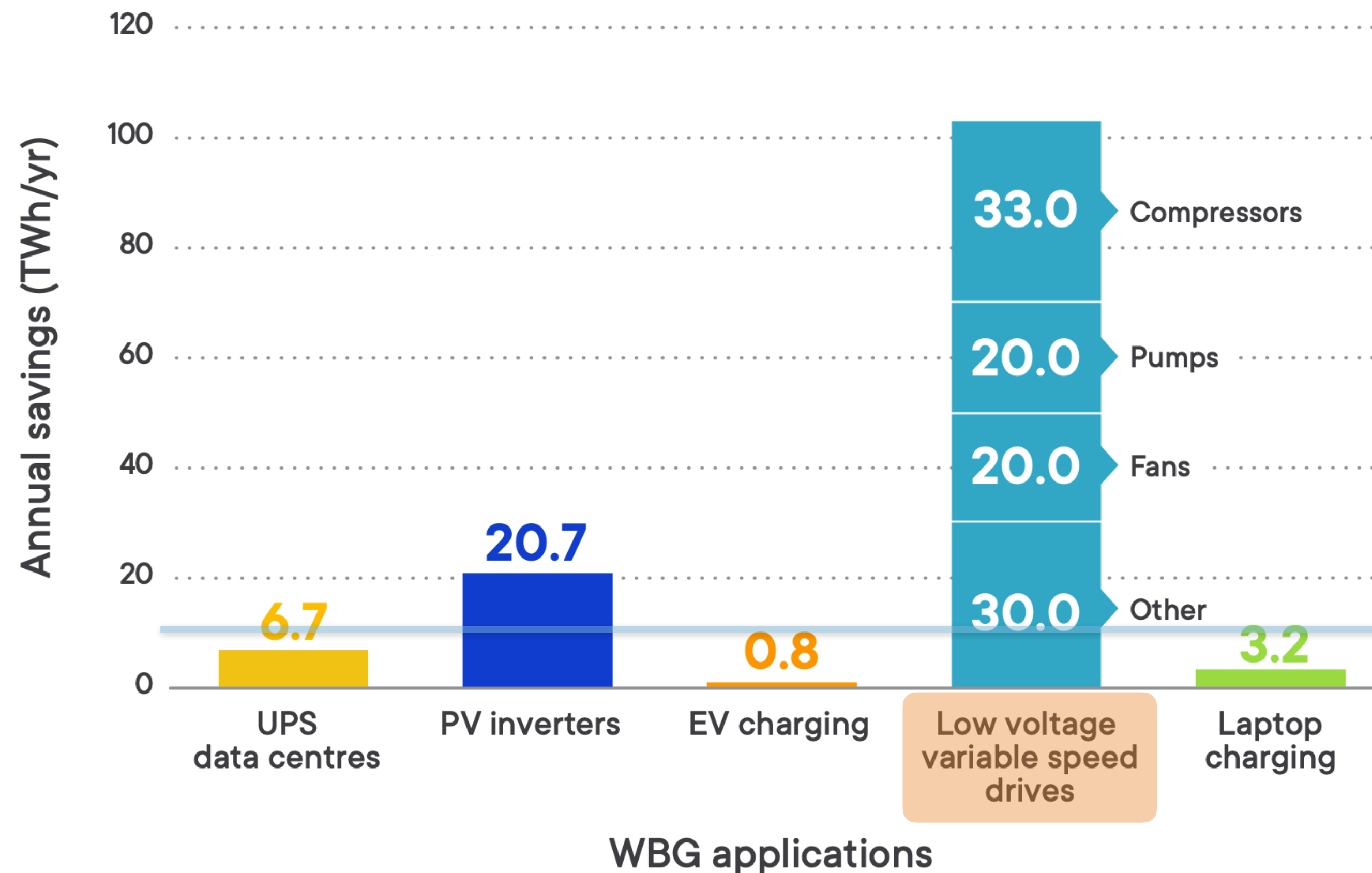
Load

Reference



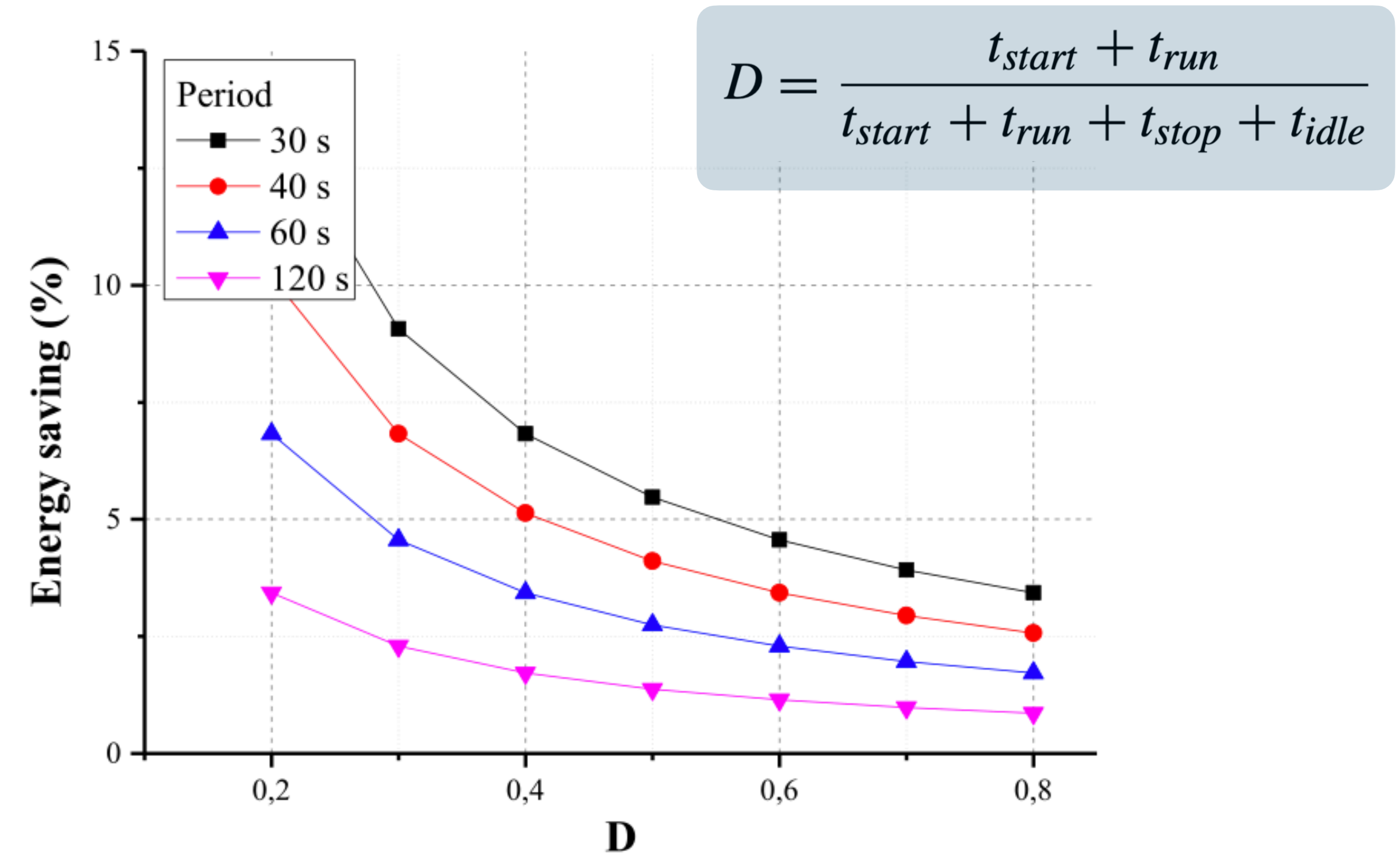
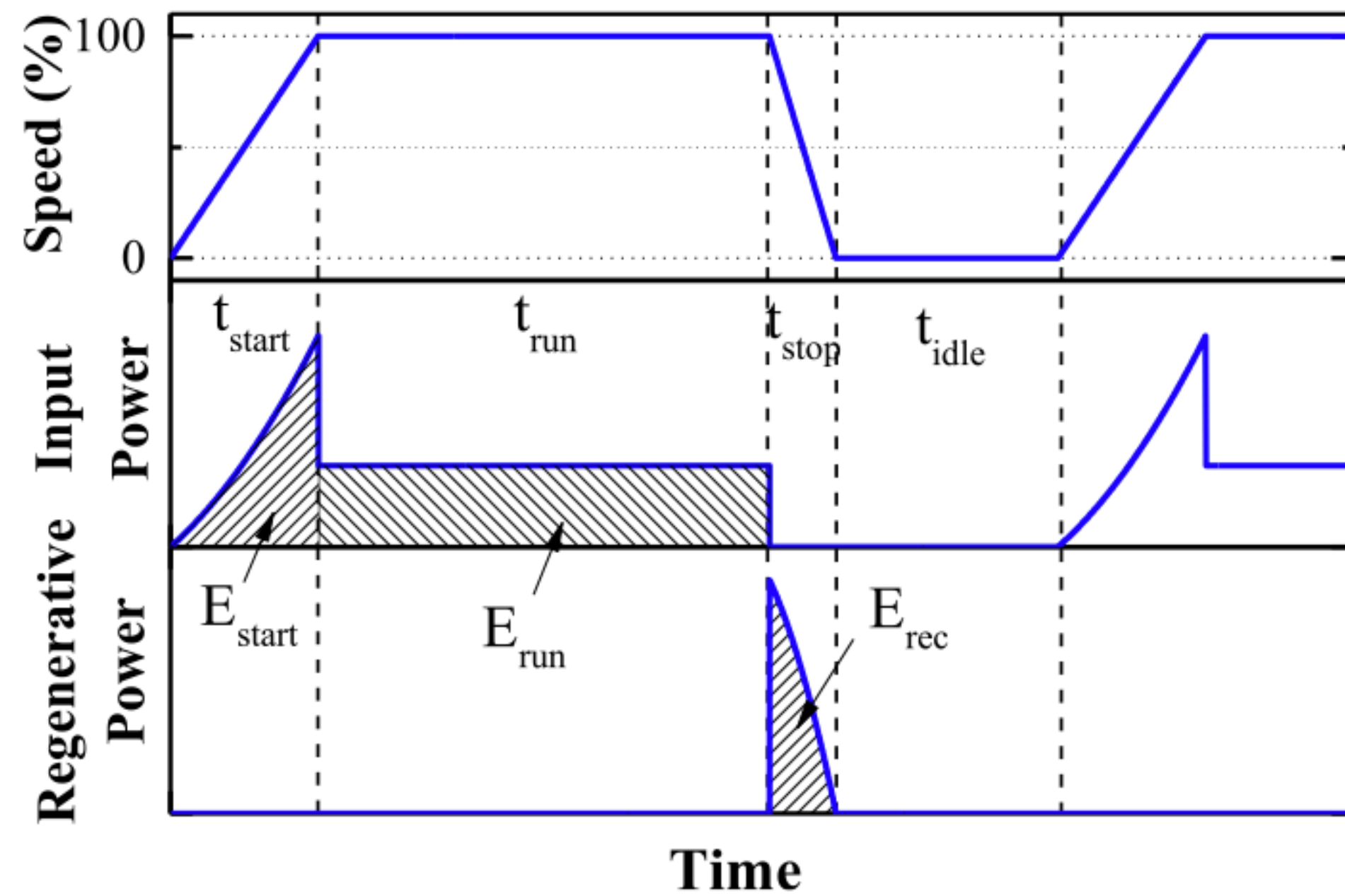


# Potential energy savings for different applications in 2021



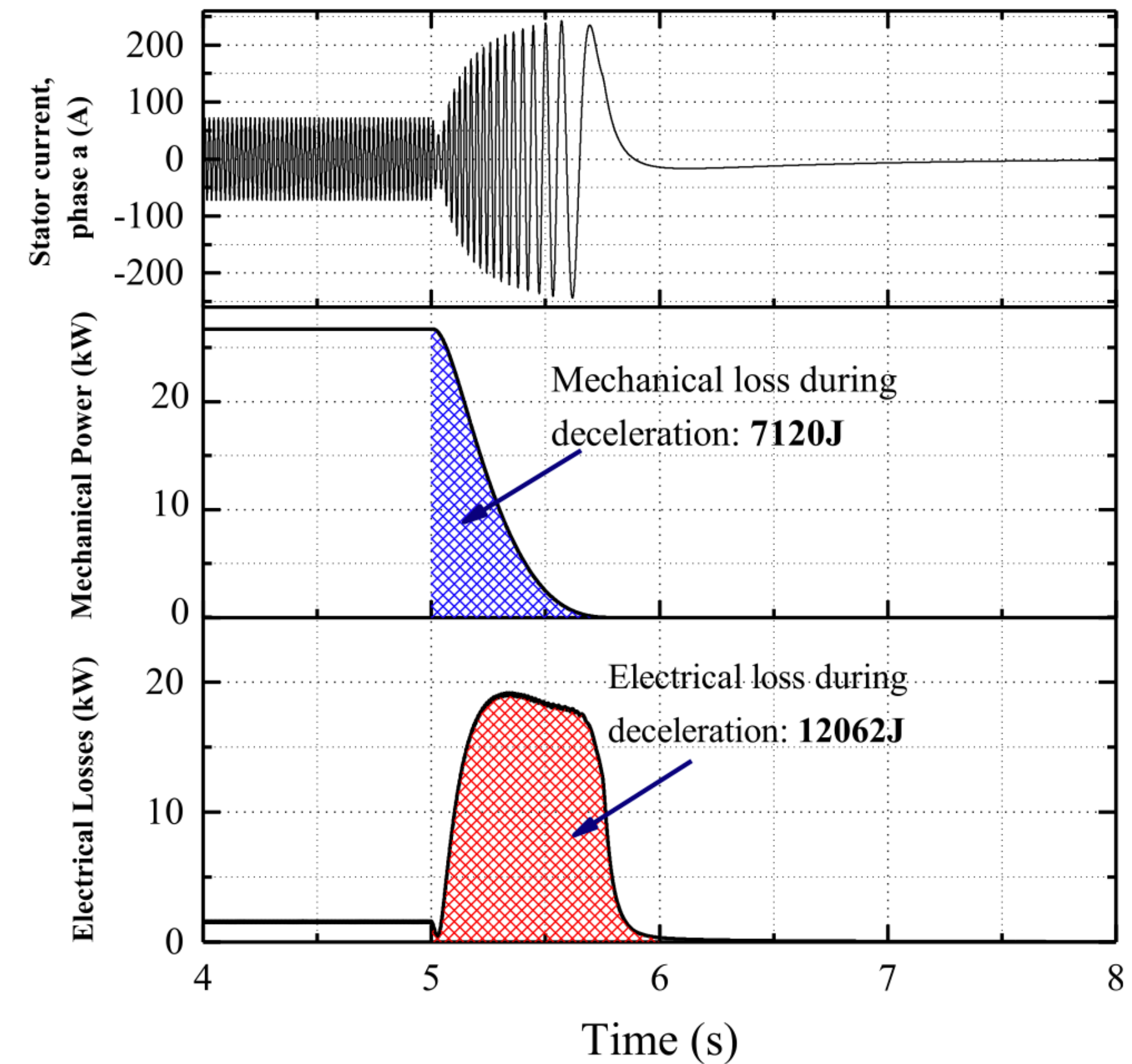
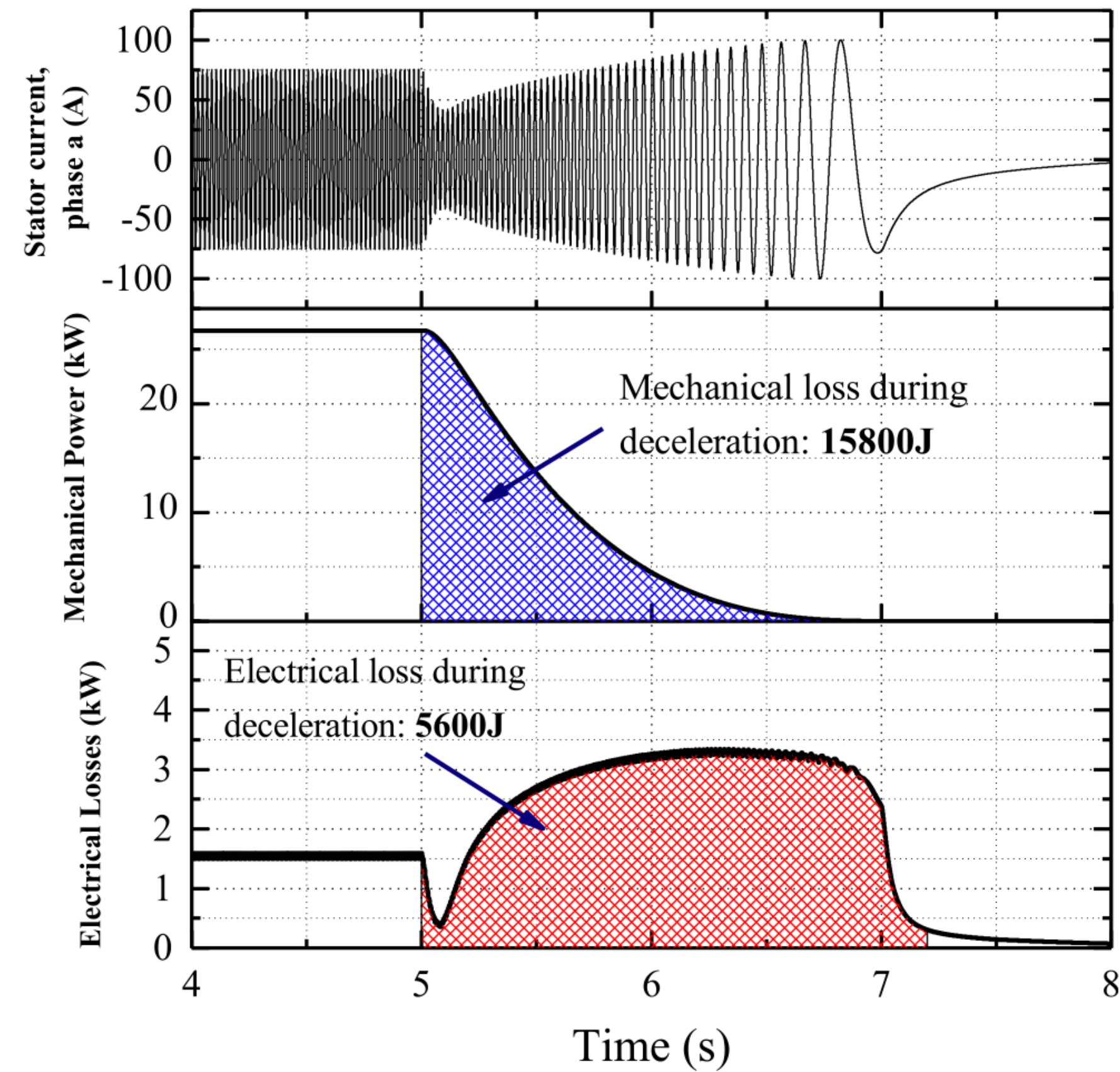


# Energy lost (or recovered) during motor deceleration



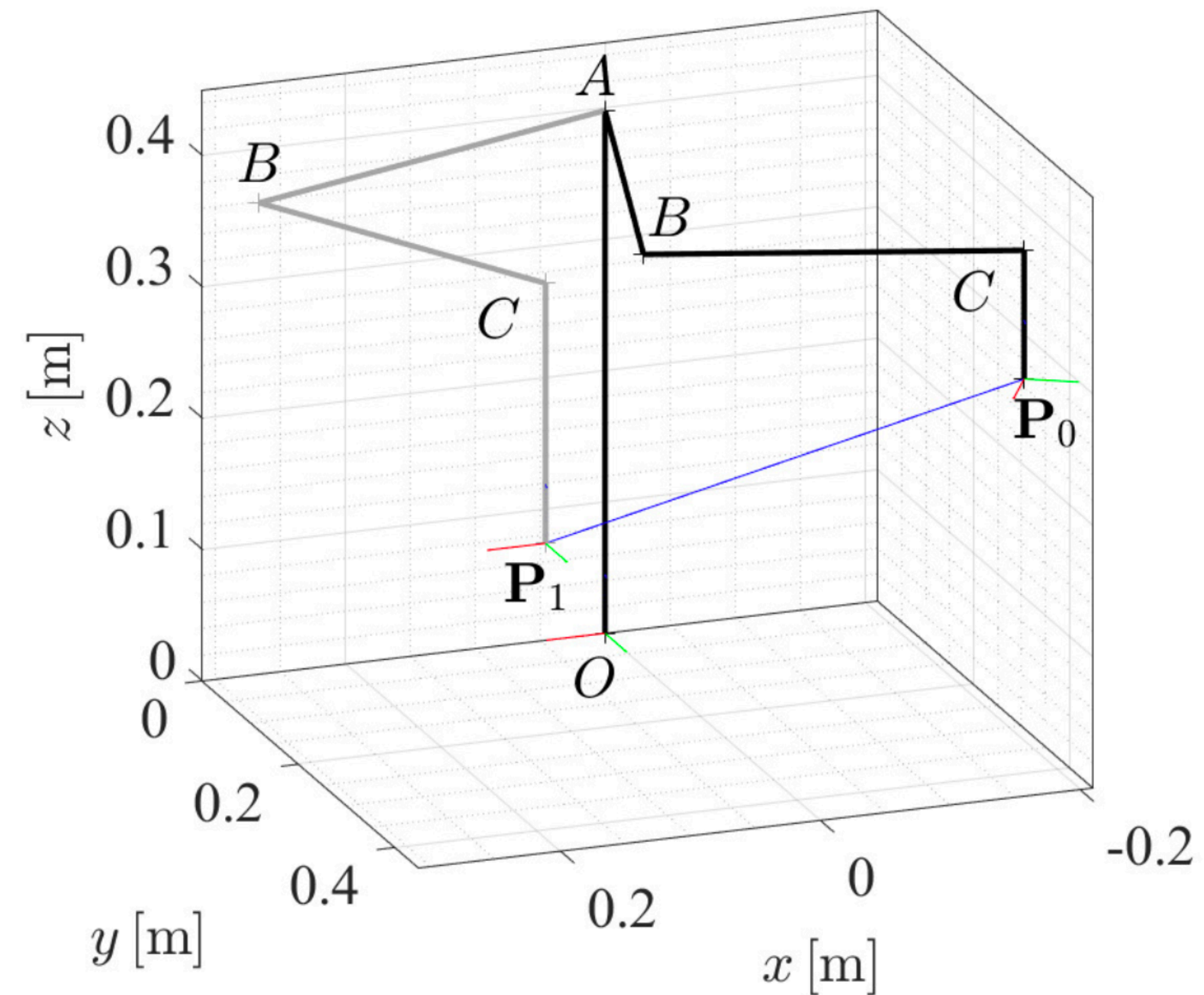
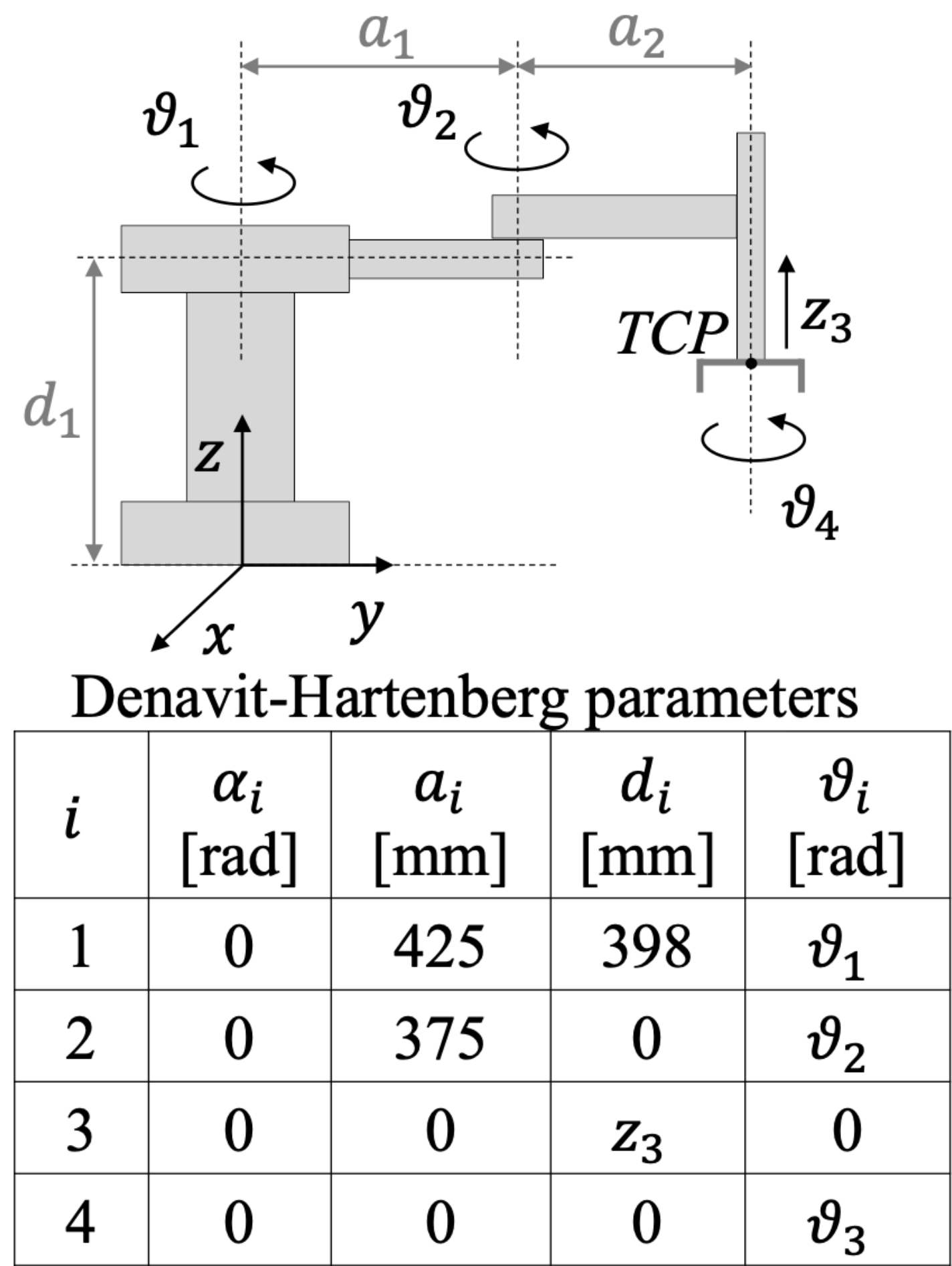


# Energy losses during motor deceleration



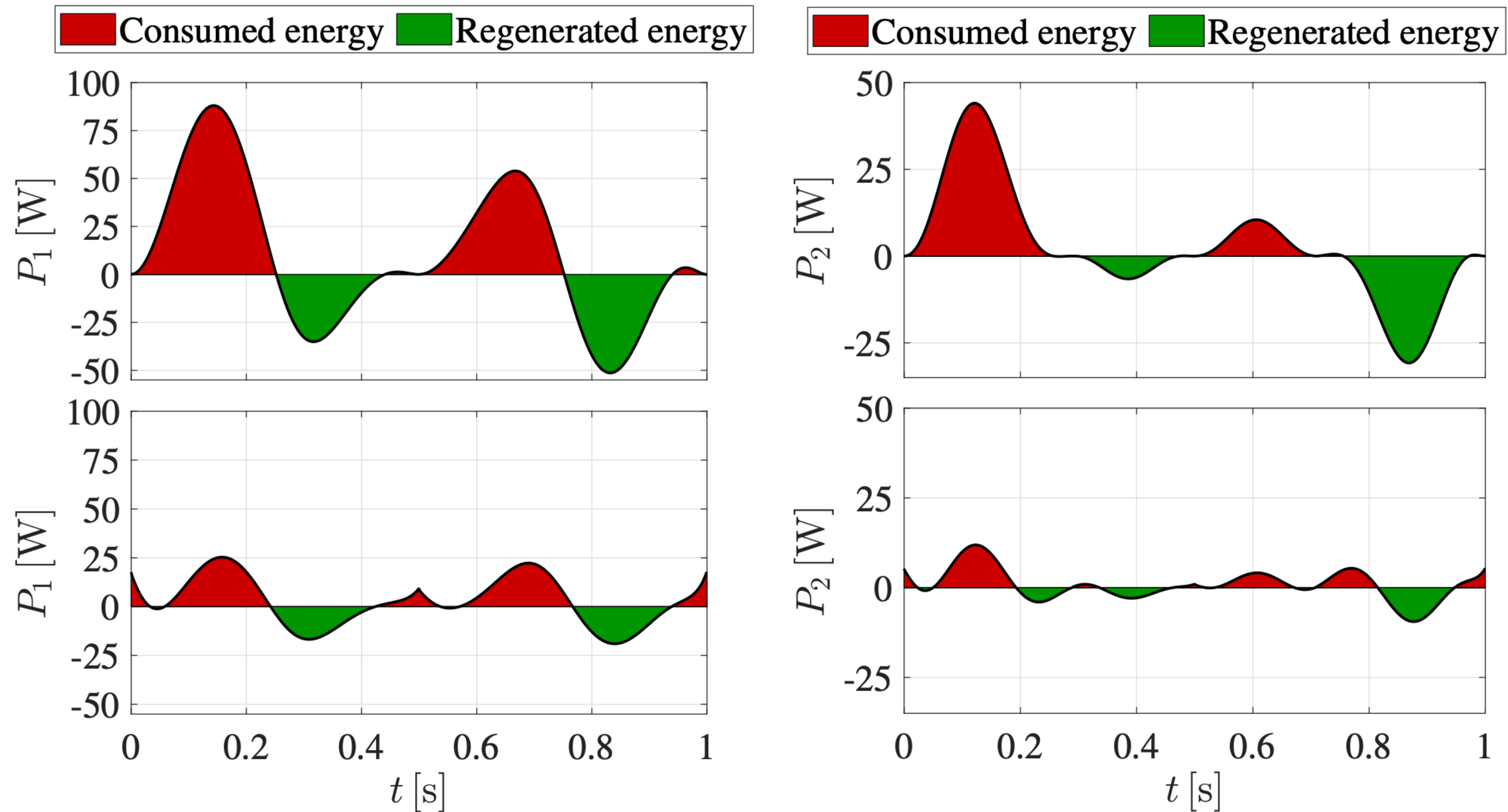


# Energy recovery potential in industrial robots





# Energy recovery potential in industrial robots





# Integrated motor drives

Industrial examples



<https://www.synapticon.com/>

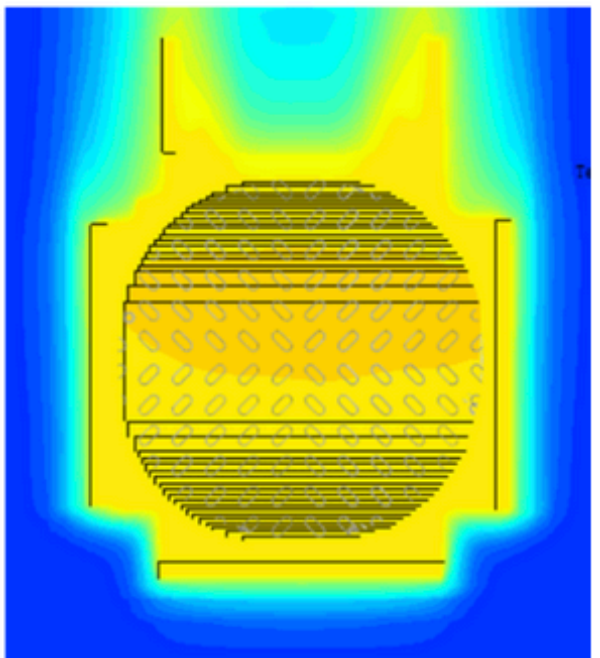
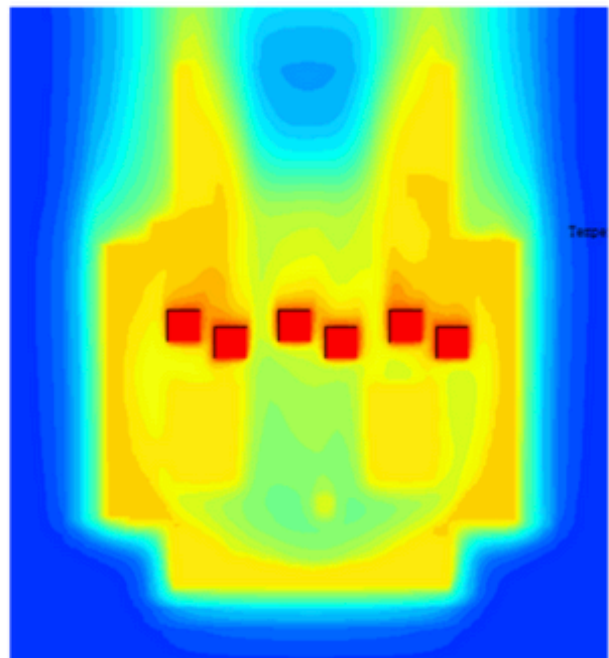
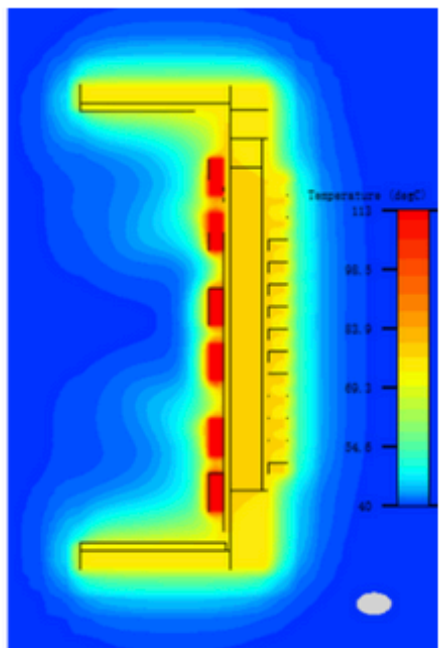
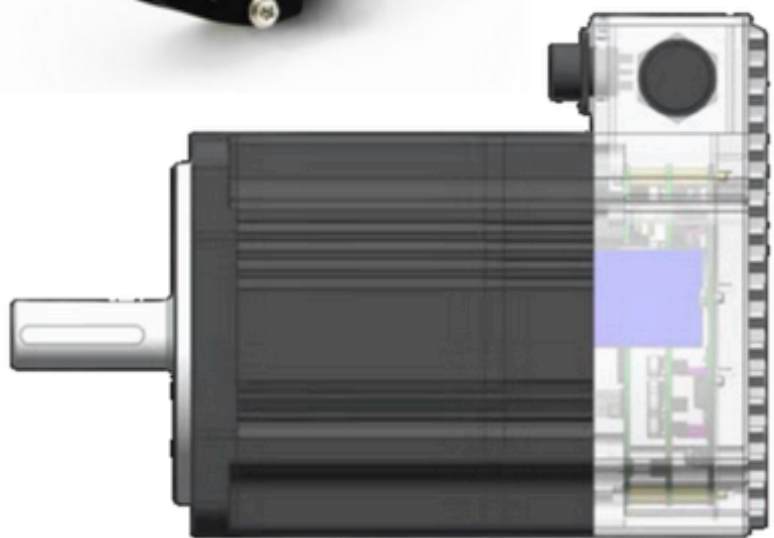
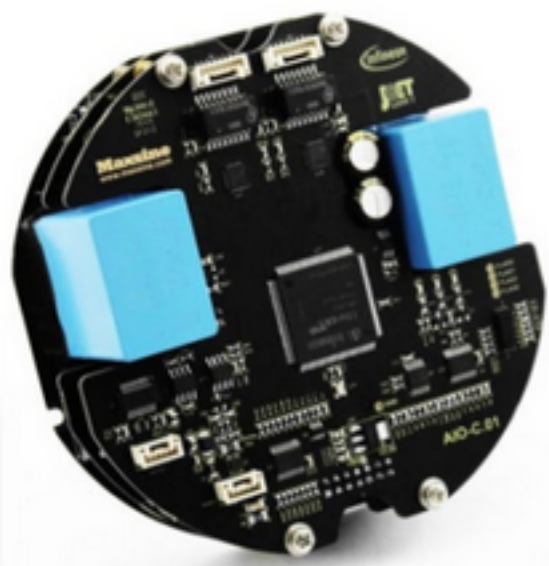


Fig. 2: Finite-element thermal analysis of a compact, fully integrated SiC-based servo.

<https://semiengineering.com/sic-and-industrial-servos-a-perfect-match/>

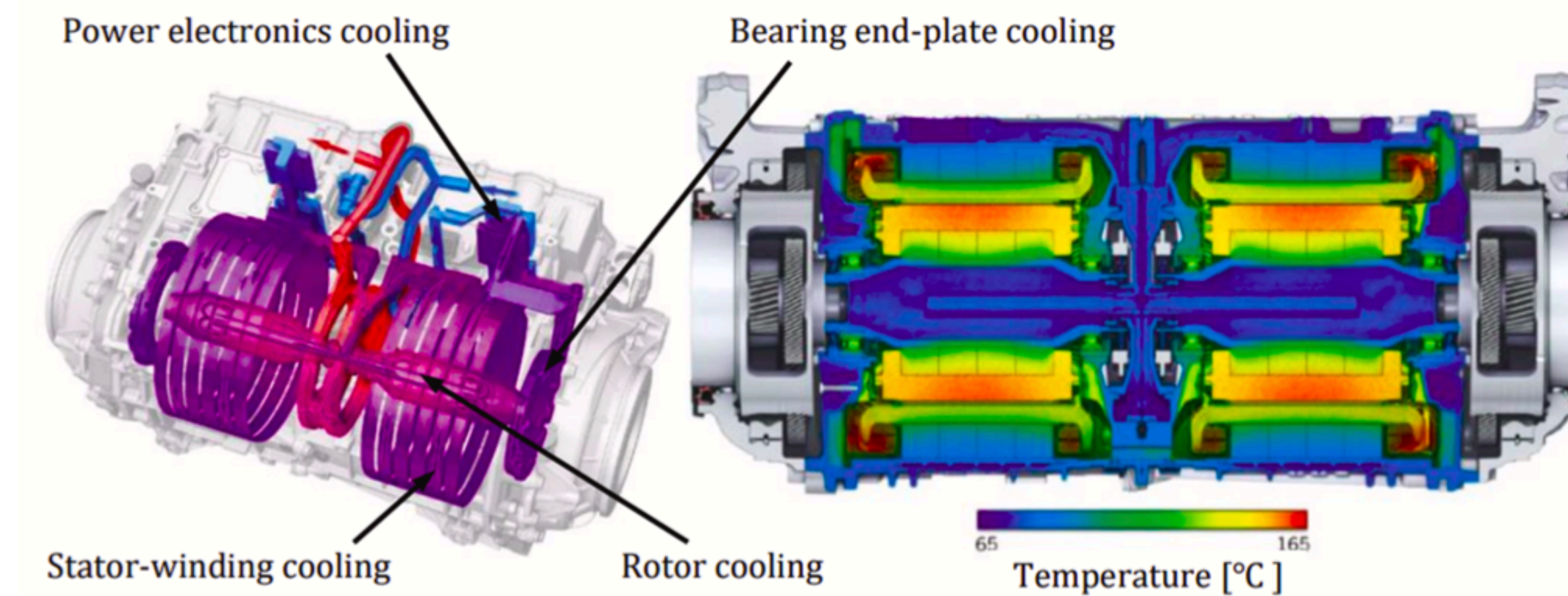
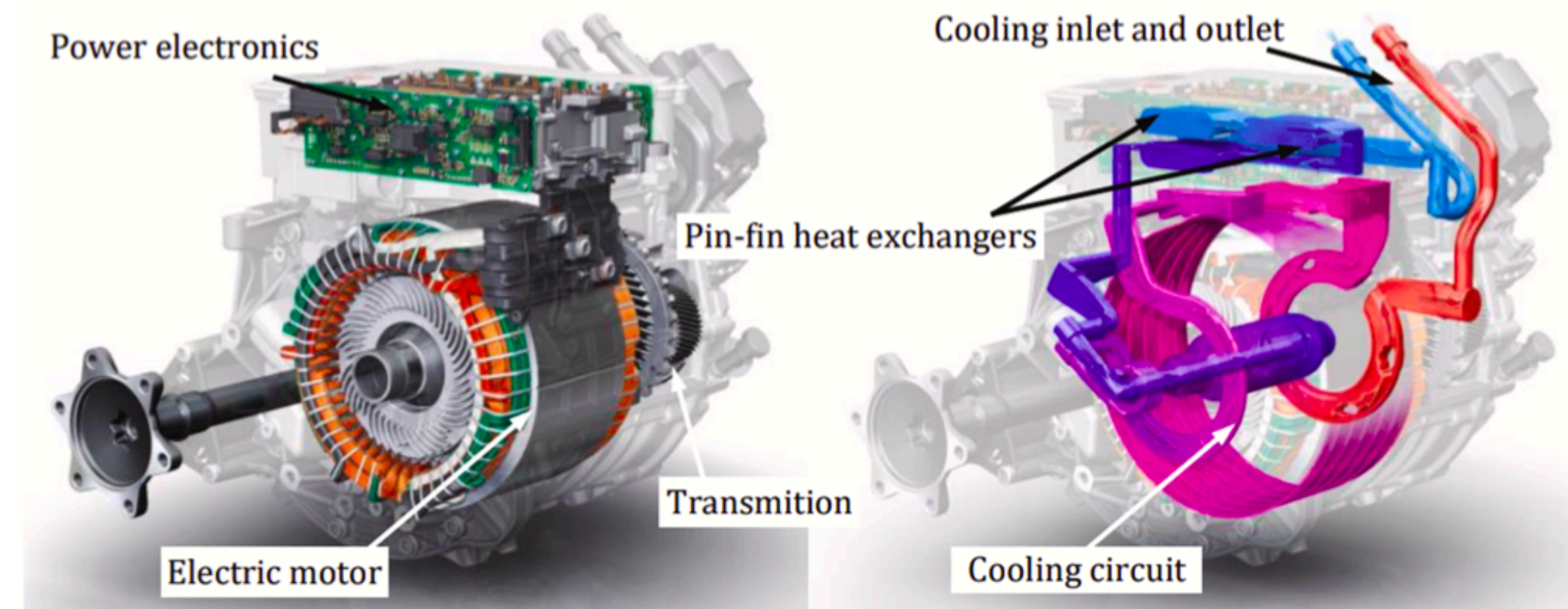


# Integrated motor drives

Great potential for improving industrial systems!

Challenges:

- Cooling (two subsystems with different requirements)
- High  $dv/dt$  right at the motor terminals (overvoltages at the winding, HF bearing currents, core losses, etc)





# Integrated motor drives

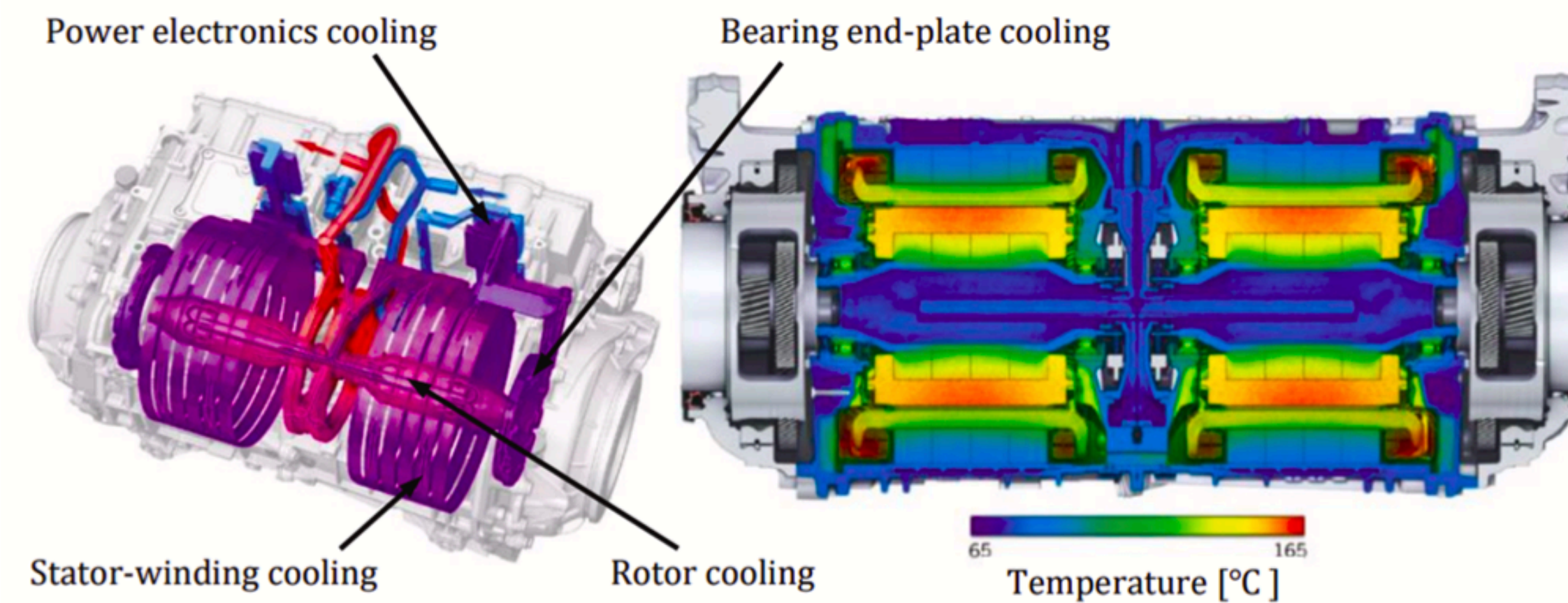
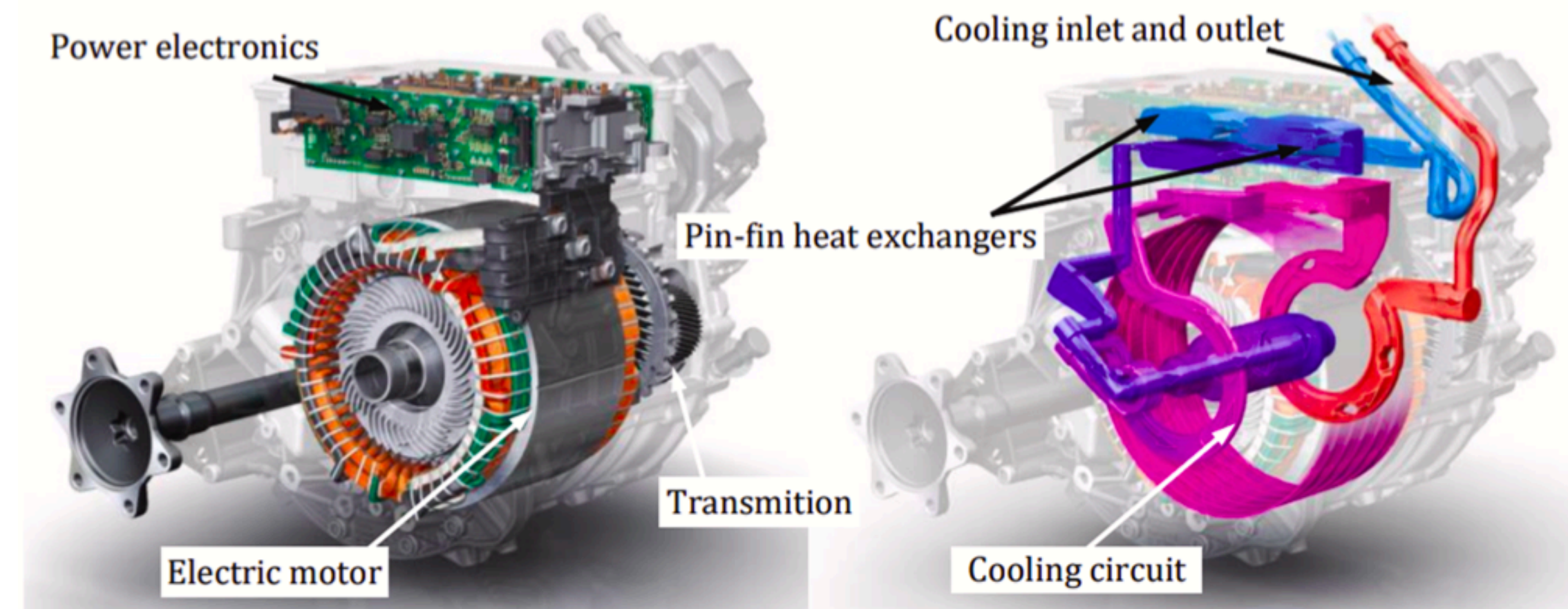
Great potential for improving industrial systems!

Challenges:

- Cooling (two subsystems with different requirements)
- High  $dv/dt$  right at the motor terminals (overvoltages at the winding, HF bearing currents, core losses, etc)

Solutions from the power converter perspective:

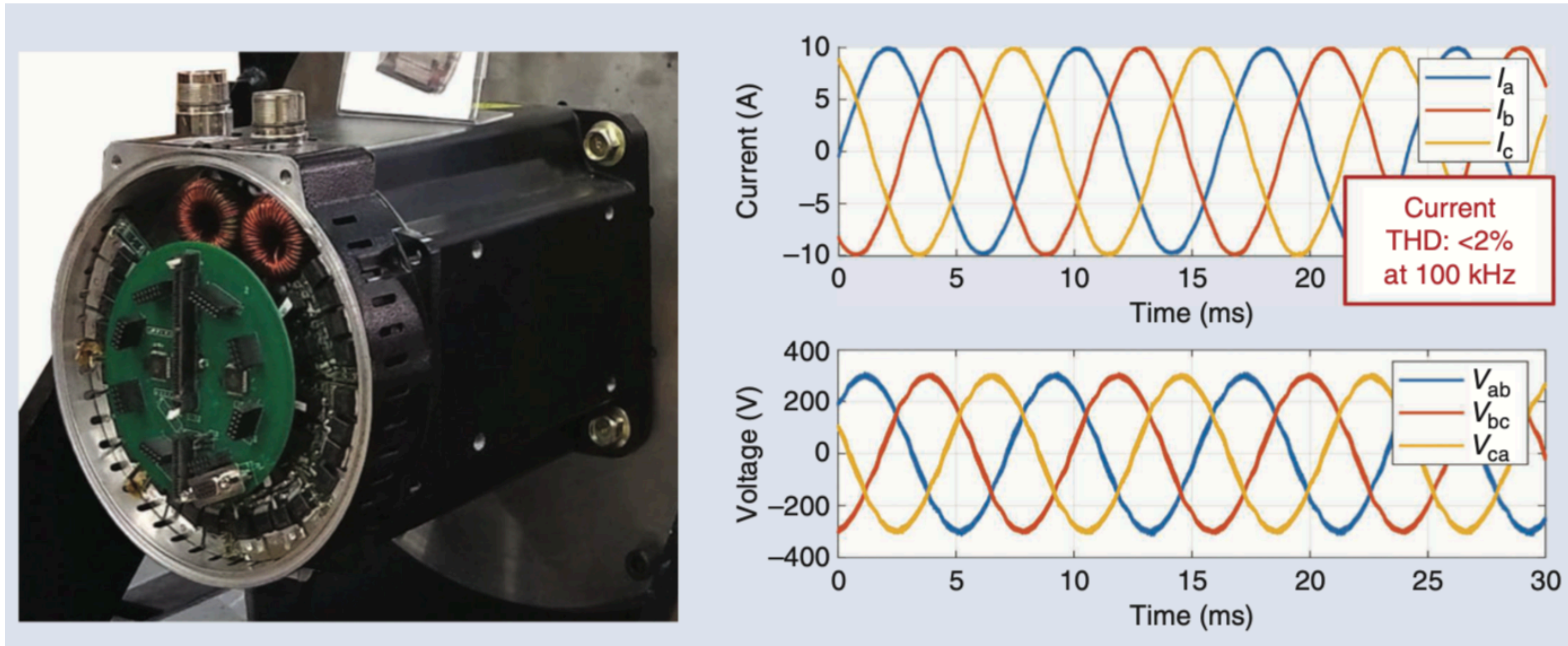
- **Ultra high efficiency**
- **Filtered voltage waveforms**





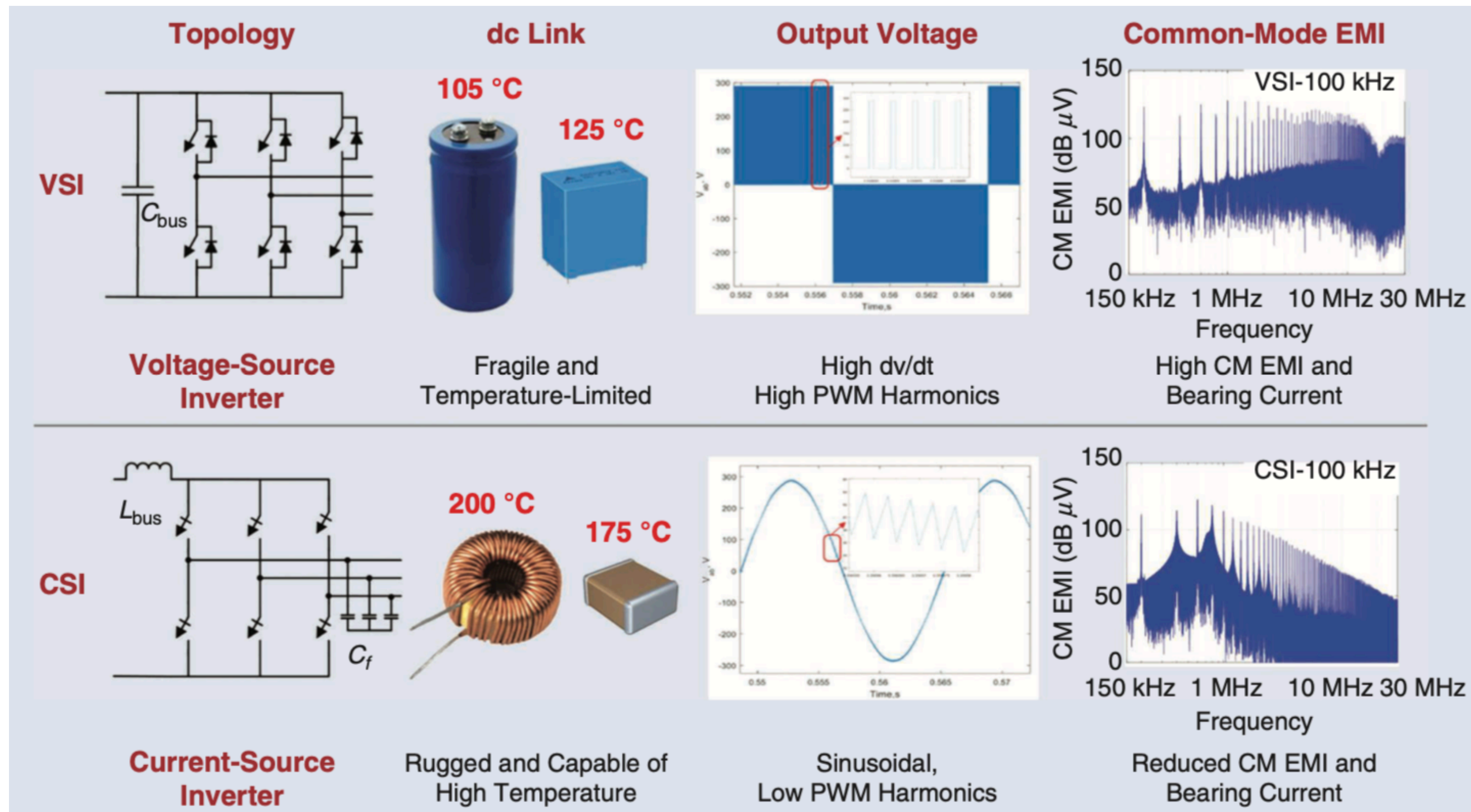
# Integrated motor drives - example based on Current Source Converters

Current DC-link Back-to-Back converters seem like an interesting solution



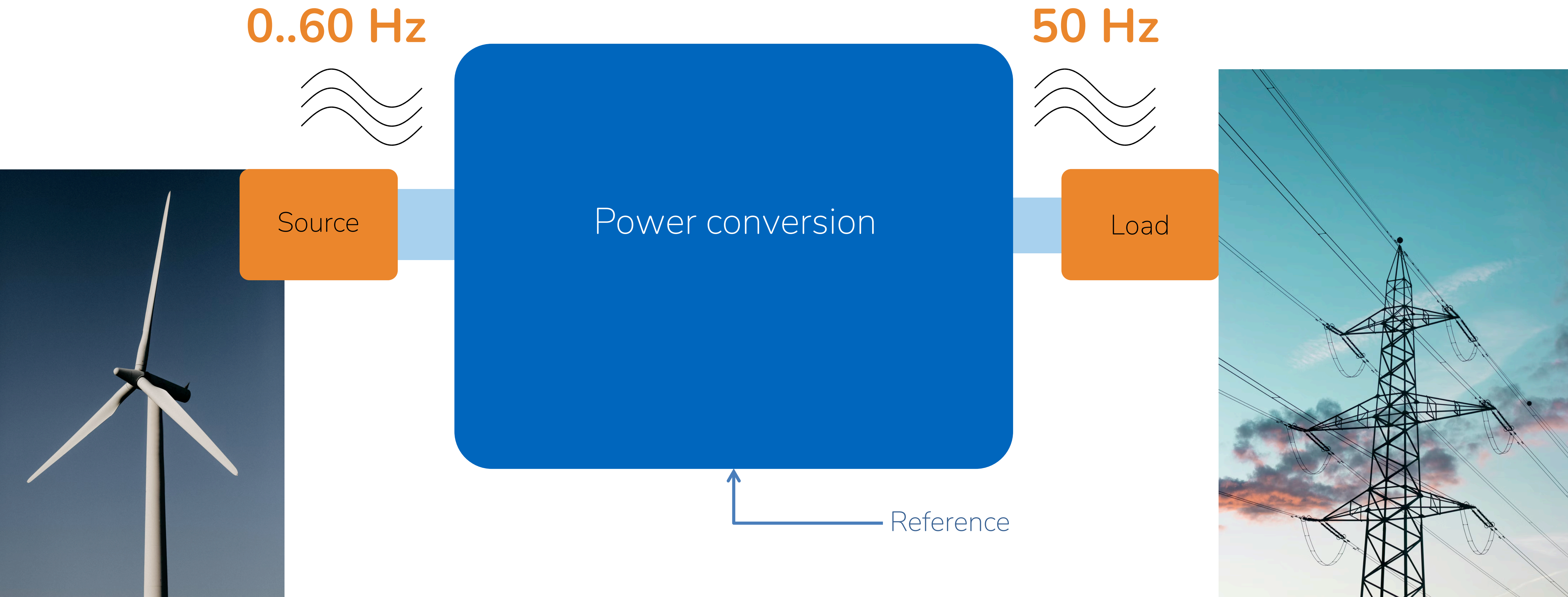


# Integrated motor drives - example based on a Current Source Converters





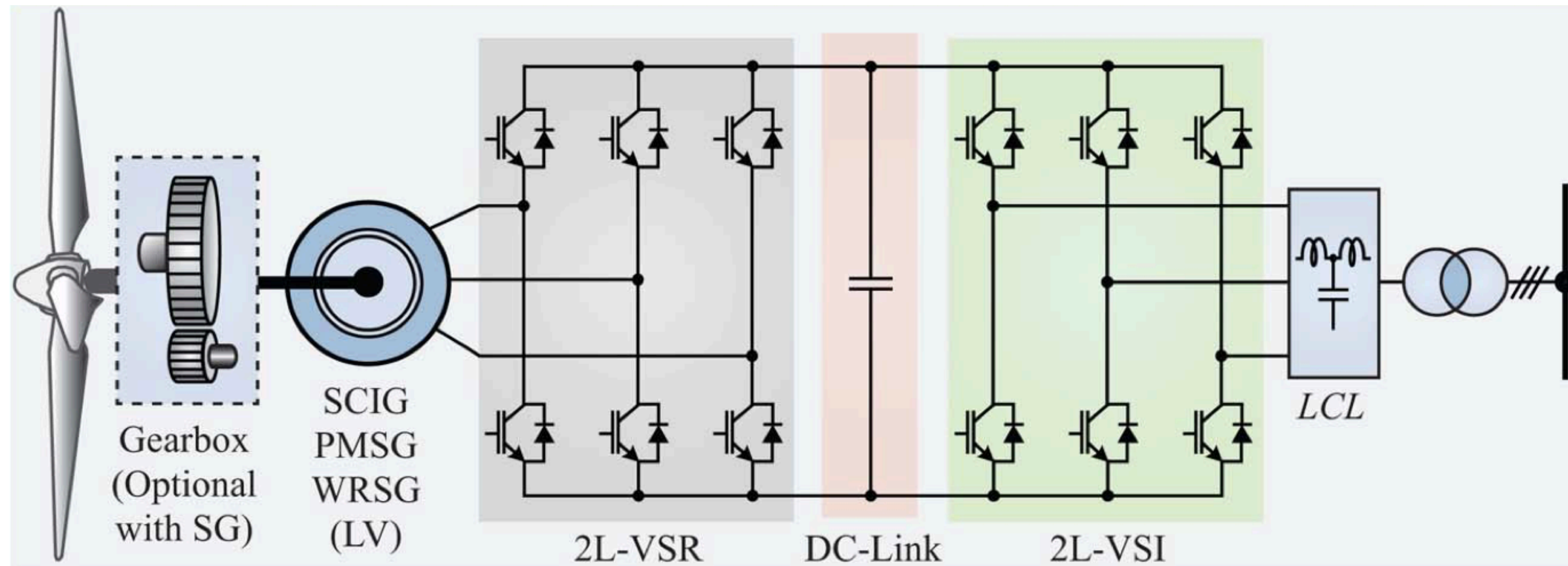
# Bidirectional motor drive applications (WECS)





# Powertrains of Wind Energy Conversion Systems

Type 4 WECS with two-level back-to-back (B2B) voltage source converters



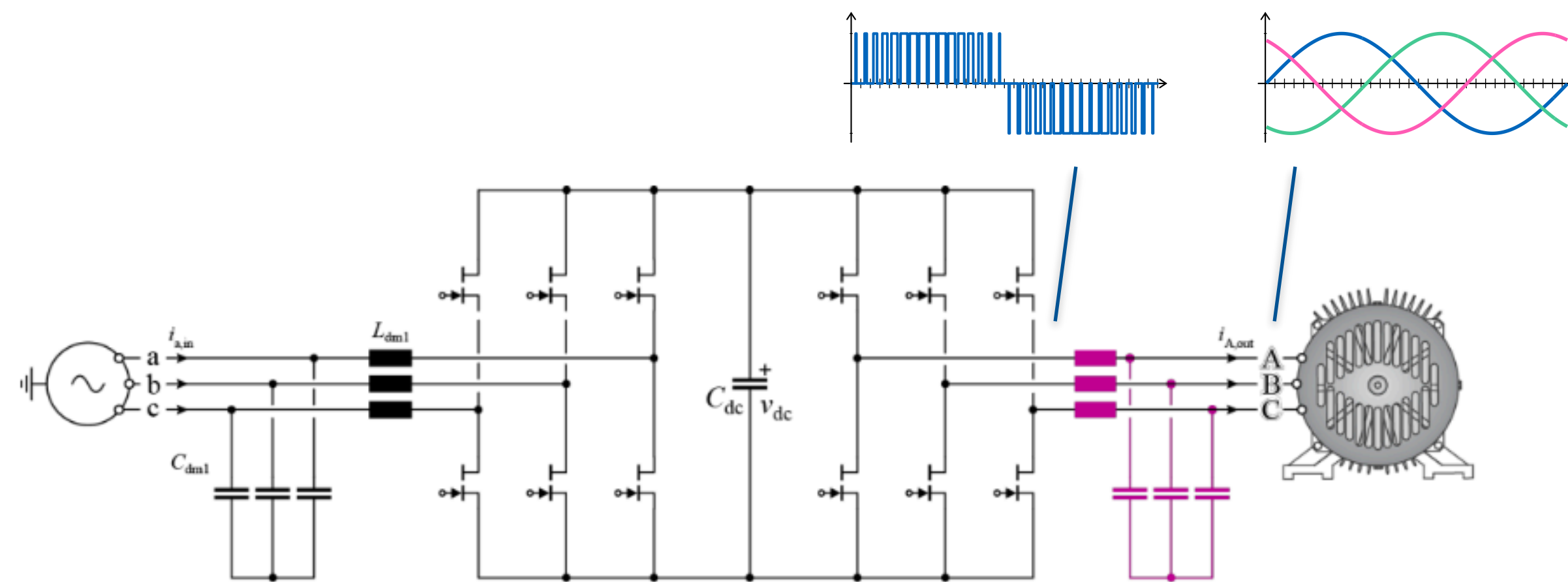
**Mainstream commercial powertrain configuration for WECSs**



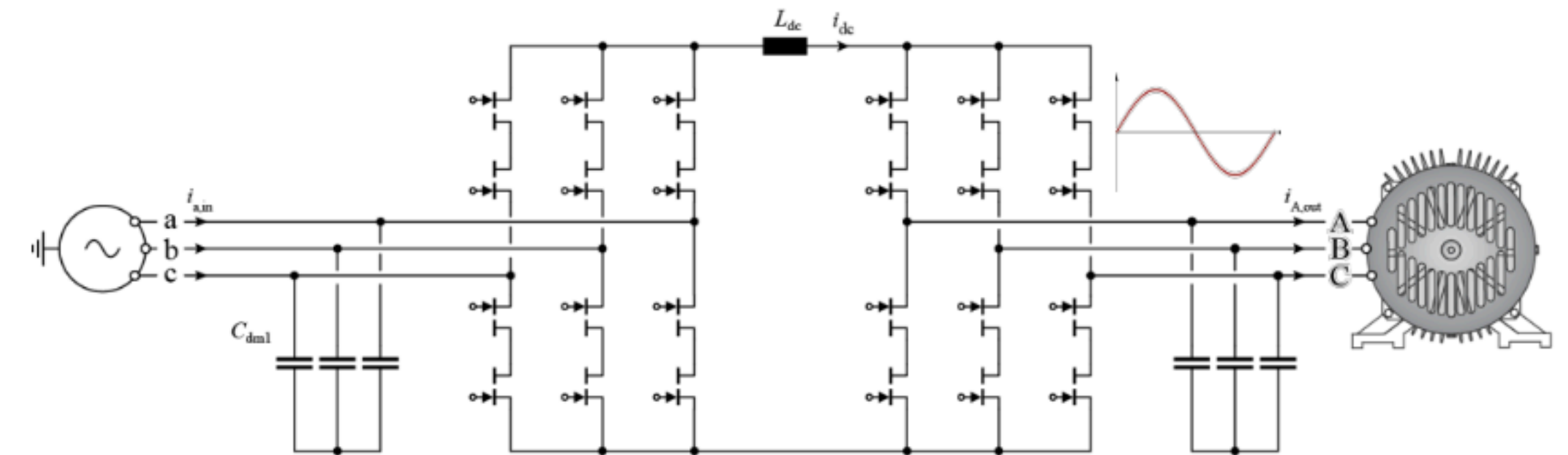
# Conventional power converter architectures for AC-AC conversion



# VSC-B2B versus CSC-B2B



VSC-B2B



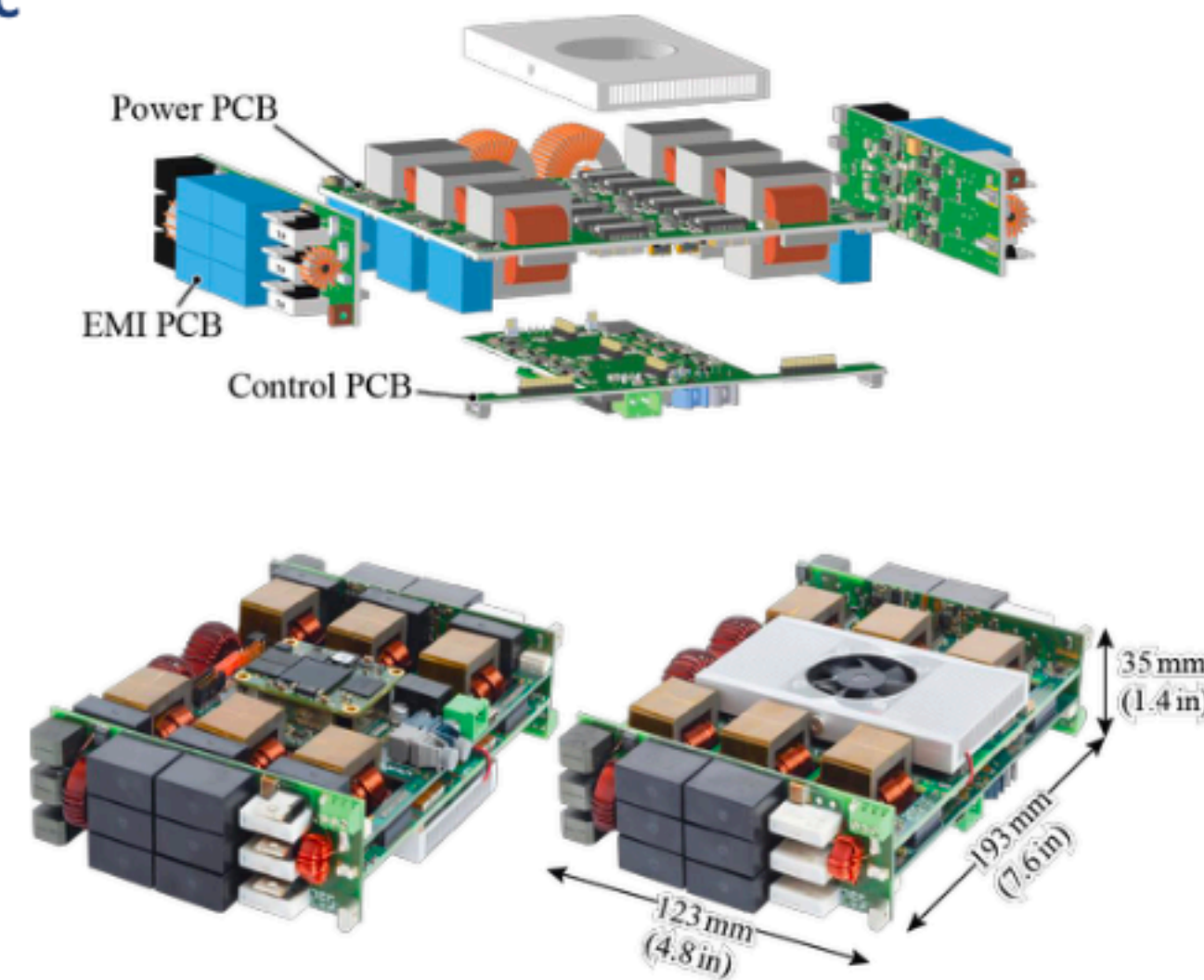
CSC-B2B



# VSC-B2B versus CSC-B2B

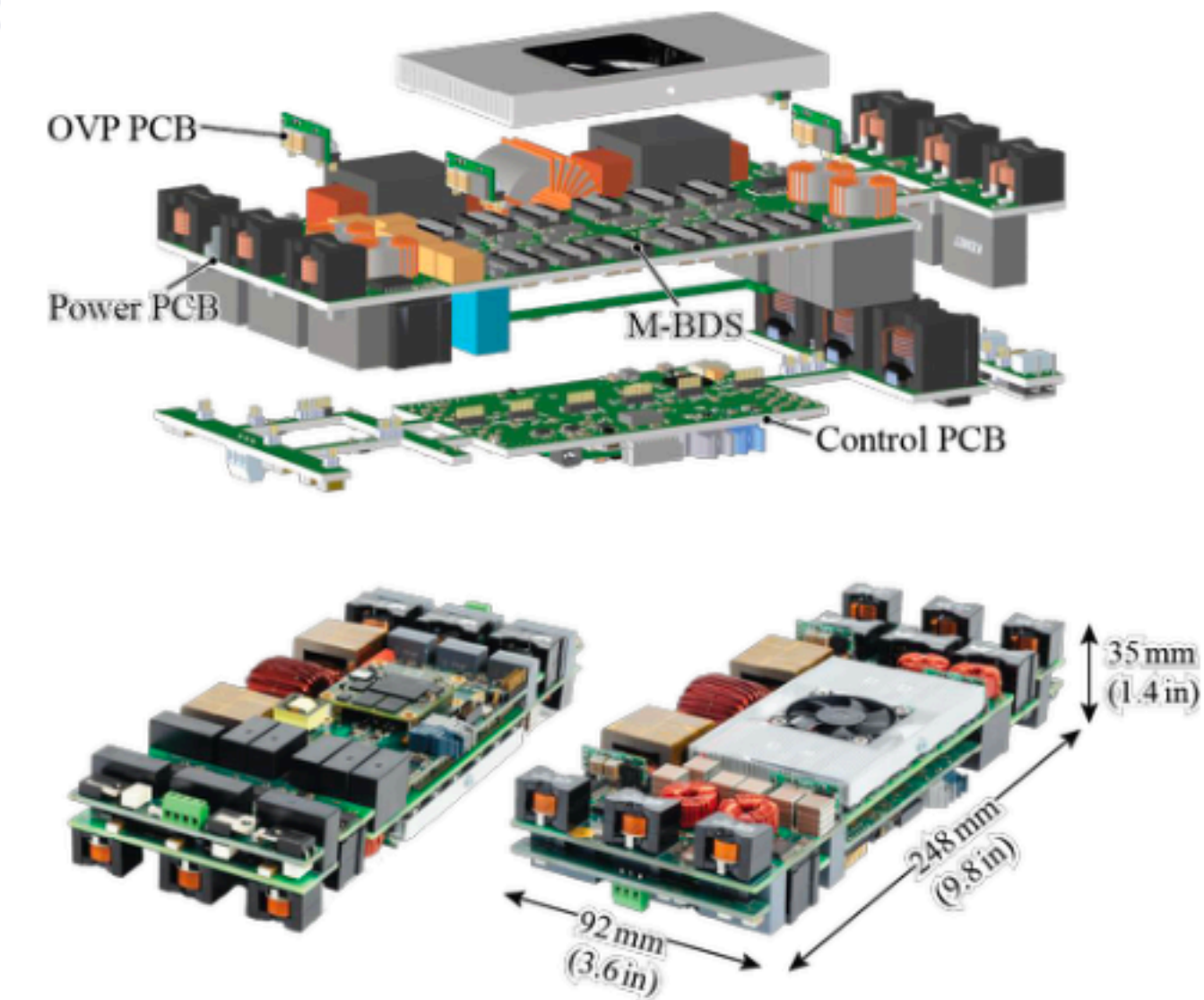
## Hardware Demonstrators (1.4 kW AC-AC VSD Incl. Grid & Motor EMI)

### ► VSC

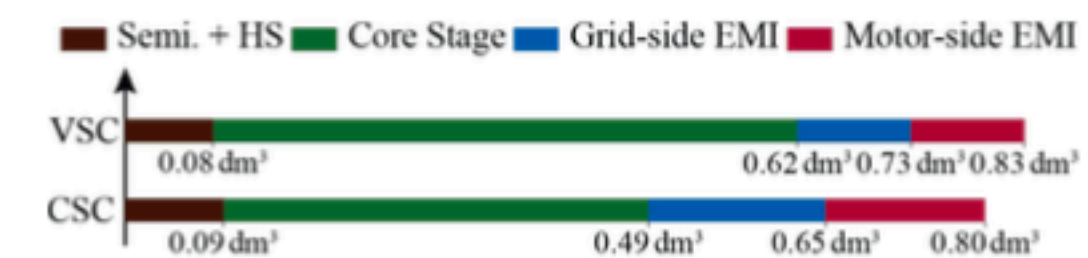


► **VSC Power Density : 1.7 kW/l**  
(1.9 kW/l Without Full Motor Filter)

### ► CSC



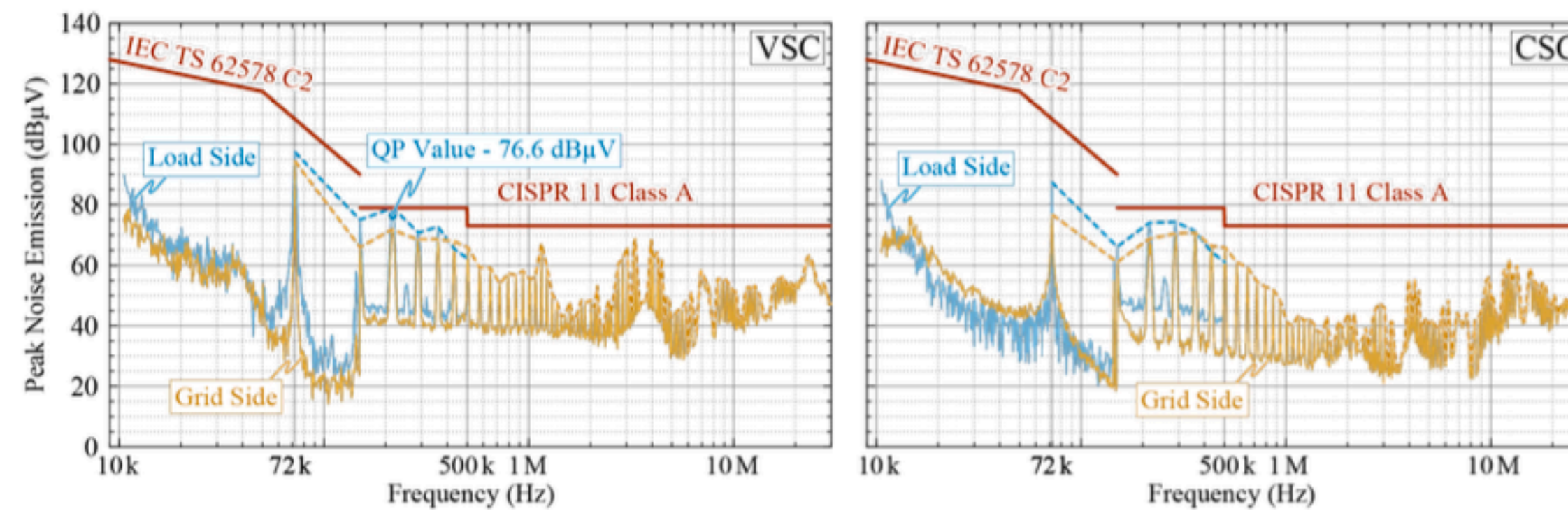
► **CSC Power Density : 1.8 kW/l**  
(2.2 kW/l Without Full Motor Filter)



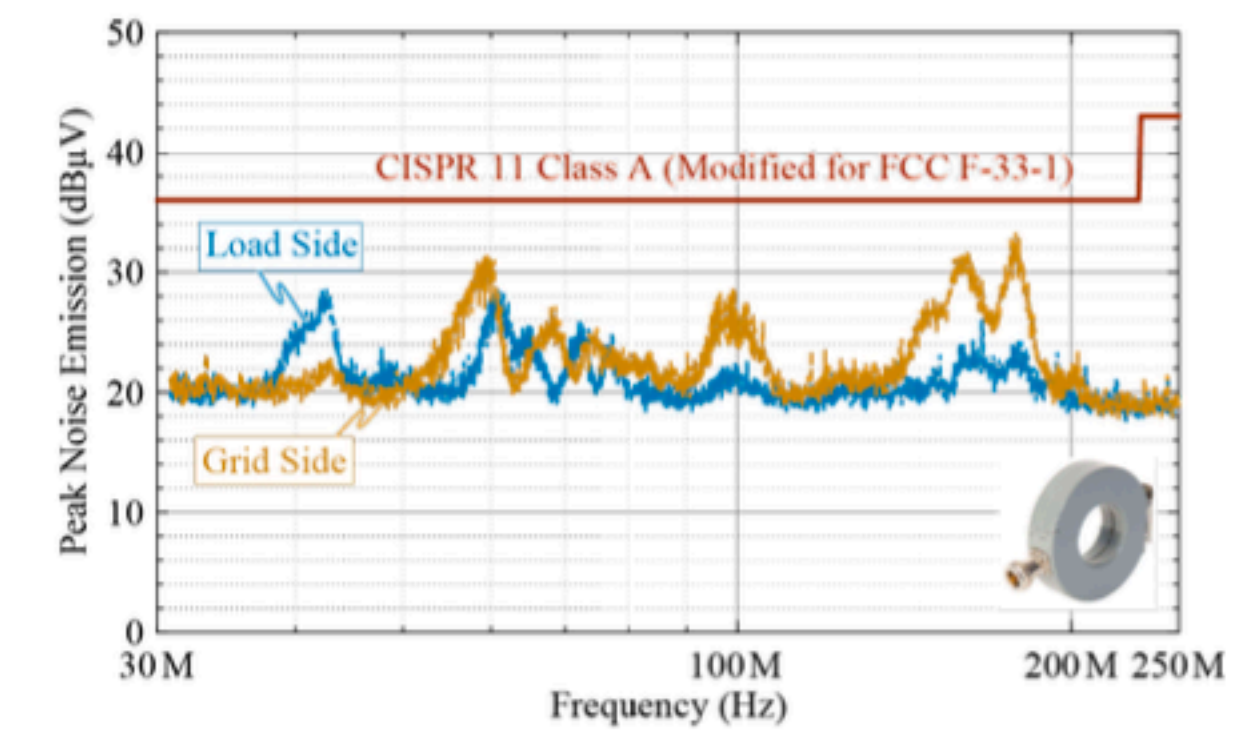


# VSC-B2B versus CSC-B2B

## ► Conducted EMI Measurements



## ► CSC Radiated EMI Measurement



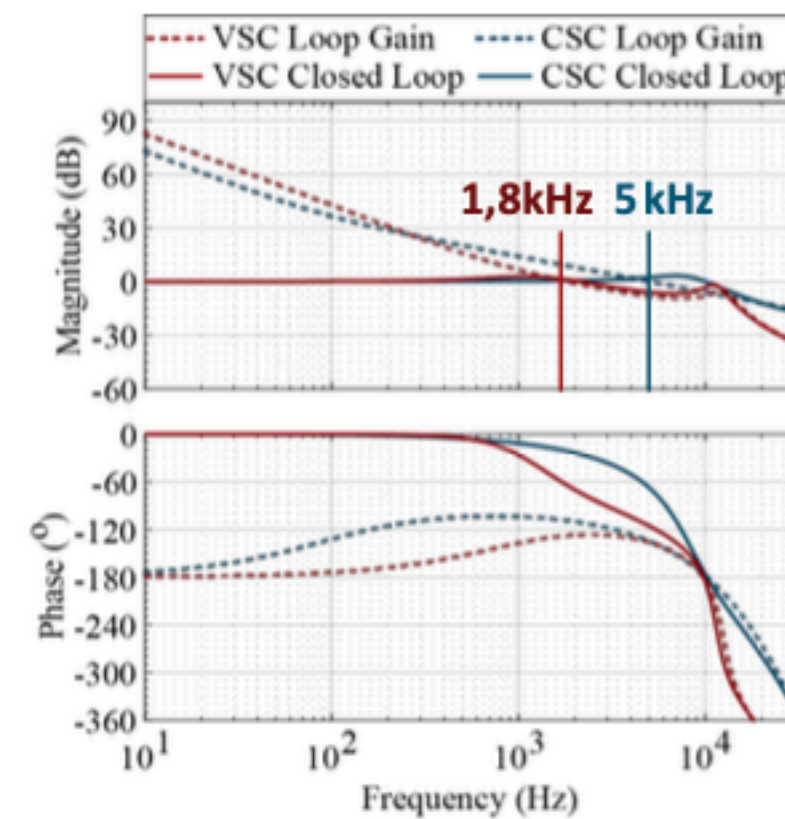
- **Both VSC and CSC Prototype Satisfy Pre-Compliance Conducted EMI Limits.**
- **CSC Satisfies Pre-Compliance Radiated EMI Limits – Use of Unshielded Cables Validated!**
  - Measured with FCC F-33-1 Current Clamp Across All Four Wires On Grid and Motor Side



# VSC-B2B versus CSC-B2B

► **Controllers for Both VSC and CSC Designed to Maximize  $v_o$  Control Bandwidth Under Identical System Constraints**

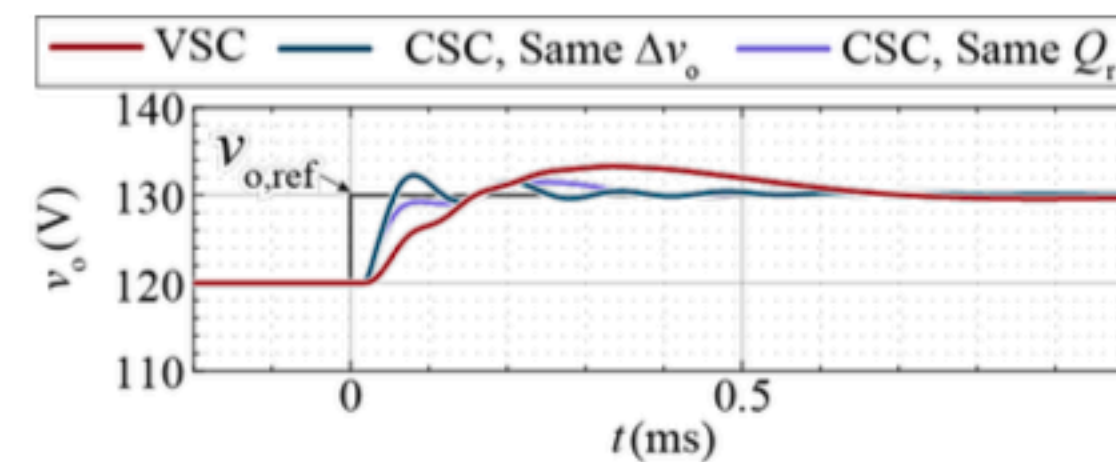
## ■ Output Voltage Loop Gain



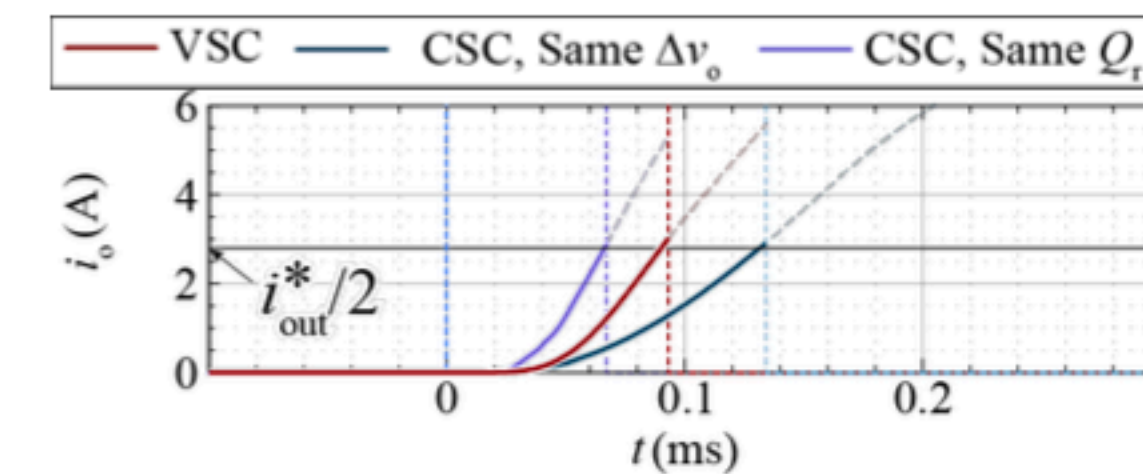
## ■ Step Response – Two Considered Cases for CSC :

- Equal Worst Case Output Voltage Ripple as VSC (**Same  $\Delta v_o \rightarrow C_{o,CSC} > C_{o,VSC}$** )
- Equal Fundamental Frequency Capacitive Reactive Power (**Same  $Q_r \rightarrow C_{o,CSC} = C_{o,VSC}$** )

### Small-Signal



### Large-Signal



► **CSC Achieves Higher Bandwidth!**

► **Small Signal: Both Cases of CSC are Faster!**

► **Large Signal: CSC, Same  $Q_r$  is Faster / CSC, Same  $\Delta v_o$  is Slower!**



# VSC-B2B versus CSC-B2B

- ▶ CSC Offers **Higher Weighted Eff.** (for Characteristic Mission Profile of a Var. Centrifugal Load According to **NEMA PI**)
  - 95.7 % for VSC vs. 96.6% for CSC → **Avg. Mission Profiles Losses of CSC < VSC By Around 20 %**

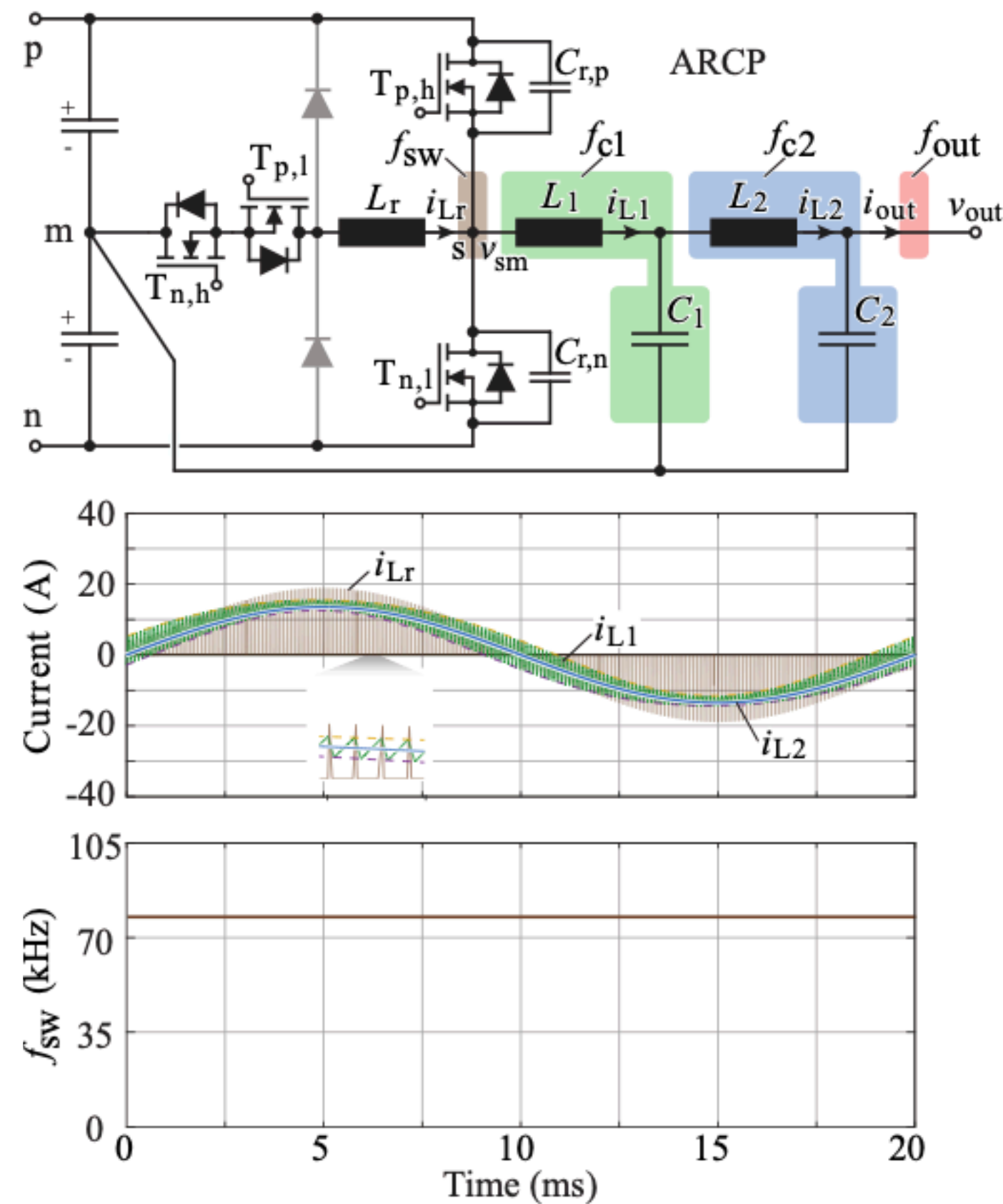


What options exist to reduce switching losses?

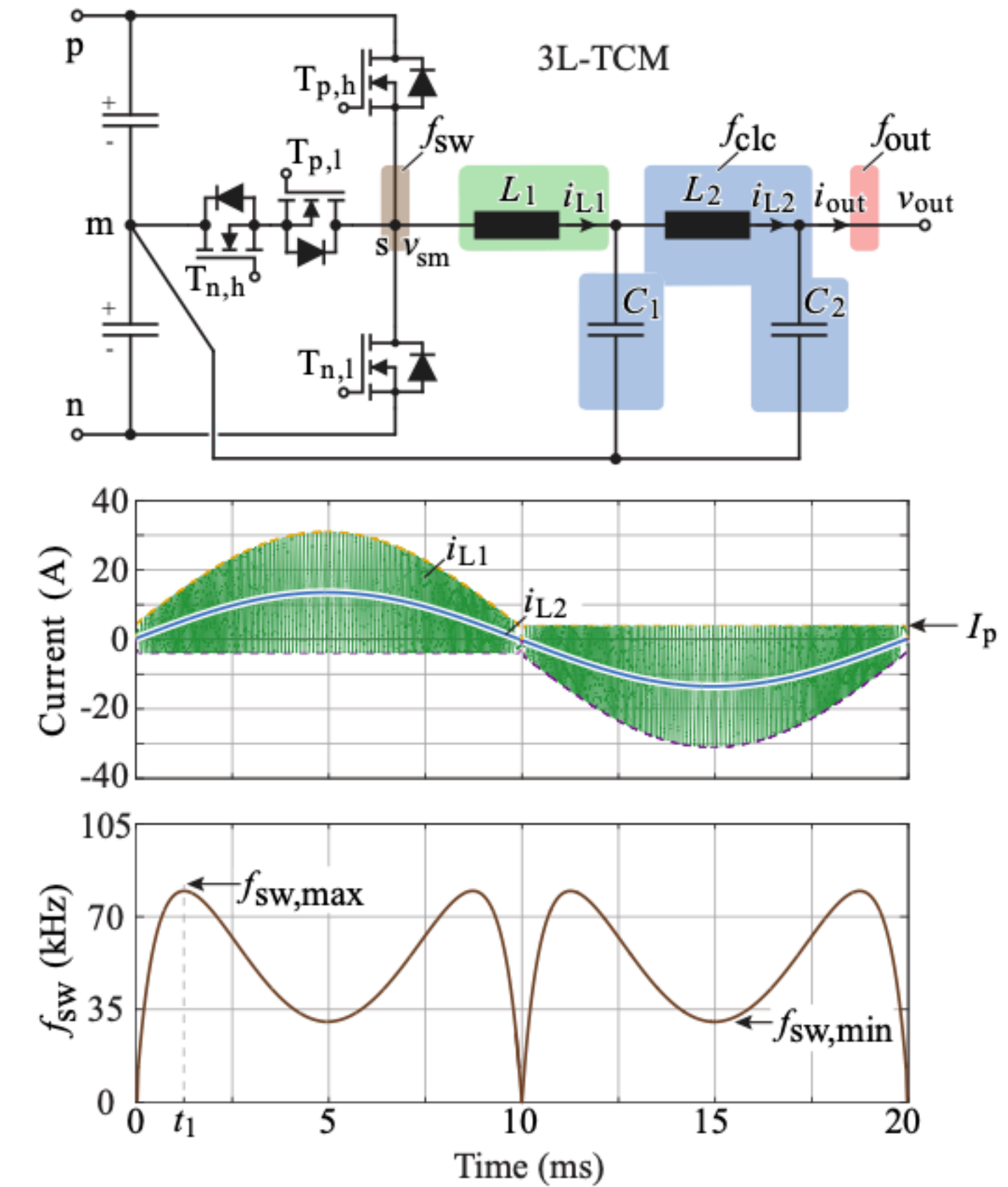


# Switching losses reduction 1 - soft-switching

## Example 1 - ARCP inverters



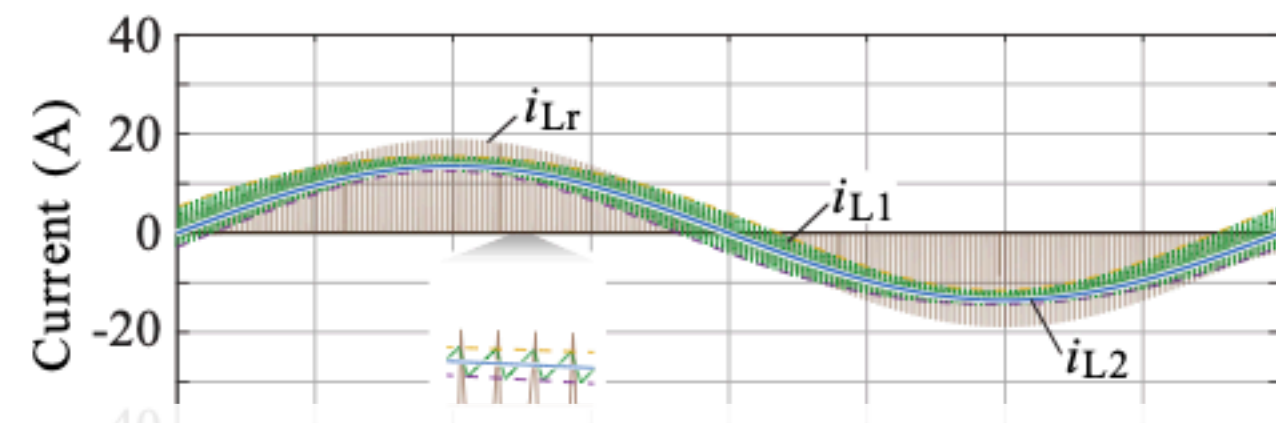
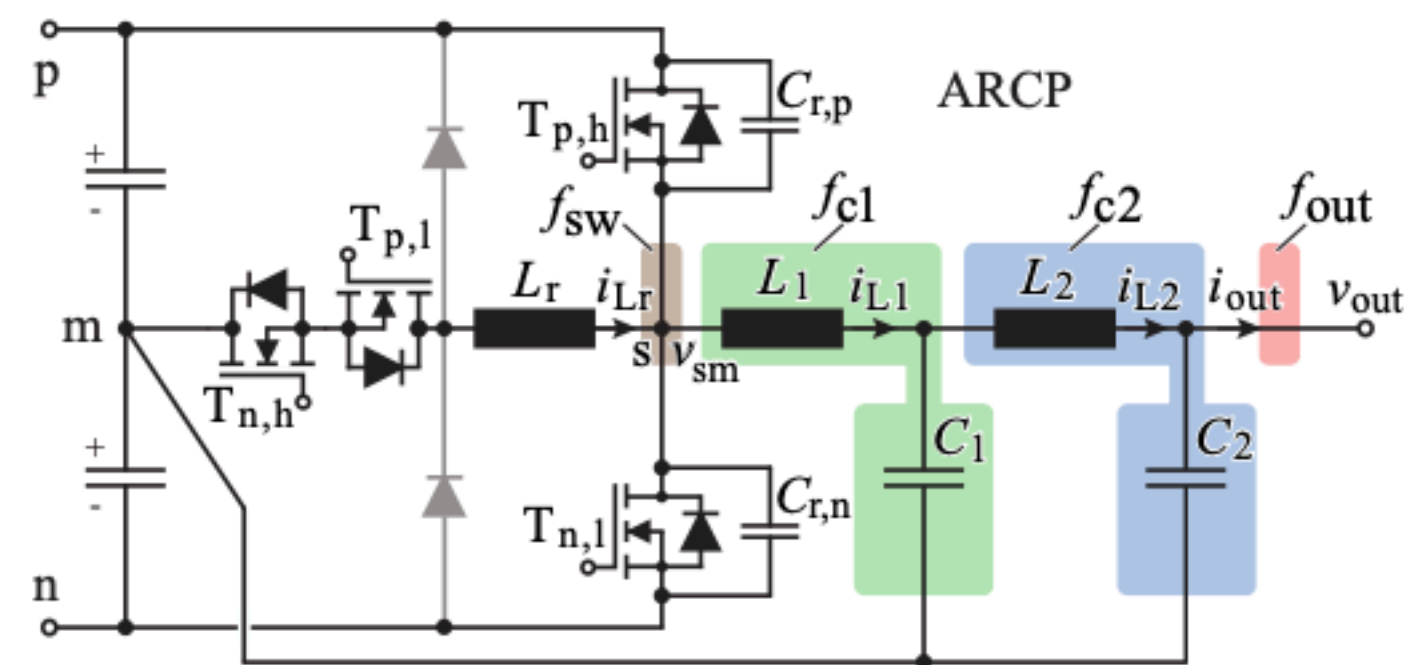
## Example 2 - TCM modulated inverters





# Switching losses reduction 1 - soft-switching

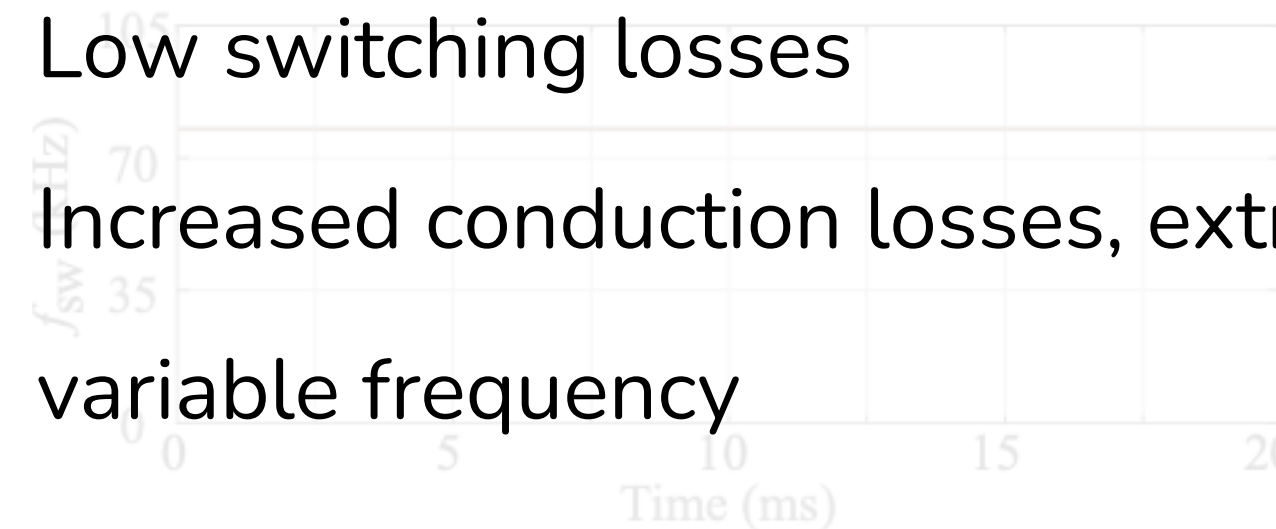
## Example 1 - ARCP inverters



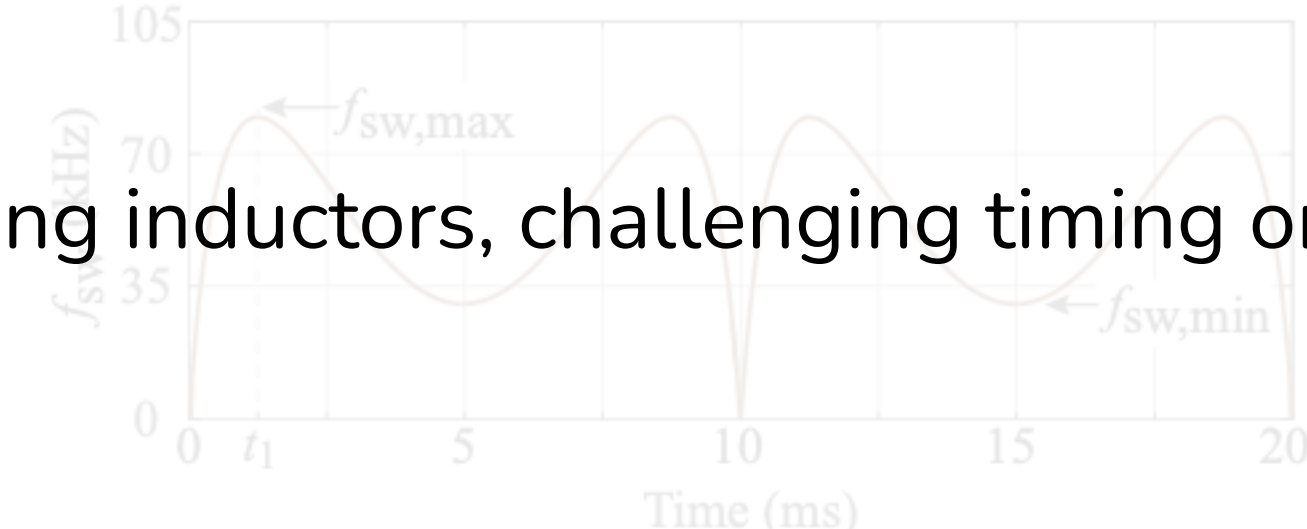
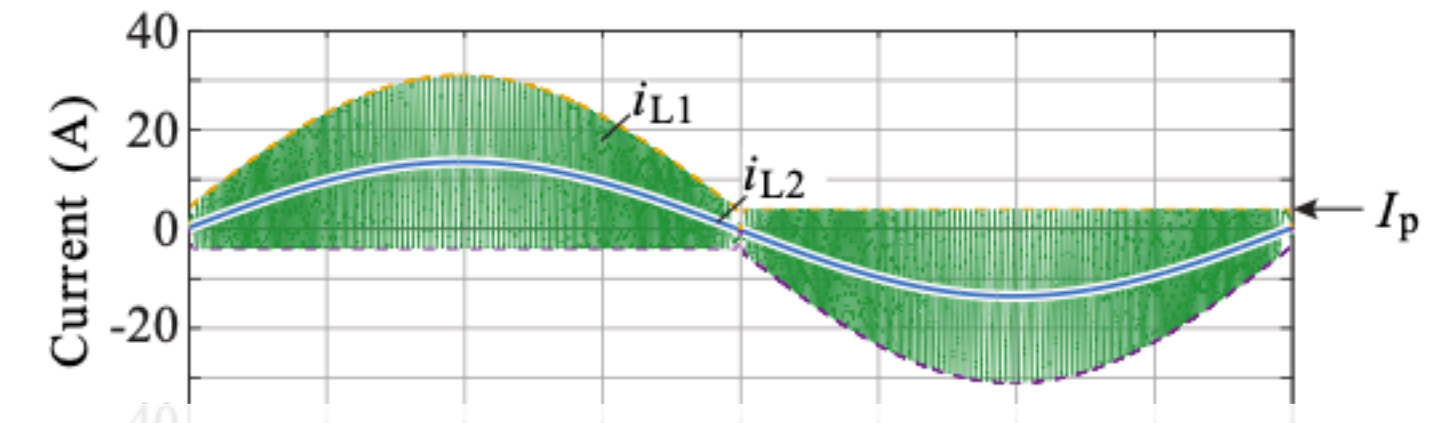
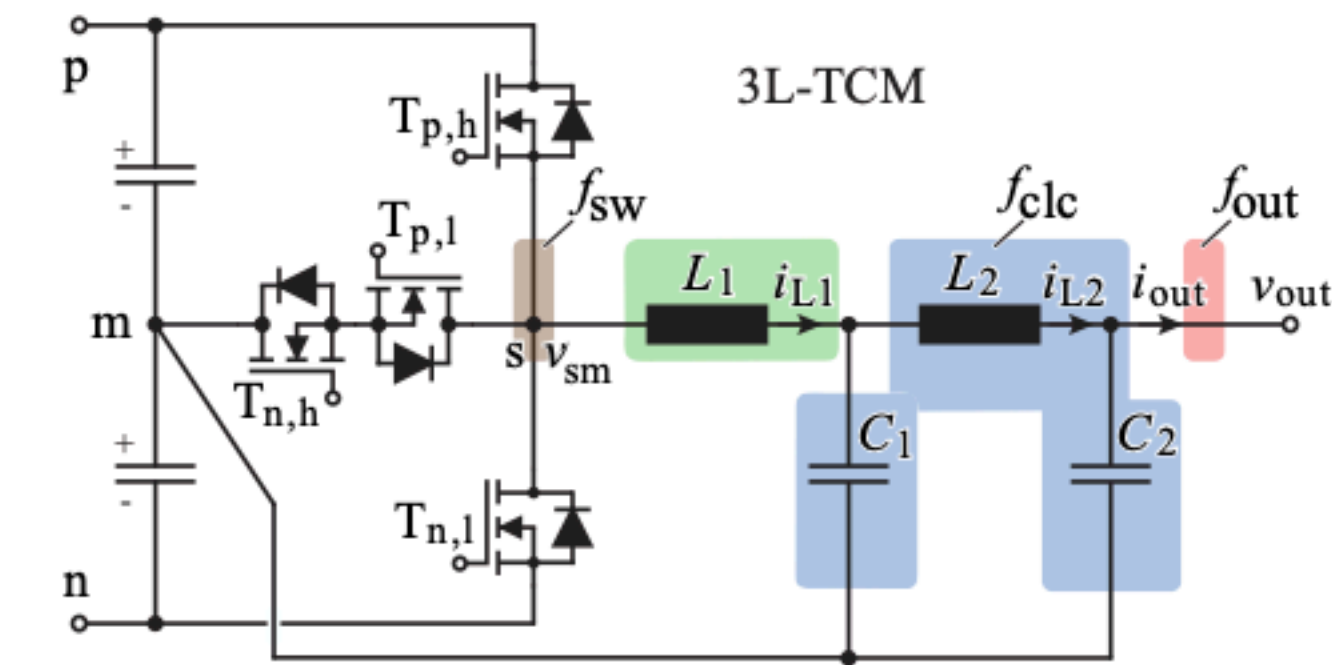
Low switching losses



Increased conduction losses, extra components, high flux swing inductors, challenging timing or highly variable frequency



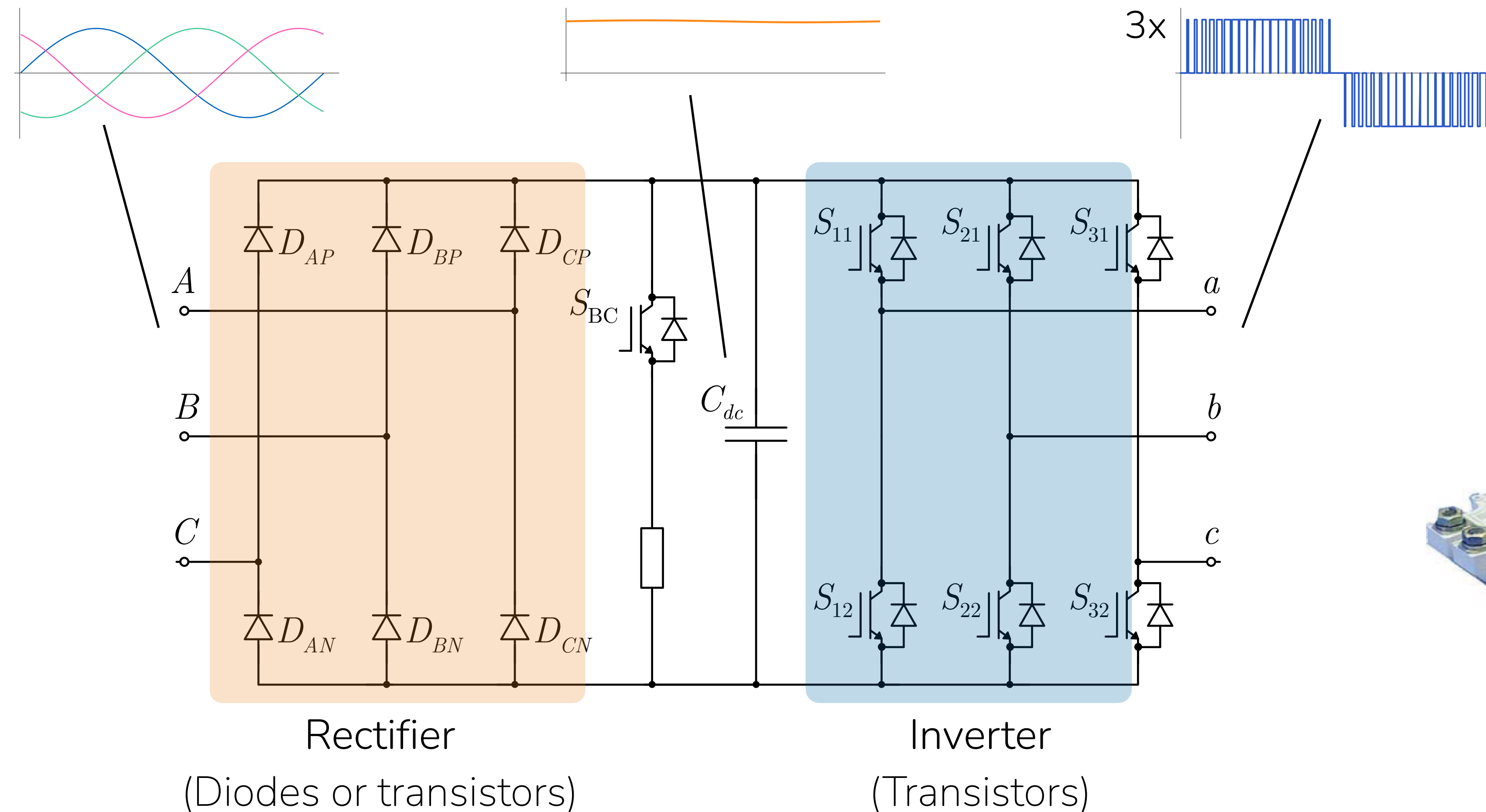
## Example 2 - TCM modulated inverters





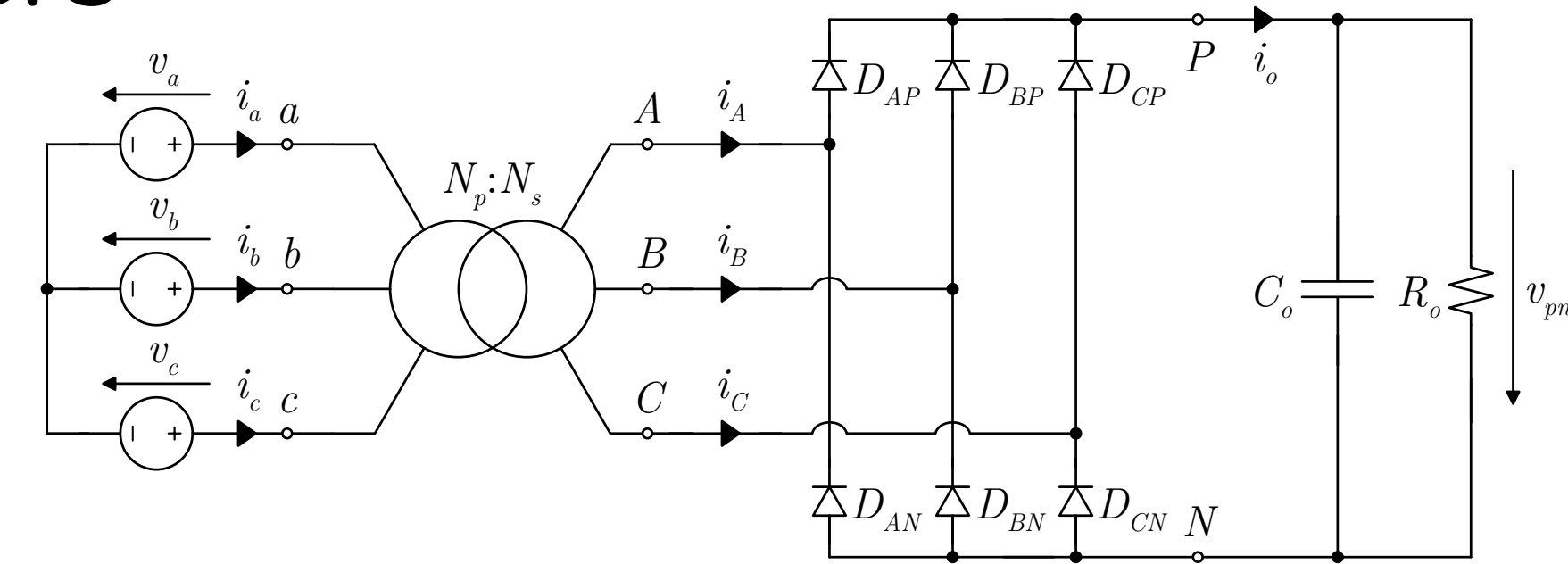
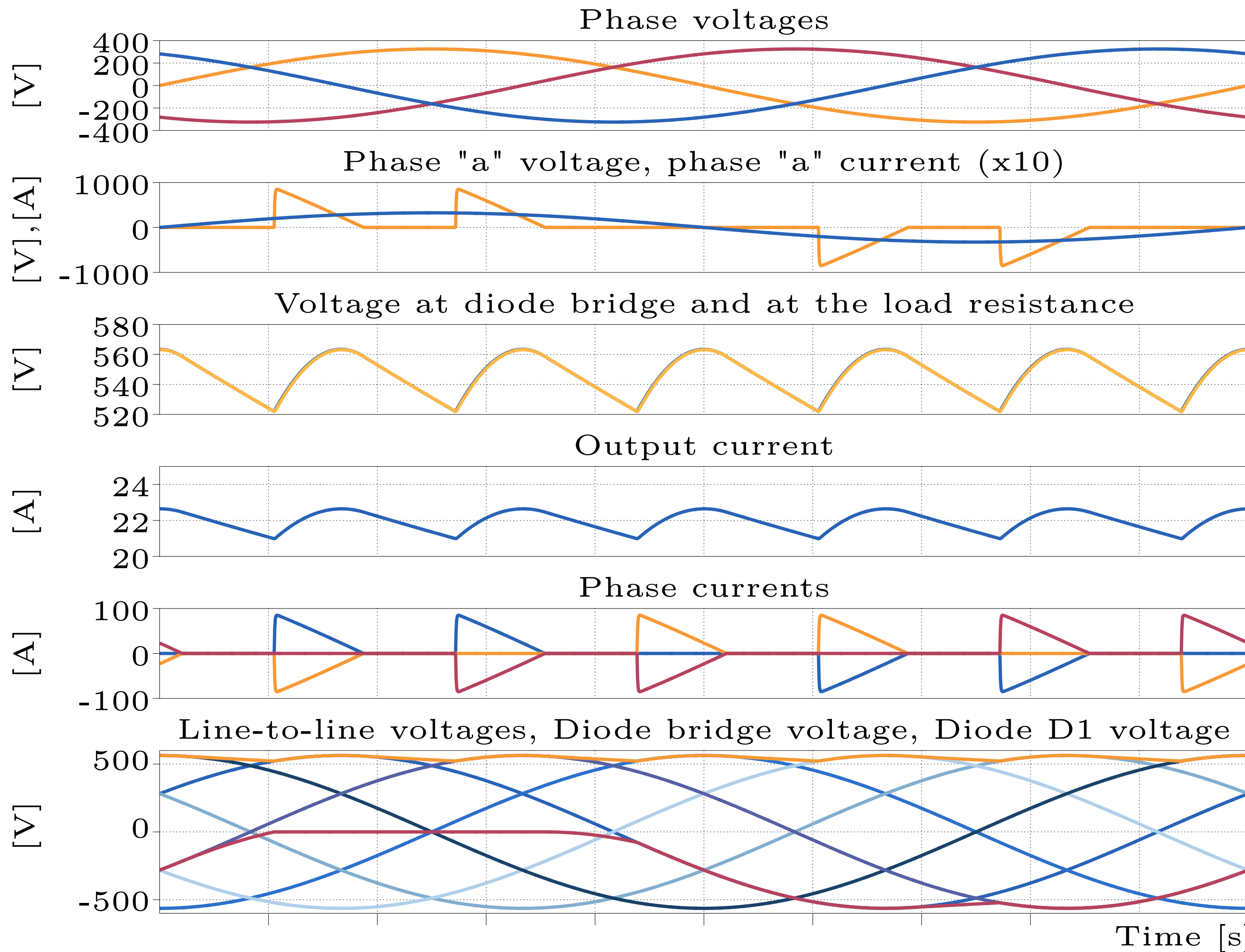
# Switching losses reduction 2 - Diode(-like) rectifiers

Typical variable speed drive





# Switching losses reduction 2 - Diode(-like) rectifiers

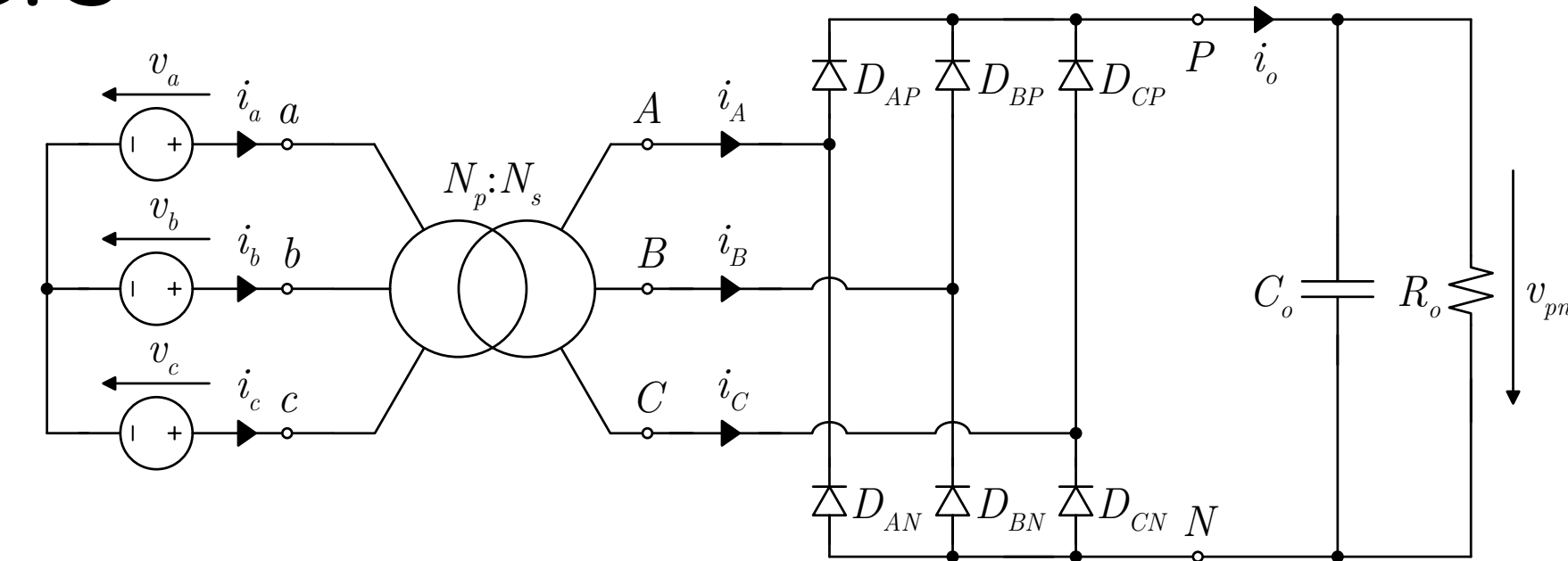
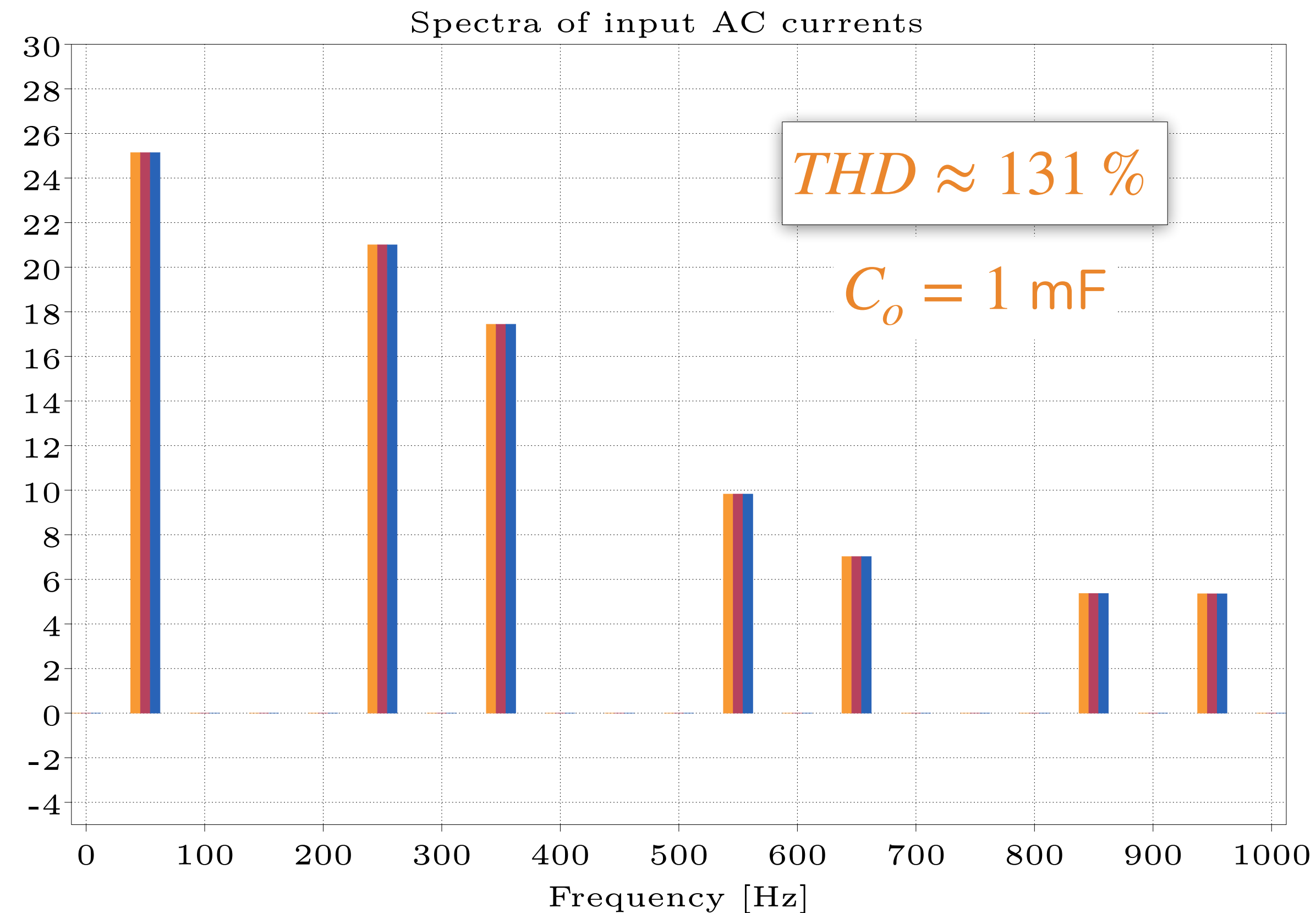


$$C_o = 1 \text{ mF}$$

$$W_{\text{stored}} = \frac{1}{2} C_o V_o^2 \approx 317 \text{ J}$$



# Switching losses reduction 2 - Diode(-like) rectifiers



A bidirectional solution can be achieved by replacing the diodes with transistors.

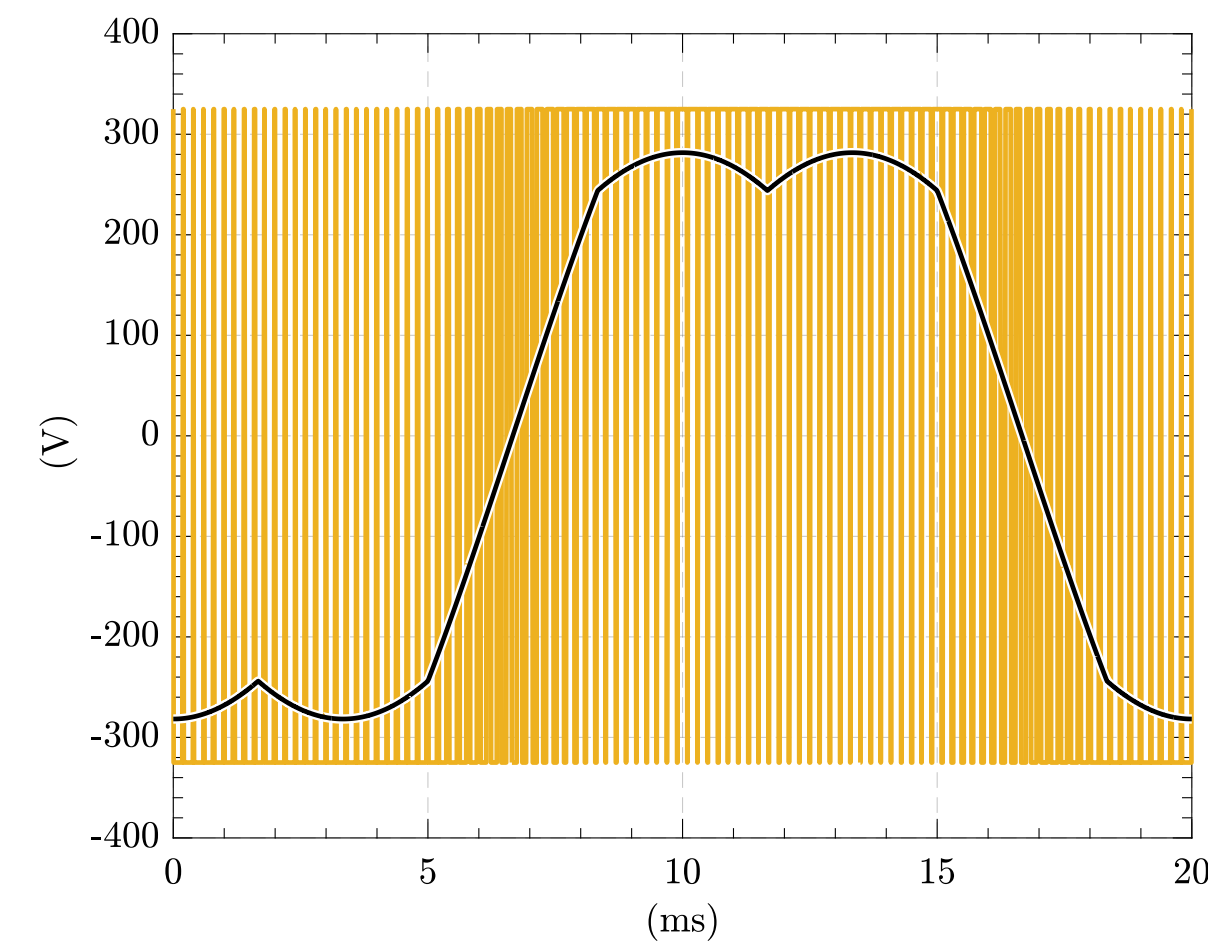
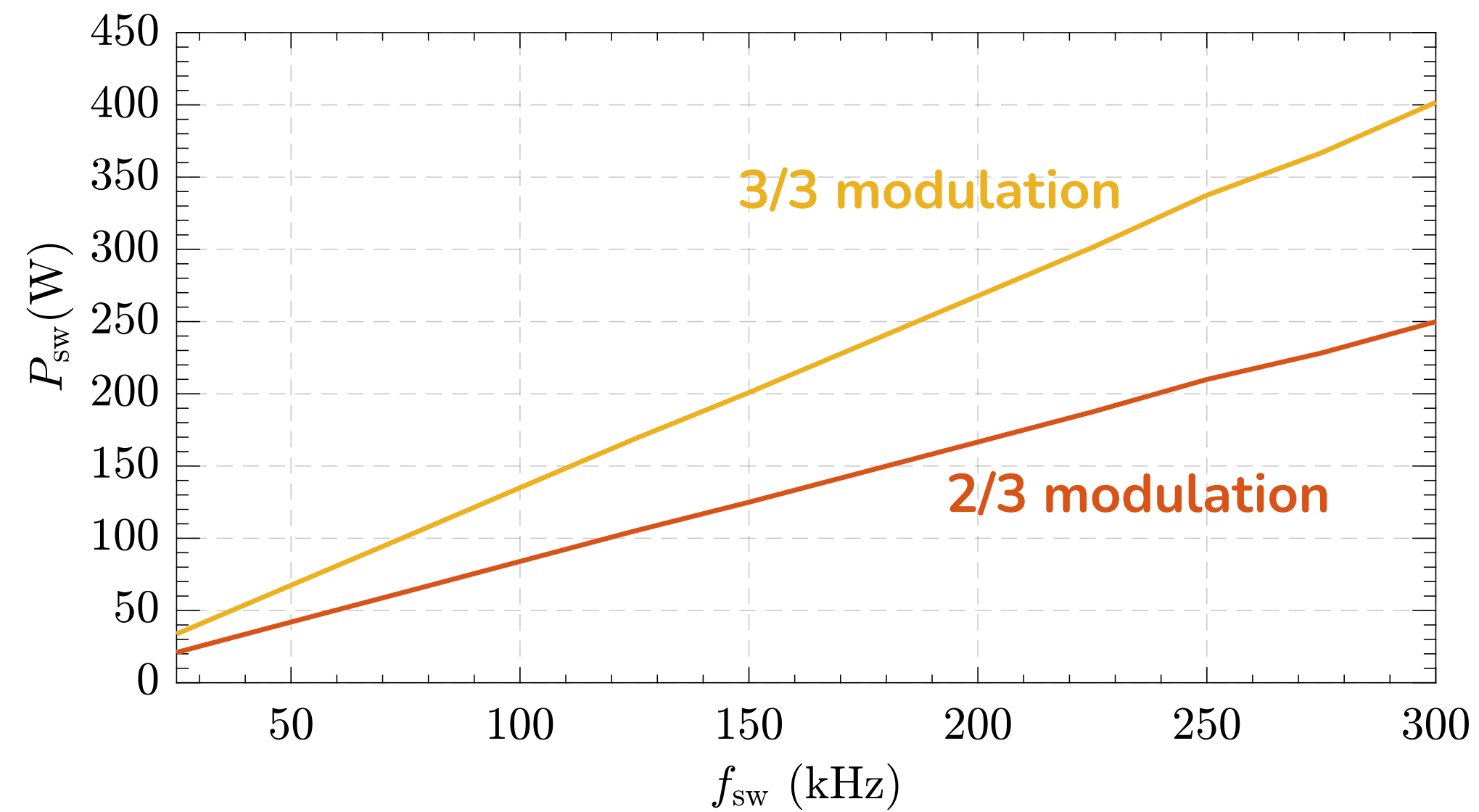


Current distortion will not be eliminated, and large energy storage -> large dimensions

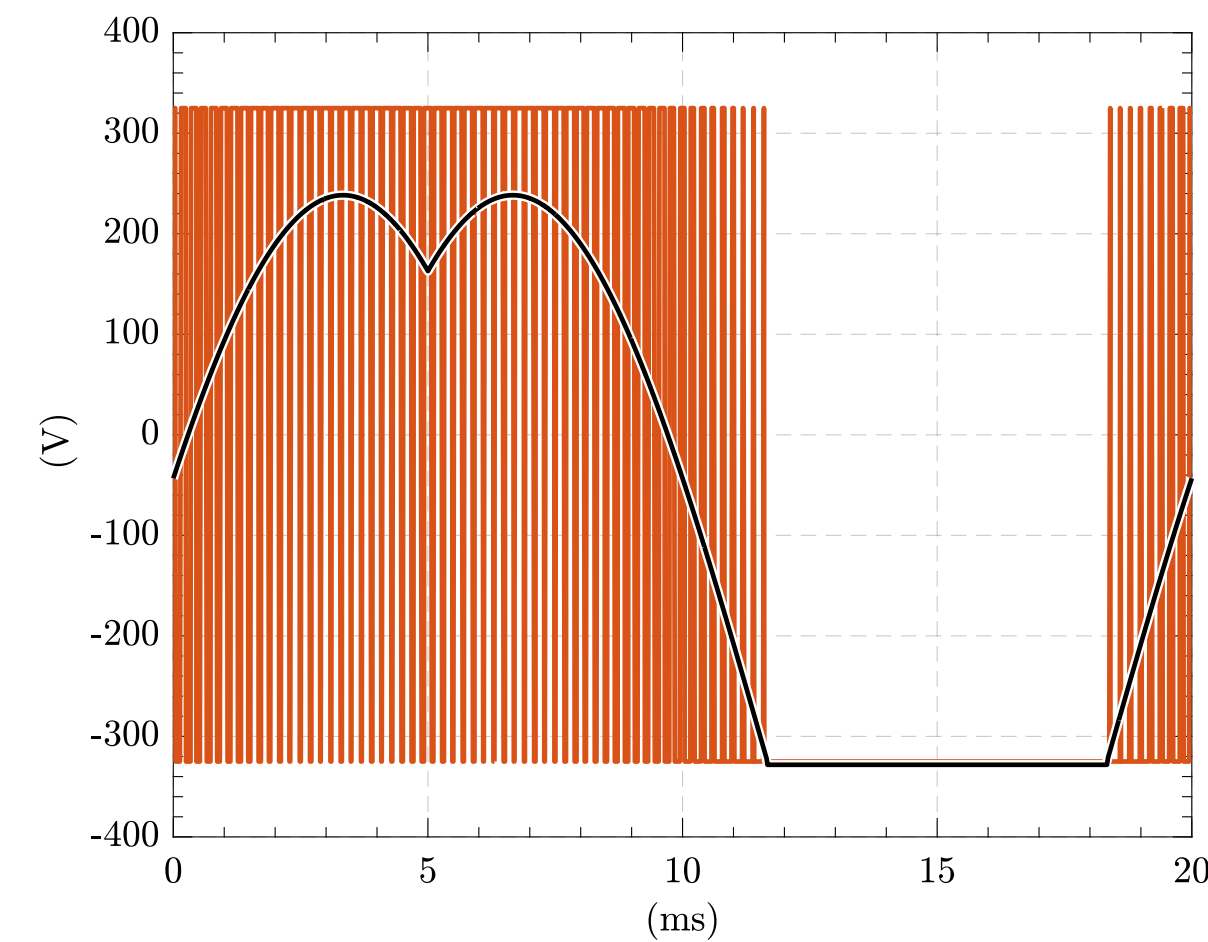


# Switching losses reduction 3 - Discontinuous modulation

Exemplary switching losses:



7-segment space vector modulation  
(3/3 modulation)

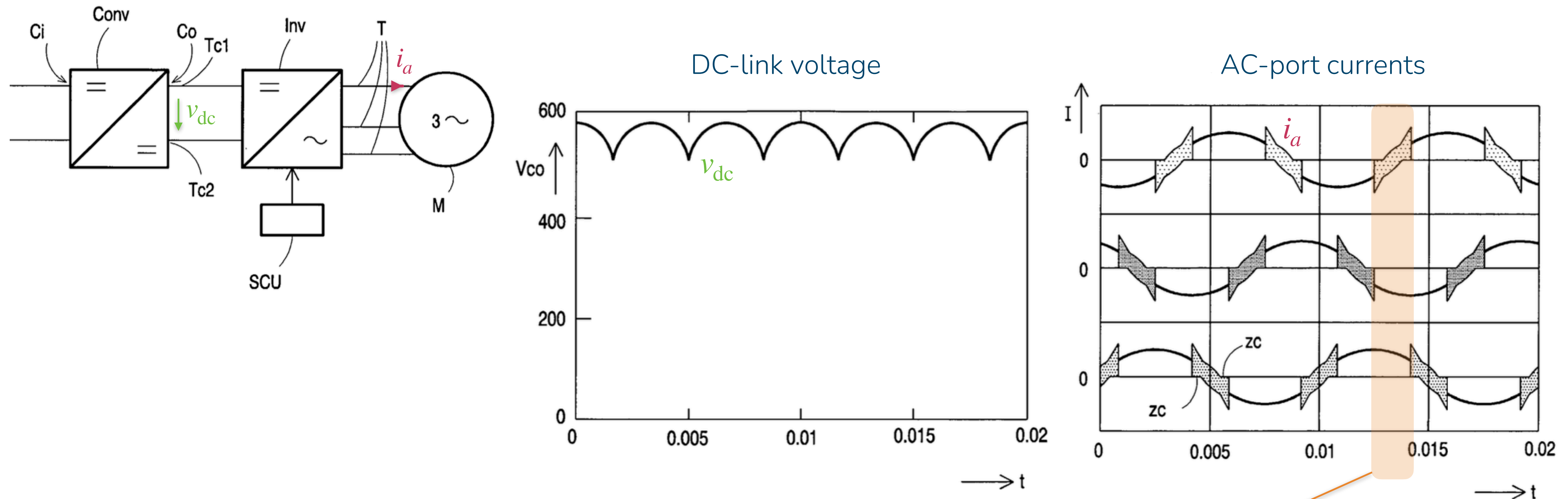


Discontinuous modulation  
(2/3 modulation)



# Switching losses reduction 4 - synergetic control/modulation

Example - Two-stage DC-DC-AC converter with 1/3 modulation at the VSI stage

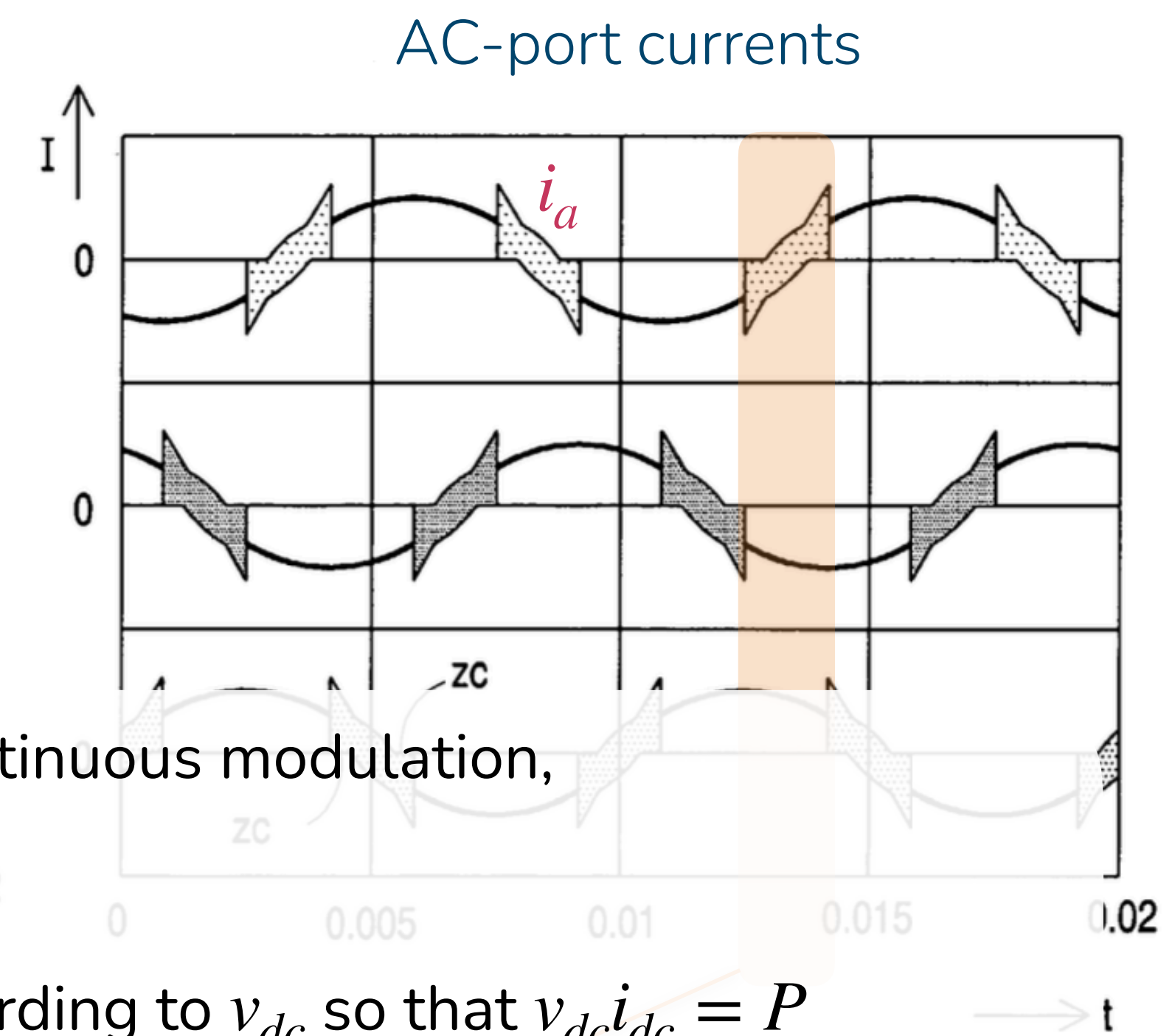
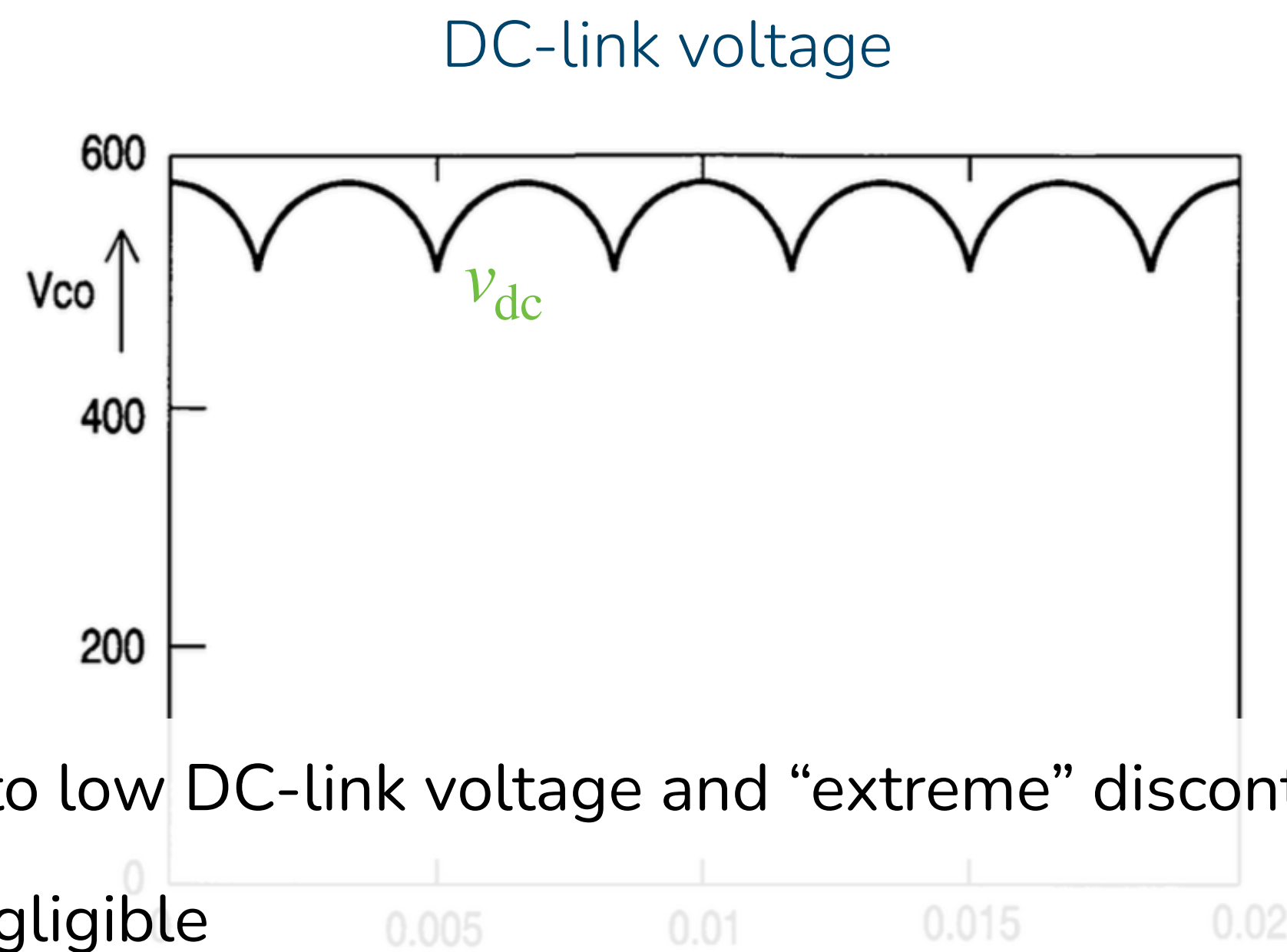
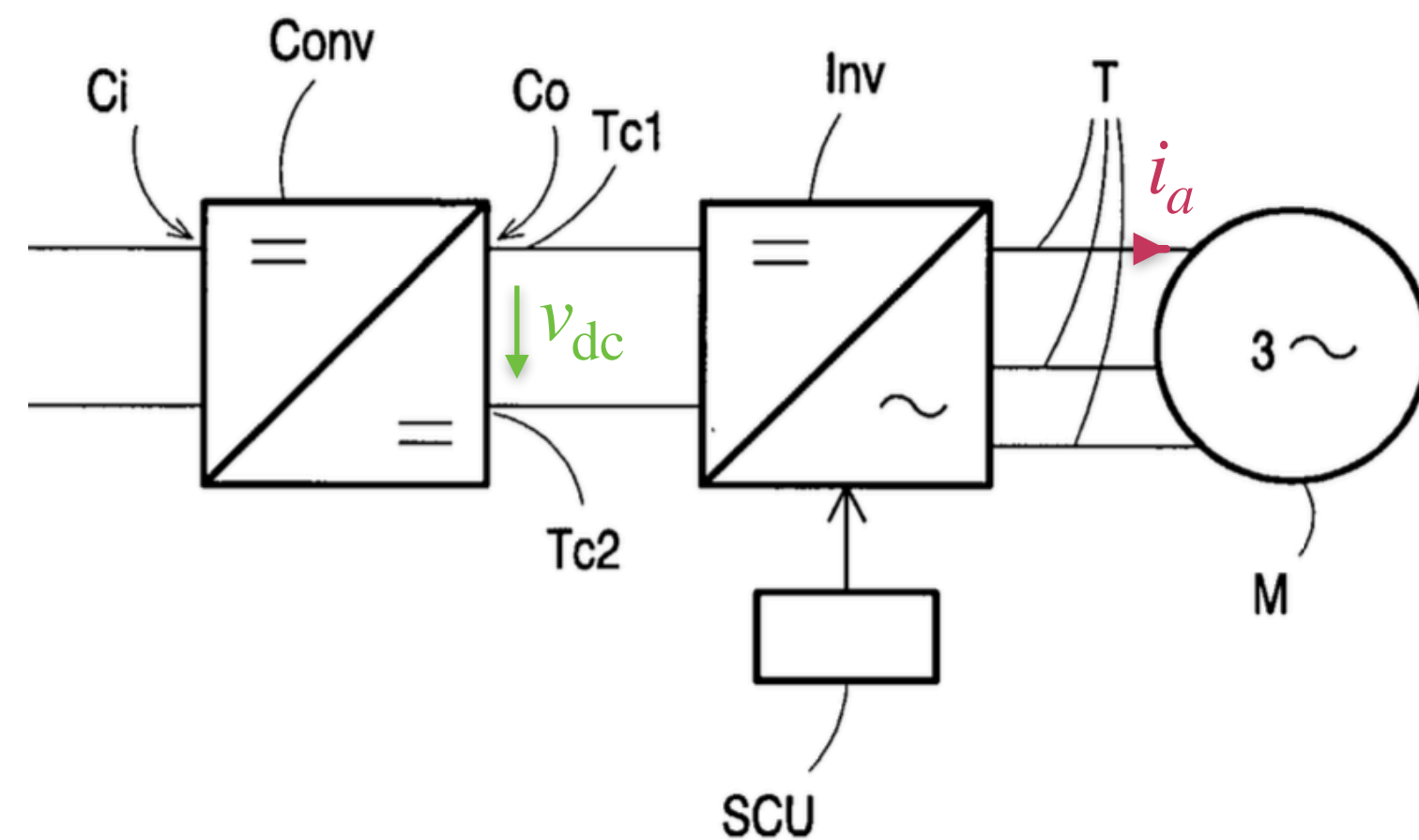


Only one leg switches at  $f_s$  -> 1/3 modulation



# Switching losses reduction 4 - synergetic control

Example - Two-stage DC-DC-AC converter with 1/3 modulation at the VSI stage



Low switching losses due to low DC-link voltage and “extreme” discontinuous modulation, conduction changes are negligible



A DC-DC stage is needed, which should shape its DC-link current according to  $v_{dc}$  so that  $v_{dc}i_{dc} = P$

-> not optimal DC-DC operation

Only one leg switches at  $f_{fs}$  -> 1/3 modulation

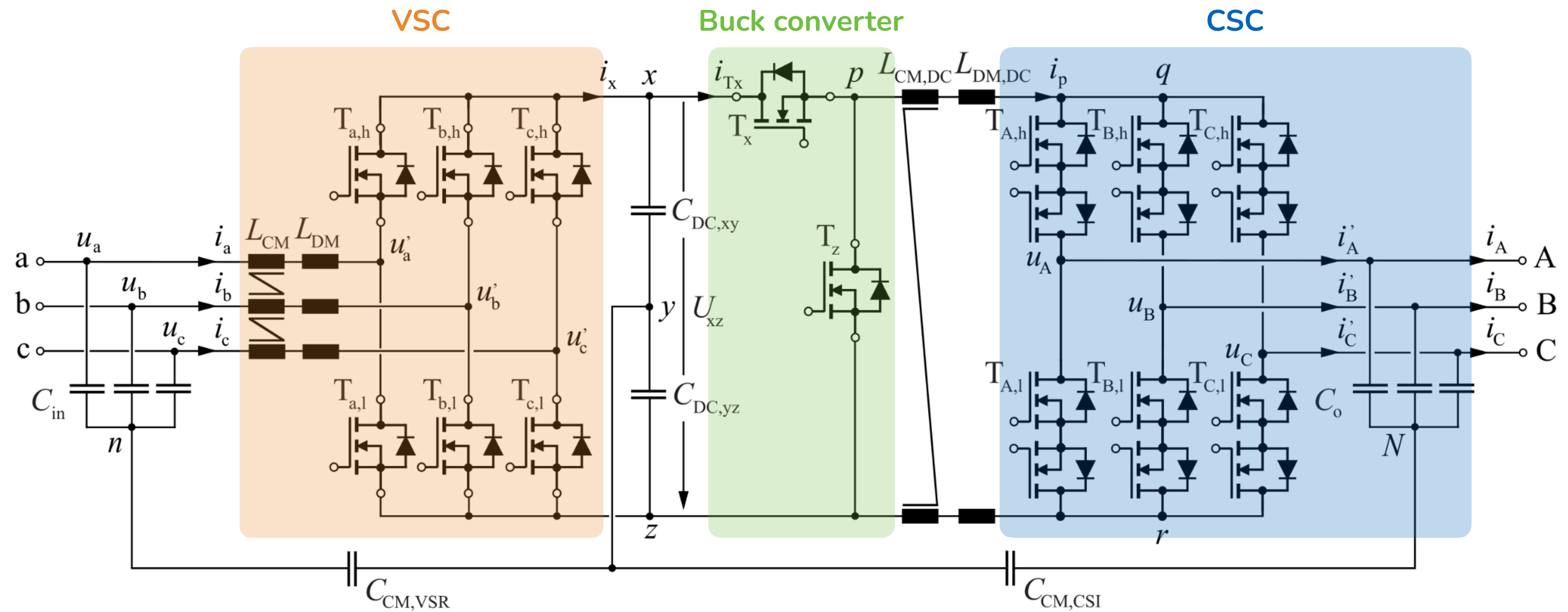


New concept 1 - VSC+BC+CSC



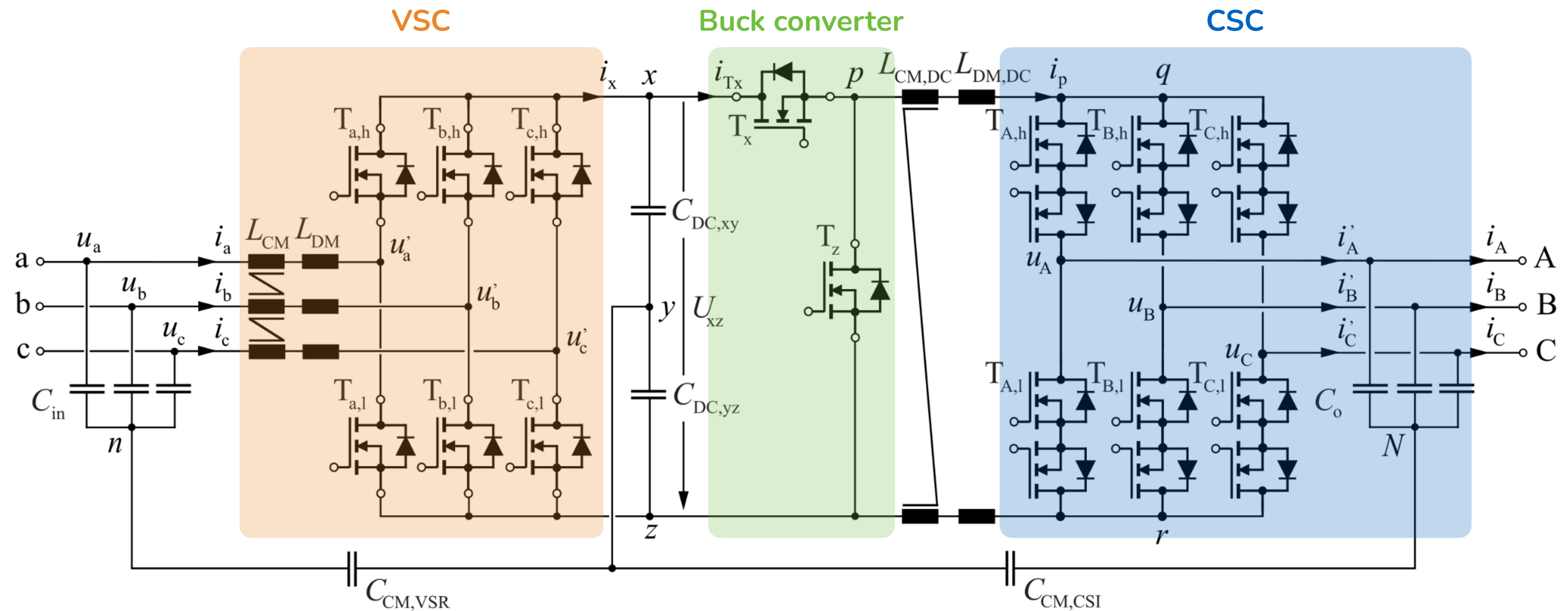
# VSC + Bidirectional buck converter + CSC

# Topology



# VSC + Bidirectional buck converter + CSC

Topology



The intermediate DC-DC converter enables synergies among all converter stages !



# Modulation principle

Grid side voltages,

$$u_j = \hat{U}_m \sin(\omega_m t - \theta_j), \text{ with } j = a, b, c$$

$$\theta_a = 0, \theta_b = \frac{2\pi}{3}, \theta_c = -\frac{2\pi}{3},$$

Motor side currents,

$$i_j = \hat{I}_{o,pk} \sin(\omega_o t - \phi - \theta_j), \text{ with } j = A, B, C$$

$$\theta_A = 0, \theta_B = \frac{2\pi}{3}, \theta_C = -\frac{2\pi}{3},$$

Organizing the voltages according to their amplitudes:

$$u_{\max} = \max(u_a, u_b, u_c)$$

$$u_{\min} = \min(u_a, u_b, u_c)$$

$$u_{\text{mid}} = -(u_{\text{VSR,max}} + u_{\text{VSR,min}})$$

For 1/3 modulation, the rectifier DC-link voltage has to follow,

$$U_{xz} = U_{13} = u_{\max} - u_{\min}$$

For the CSS, we want to operate it with just two phase legs switching at any given switching period. Thus, the CSC DC-link current has to follow

$$i_p = i_{23} = \max(|i_A|, |i_B|, |i_C|)$$

# Modulation principle

Rewriting,  $U_{xz} = U_{13} = u_{\max} - u_{\min}$  and  $i_p = i_{23} = \max(|i_A|, |i_B|, |i_C|)$

Now, we need modulation/reference signals that would generate proper voltages and currents in both AC ports.  
Thus, the modulation signals should be,

**VSC**

$$\begin{aligned} d_{\max} &= 2U_{xz}^{-1}(u_{\max} + u_{yn}) \\ d_{\text{mid}} &= 2U_{xz}^{-1}(u_{\text{mid}} + u_{yn}) \\ d_{\min} &= 2U_{xz}^{-1}(u_{\min} + u_{yn}) \end{aligned}$$

with,

$$u_{yn} = -(u_{\max} + u_{\min})/2.$$

**CSC** (for  $-\pi/6 \leq \theta \leq \pi/6$ )

$$\begin{aligned} d_{[\text{AC}]} &= 0.5 m_{\text{CSI}} \cos \theta + 0.5\sqrt{3} m_{\text{CSI}} \sin \theta \\ d_{[\text{AB}]} &= 0.5 m_{\text{CSI}} \cos \theta - 0.5\sqrt{3} m_{\text{CSI}} \sin \theta \\ d_{[\text{zero}]} &= 1 - d_{[\text{AC}]} - d_{[\text{AB}]} = 0 \end{aligned}$$

+



# Modulation principle

Rewriting,  $U_{xz} = U_{13} = u_{\max} - u_{\min}$  and  $i_p = i_{23} = \max(|i_A|, |i_B|, |i_C|)$

Now, we need modulation/reference signals that would generate proper voltages and currents in both AC ports.

Thus, the modulation signals should be,

**VSC**

$$\begin{aligned} d_{\max} &= 2U_{xz}^{-1}(u_{\max} + u_{yn}) \\ d_{\text{mid}} &= 2U_{xz}^{-1}(u_{\text{mid}} + u_{yn}) \\ d_{\min} &= 2U_{xz}^{-1}(u_{\min} + u_{yn}) \end{aligned}$$

with,

$$u_{yn} = -(u_{\max} + u_{\min})/2.$$

**CSC** (for  $-\pi/6 \leq \theta \leq \pi/6$ )

$$\begin{aligned} d_{[\text{AC}]} &= 0.5 m_{\text{CSI}} \cos \theta + 0.5\sqrt{3} m_{\text{CSI}} \sin \theta \\ d_{[\text{AB}]} &= 0.5 m_{\text{CSI}} \cos \theta - 0.5\sqrt{3} m_{\text{CSI}} \sin \theta \\ d_{[\text{zero}]} &= 1 - d_{[\text{AC}]} - d_{[\text{AB}]} = 0 \end{aligned}$$

The DC-DC converter must adapt its **voltage-port** current and **current-port** voltage so that power is constant.

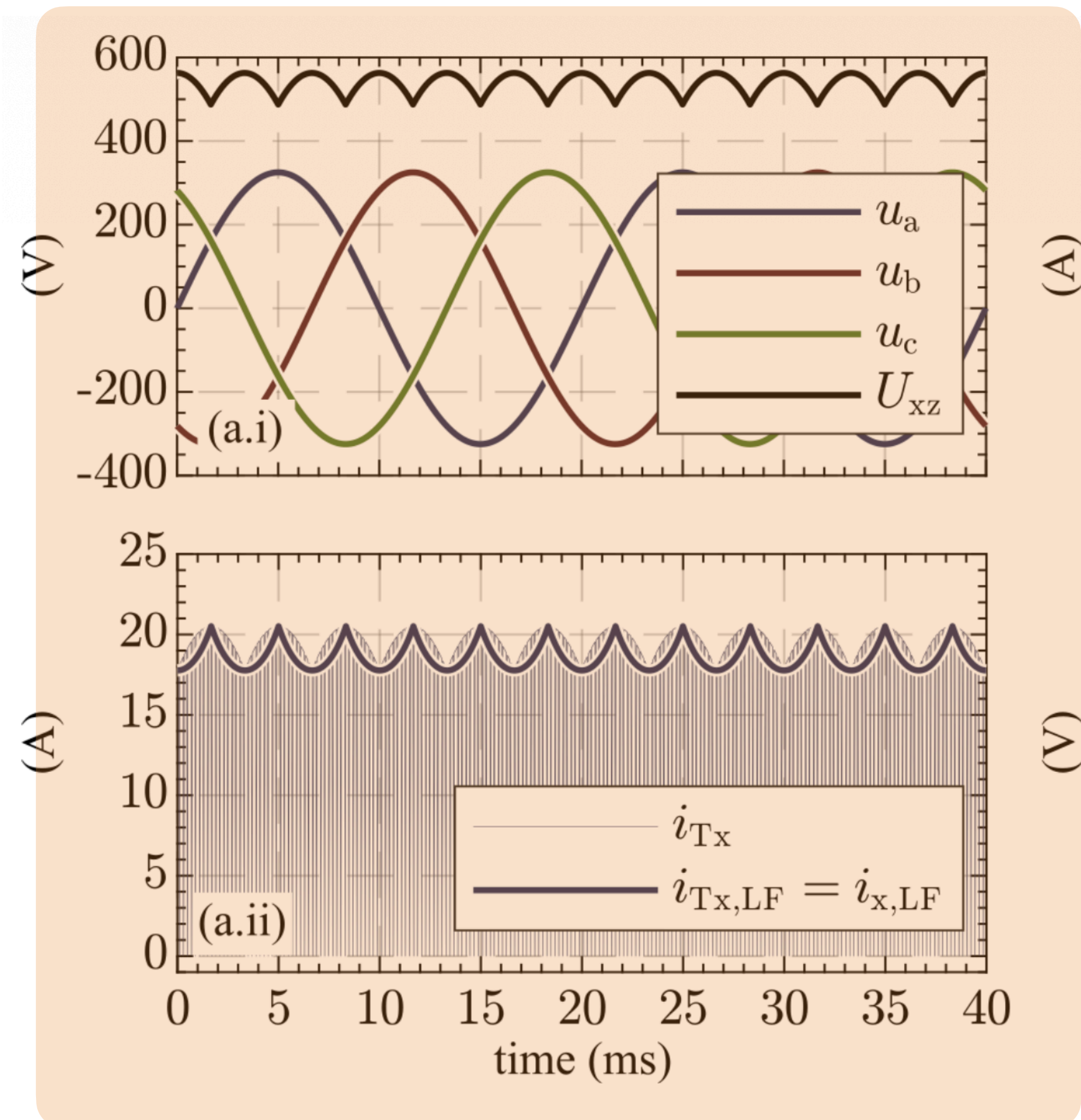
Thus,

$$d_{\text{DC/DC}} = \frac{u_{\text{qr,LF}}}{U_{xz}} = \frac{i_{\text{x,LF}}}{i_p} \quad \text{Buck converter}$$

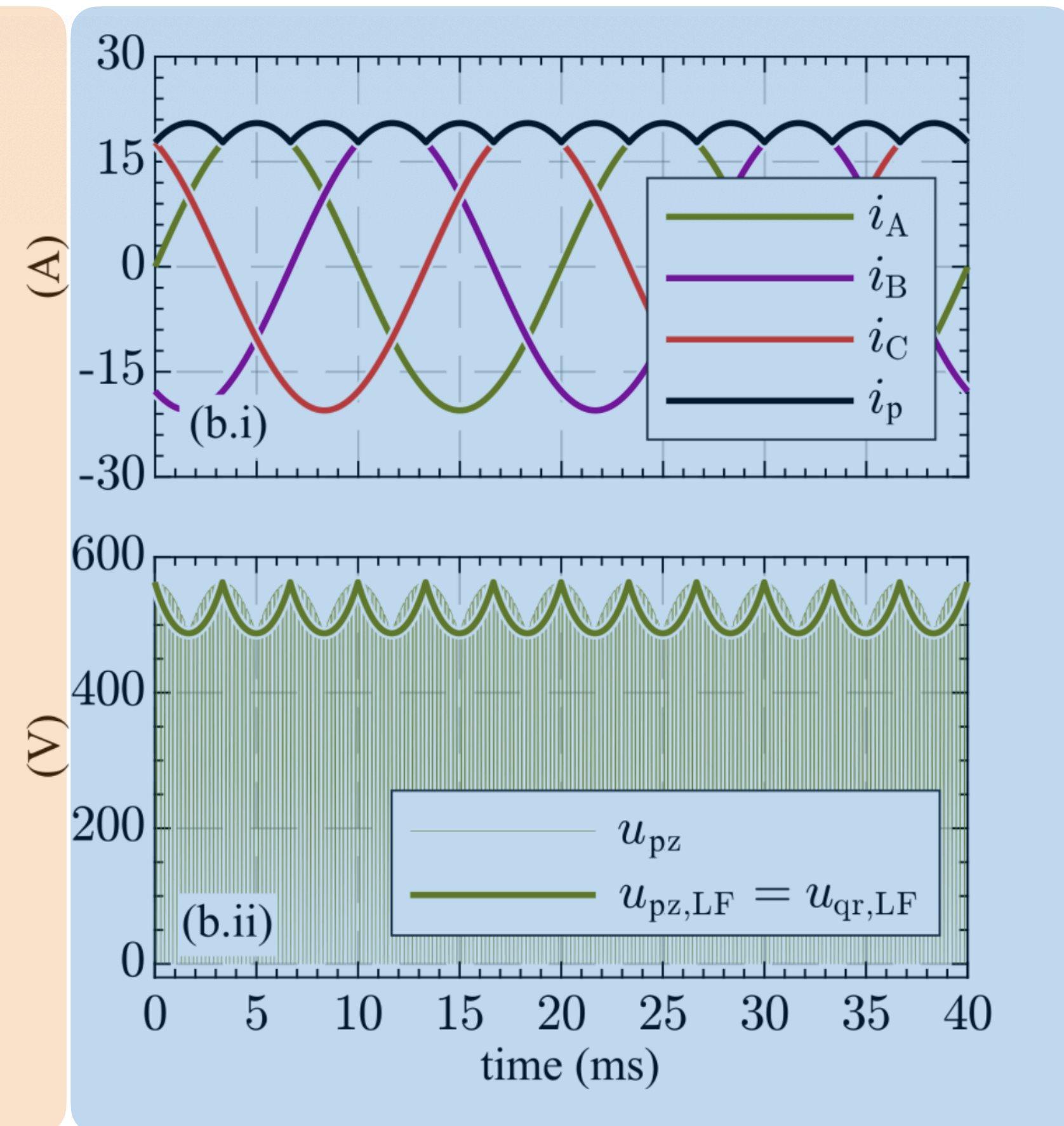
# VSC+BC+CSC operation principle

Main waveforms

VSC



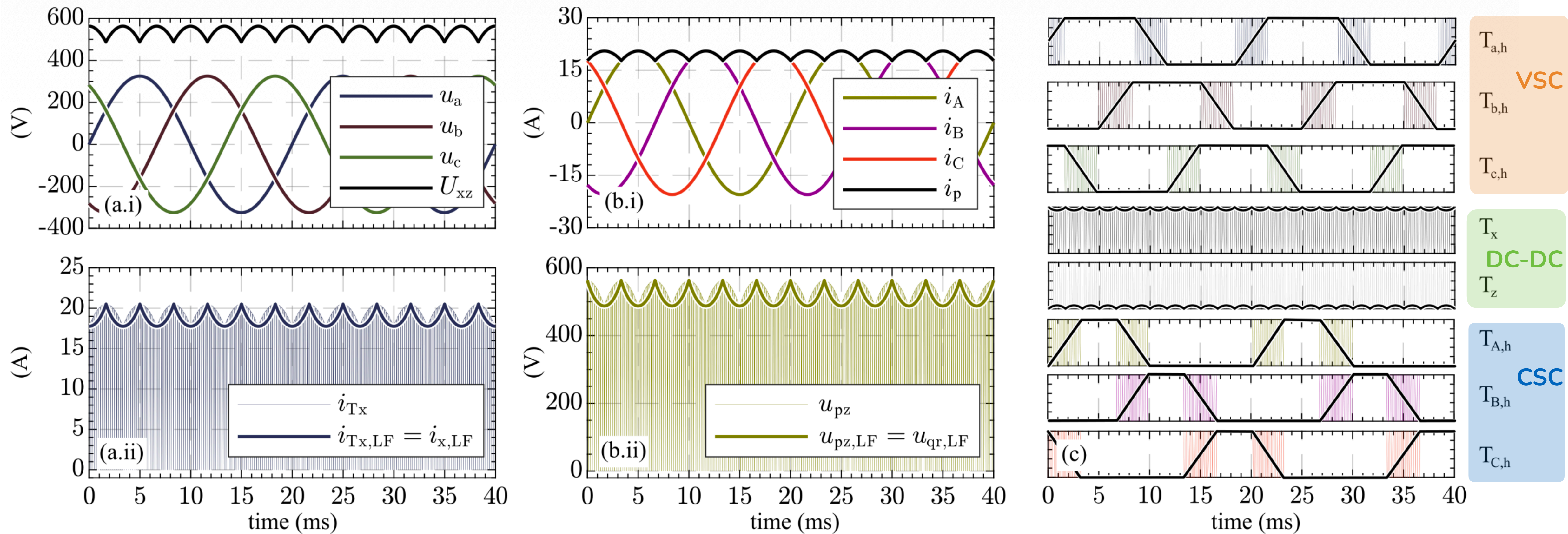
CSC





# VSC+BC+CSC operation principle

## Main waveforms



# Operation limits

Power conservation should be observed:  $P = U_{xz} i_{x,LF} = u_{qr,LF} i_p$

The other physical restrictions are:  $U_{xz} \geq u_{qr,LF}$  ,  $i_{x,LF} \leq i_p$  ,  $d_{DC/DC} \leq 1$

Thus, the following relation must hold  $\frac{P}{U_{xz} i_p} = \frac{P}{U_{13} i_{23}} = \frac{(3/2) \hat{U}_{o,pk} \hat{I}_{o,pk} PF}{U_{13} i_{23}} \leq 1$    $\hat{U}_{o,pk,max} = \frac{\sqrt{3} \hat{U}_{m,pk}}{2 PF}$   
Maximum output voltage



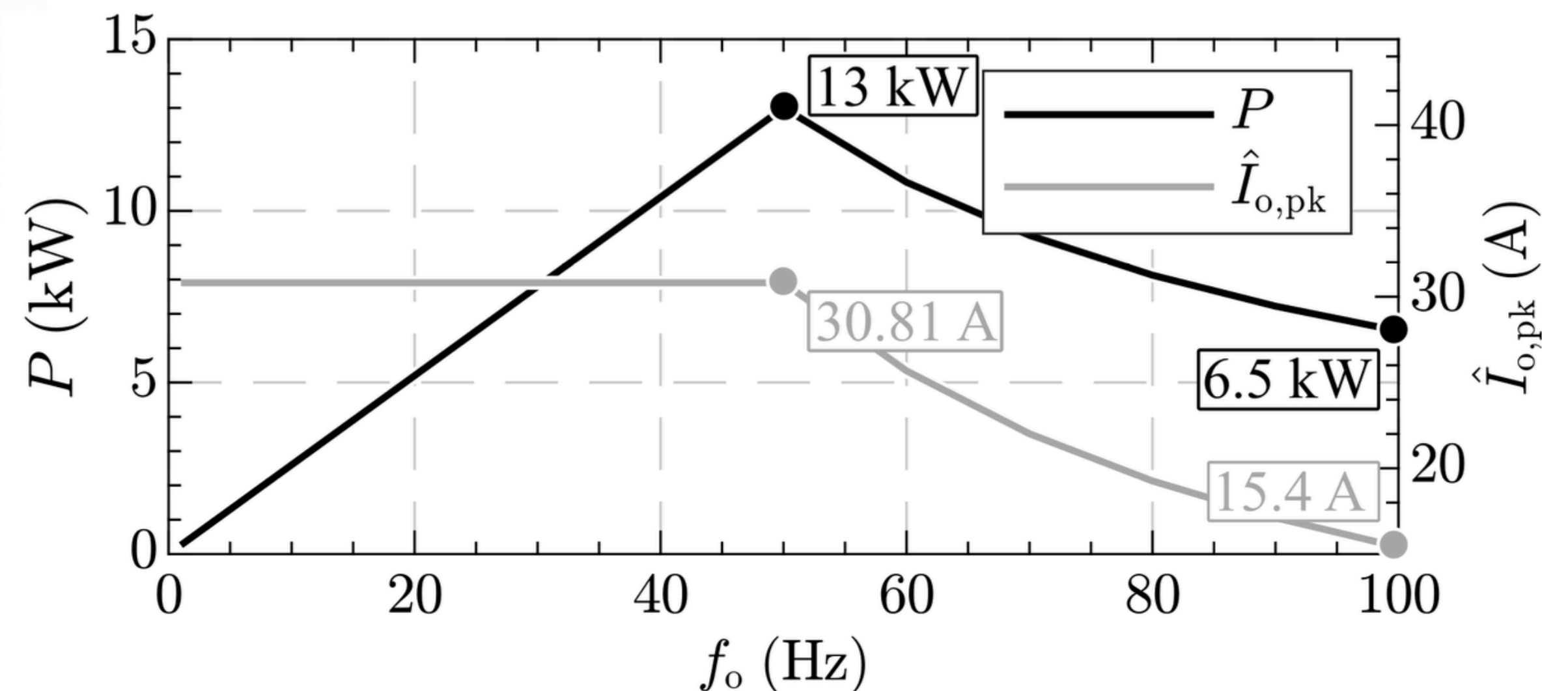
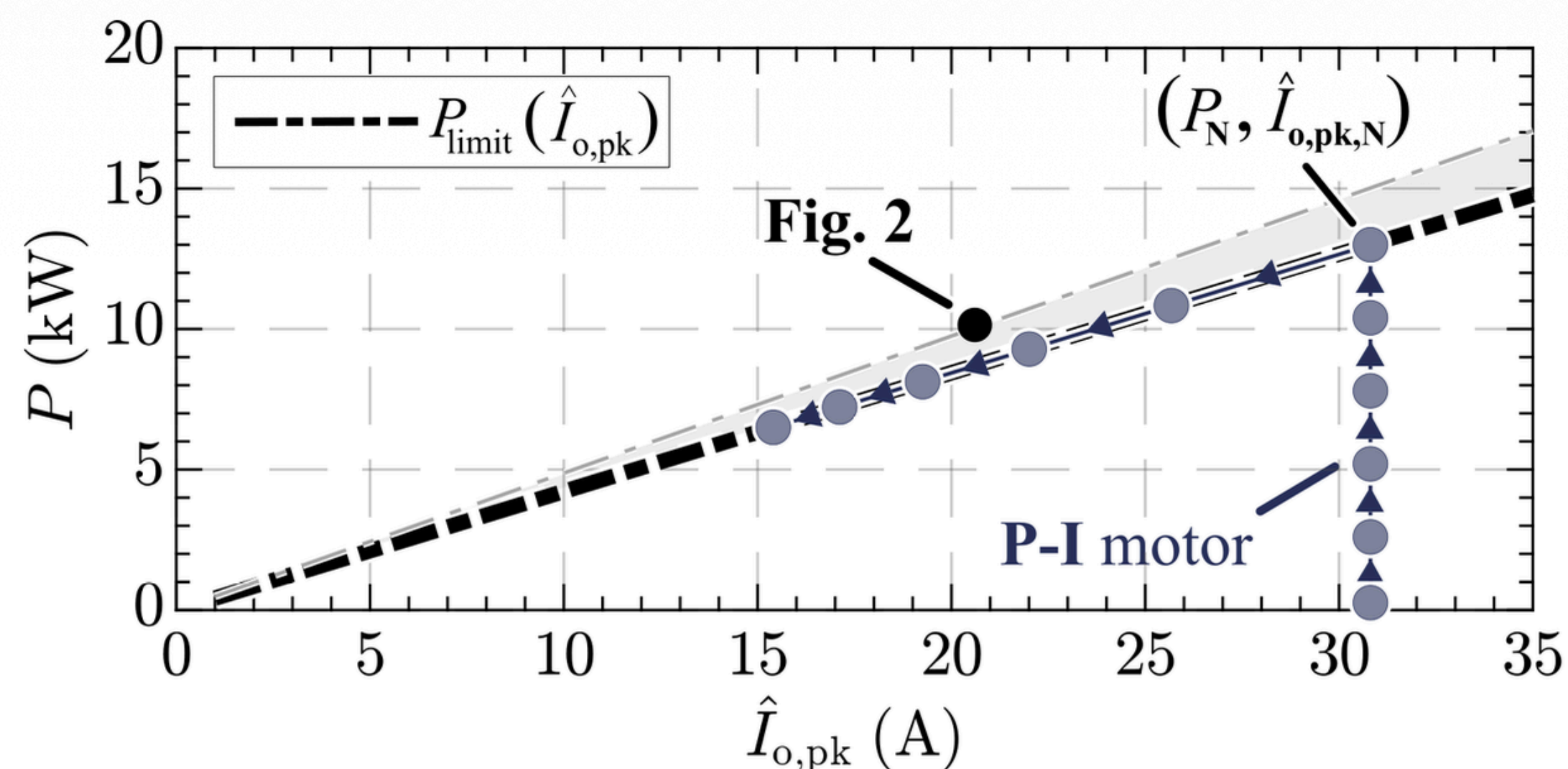
# Operation limits

Power conservation should be observed:  $P = U_{xz} i_{x,LF} = u_{qr,LF} i_p$

The other physical restrictions are:  $U_{xz} \geq u_{qr,LF}$  ,  $i_{x,LF} \leq i_p$  ,  $d_{DC/DC} \leq 1$

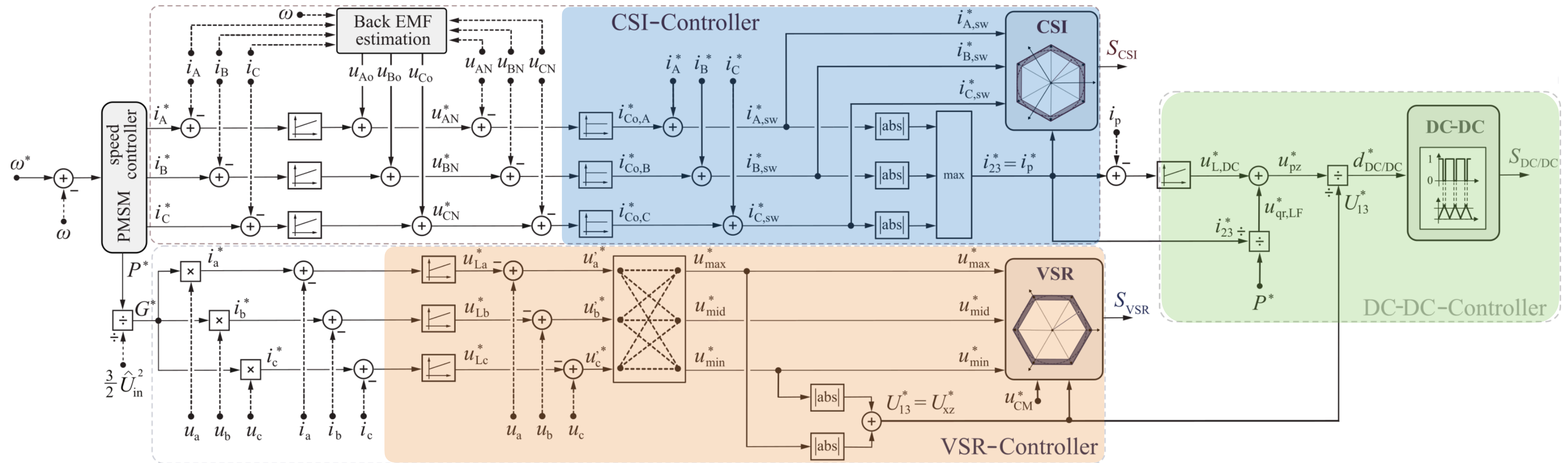
Thus, the following relation must hold  $\frac{P}{U_{xz} i_p} = \frac{P}{U_{13} i_{23}} = \frac{(3/2) \hat{U}_{o,pk} \hat{I}_{o,pk} PF}{U_{13} i_{23}} \leq 1 \Rightarrow \hat{U}_{o,pk,max} = \frac{\sqrt{3} \hat{U}_{m,pk}}{2 PF}$

Maximum output voltage



Gain limitation is not a problem for this kind of motor drive operation!

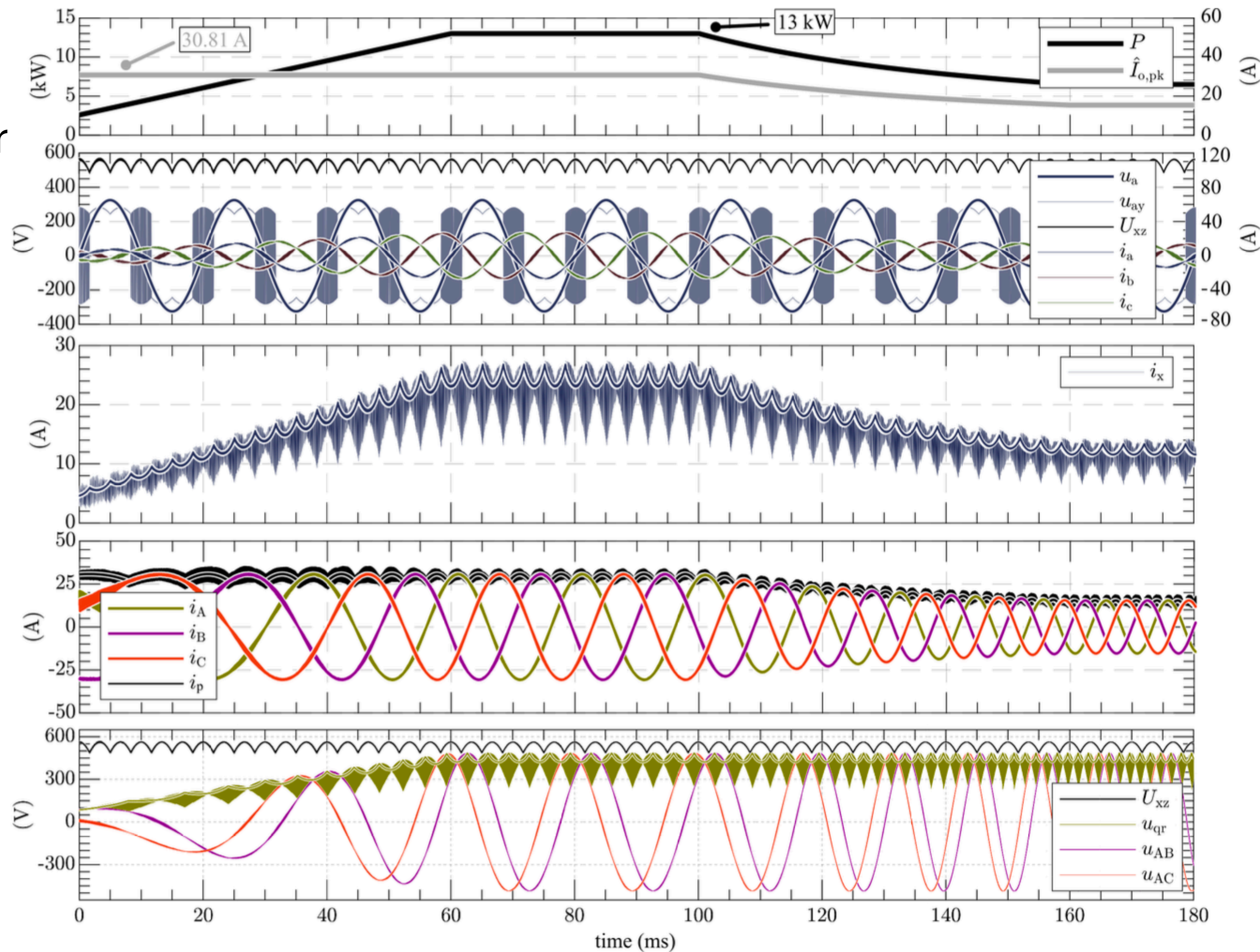
# Control principle





# Accelerating a motor

| Description                  | Value       |
|------------------------------|-------------|
| Nominal power                | 13 kW       |
| Nominal peak current         | 30.81 A     |
| Nominal electrical frequency | 50 Hz       |
| Electrical frequency range   | [0, 100] Hz |
| Nominal RMS phase voltage    | 200 V       |
| Nominal Power Factor         | 1.0         |





# Comparison with VSC-B2B

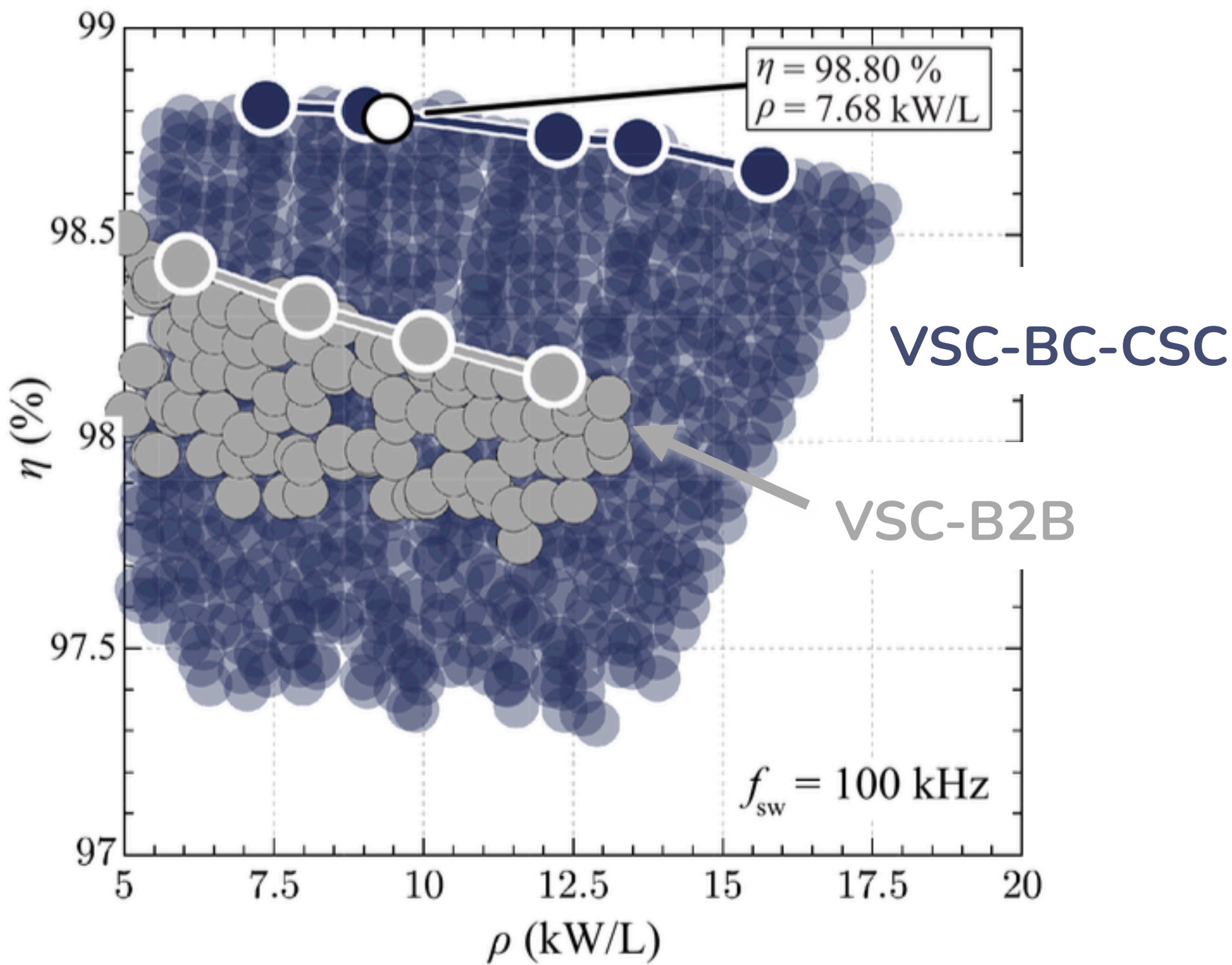
Load specifications:

| Description                  | Value       |
|------------------------------|-------------|
| Nominal power                | 13 kW       |
| Nominal peak current         | 30.81 A     |
| Nominal electrical frequency | 50 Hz       |
| Electrical frequency range   | [0, 100] Hz |
| Nominal RMS phase voltage    | 200 V       |
| Nominal Power Factor         | 1.0         |

Chosen design parameters:

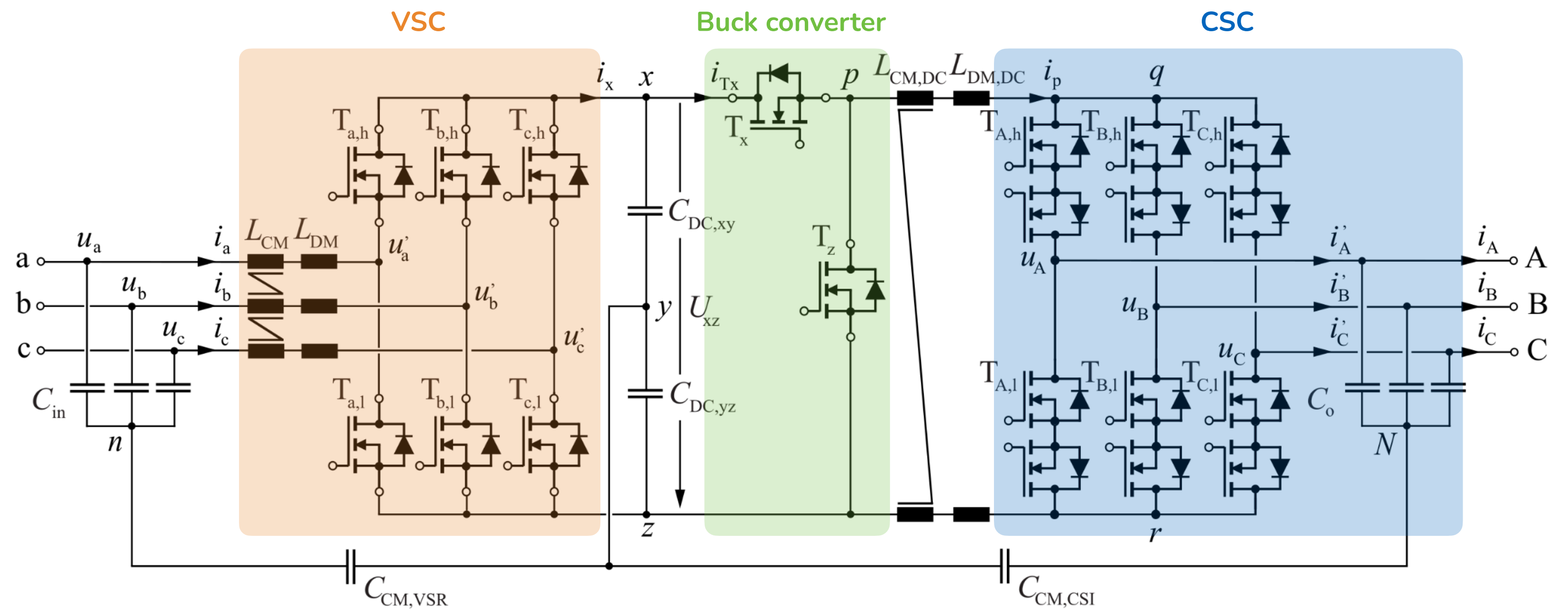
| Description    | Value                                              |
|----------------|----------------------------------------------------|
| $f_{sw}$       | Switching freq. 100 kHz                            |
| $T_{VSR}$      | VSR semiconductor SCT012W90G3AG (900 V, 12 mΩ)     |
| $T_{DC/DC}$    | DC/DC semiconductor C3M0030090K (900 V, 30 mΩ)     |
| $T_{CSI}$      | CSI semiconductor C3M0010090K (900 V, 10 mΩ)       |
| $L_{DM}$       | VSR DM inductor 176 μH (2×N87 E65/32/27, 14 turns) |
| $L_{CM}$       | VSR CM inductor 1.2 mH (VAC 40/25/15, 3×8 turns)   |
| $L_{DM,DC}$    | DC DM inductor 75.7 μH (2×N87 E30/25/16, 12 turns) |
| $L_{CM,DC}$    | DC CM inductor 1.5 mH (VAC 40/25/15, 2×9 turns)    |
| $C_{in}$       | VSR DM capacitor 2.0 μF                            |
| $C_{DC,xy-yz}$ | DC-link capacitor 9.0 μF                           |
| $C_o$          | CSI DM capacitor 5.3 μF                            |
| $C_{CM,VSR}$   | VSR CM capacitor 63 nF                             |
| $C_{CM,CSI}$   | CSI CM capacitor 76 nF                             |
| $\rho$         | Volumetric Power Density 7.68 kW/dm <sup>3</sup>   |
| $\eta$         | Efficiency 98.80 %                                 |

Efficiency vs. power density comparison:





# Critical evaluation of the VSC-BC-CSC concept

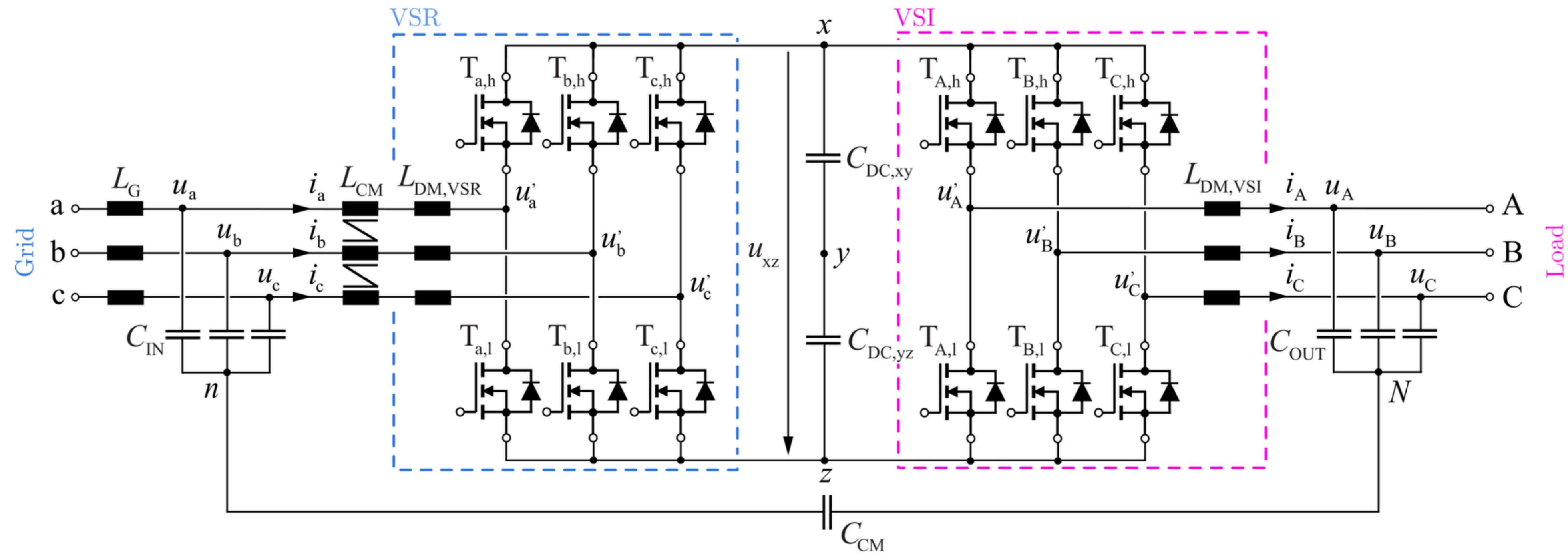


- ✓ Motor is fed with near sinusoidal voltages, switching losses are low, and conduction losses are not much altered
- ✗ Extra components when compared with VSC-B2B, CSC requires many gate drivers, **did not achieve 99%**

# New concept 2 - Three-leg operation of VSC-B2B

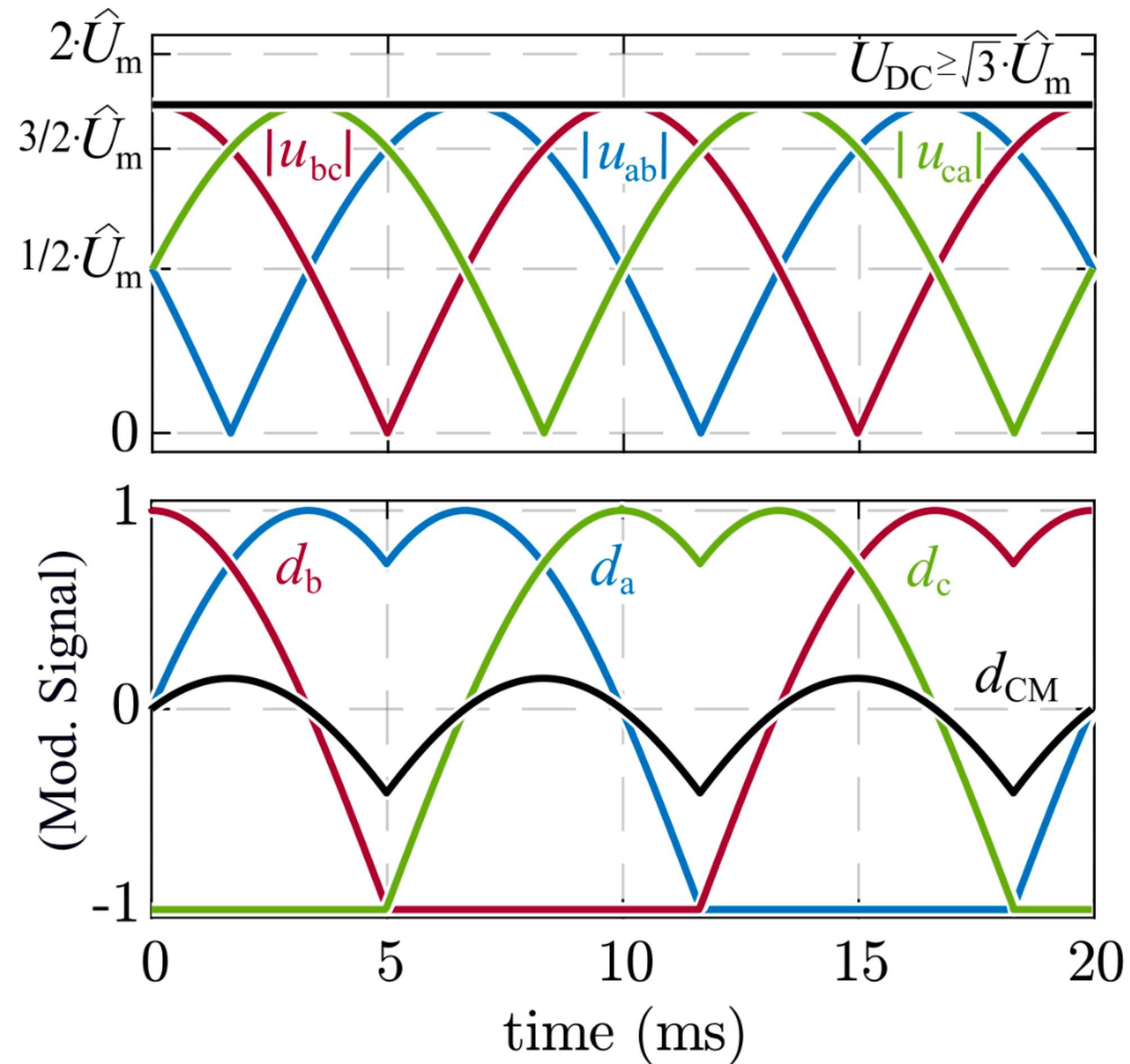


# The voltage source back-to-back AC-(DC)-AC converter



- ✓ Industry standard for bidirectional AC-AC power conversion.
- ✗ Switching losses limit the achievable maximum efficiency and, therefore, the compactness of the filters.

# Principles of discontinuous modulation for a VSC

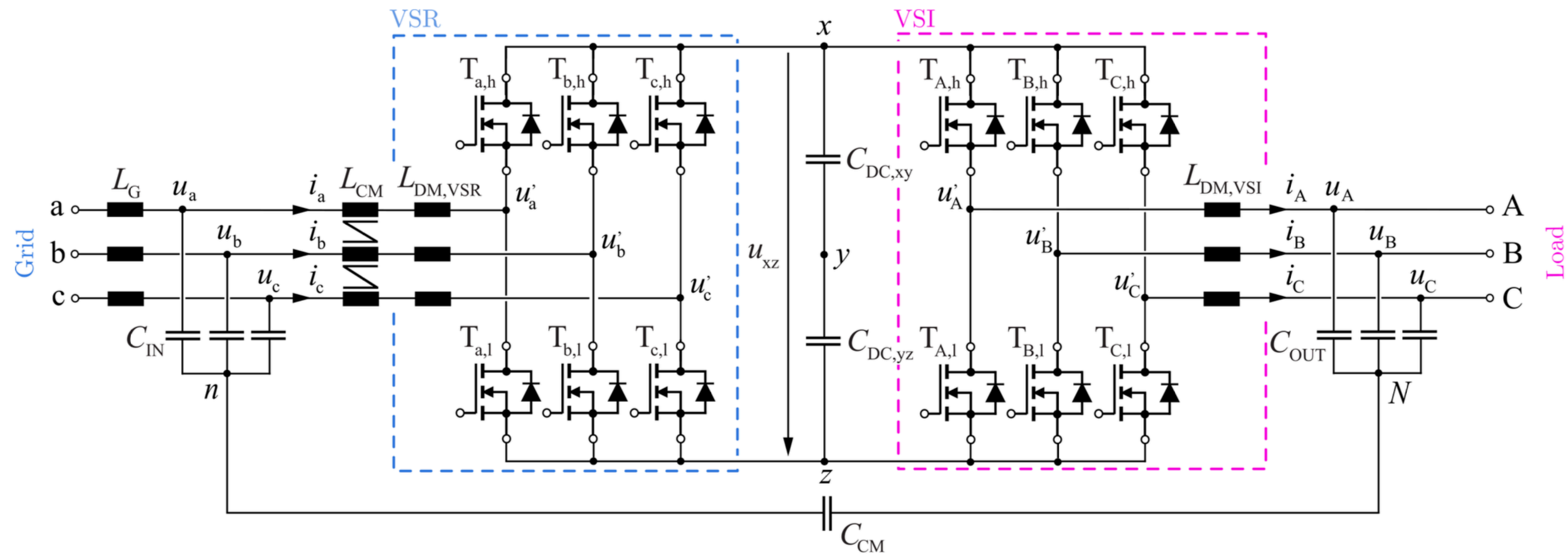


Line voltages define the minimum DC-link voltage

Modulation signals must guarantee that the output voltages are as expected, i.e.,  $v_{out,j} = (d_j - d_{CM}) U_{DC}$  with  $d_j \in [0,1]$



# The back-to-back AC-(DC)-AC converter

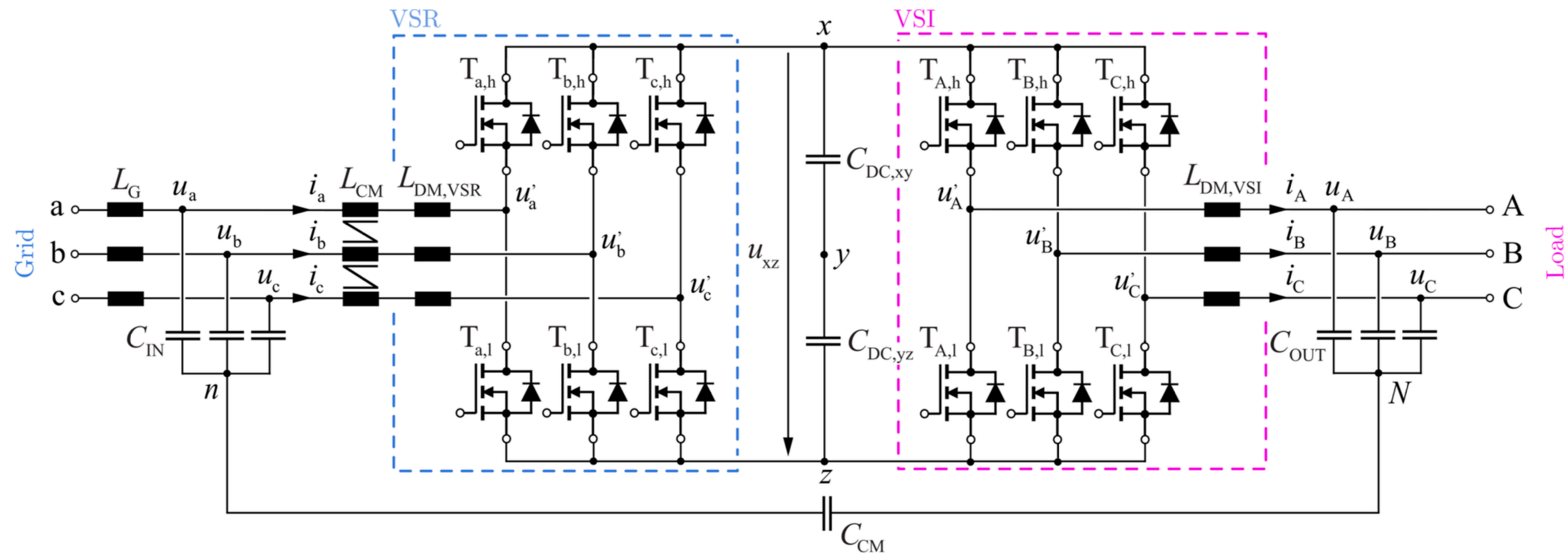


Industry standard for bidirectional AC-AC power conversion.



We, power electronics engineers, treat it like two VSC converters, i.e., use the DC-link as a decoupling network.

# The back-to-back AC-(DC)-AC converter



Let's try to see it from a different angle!



Industry standard for bidirectional AC-AC power conversion.



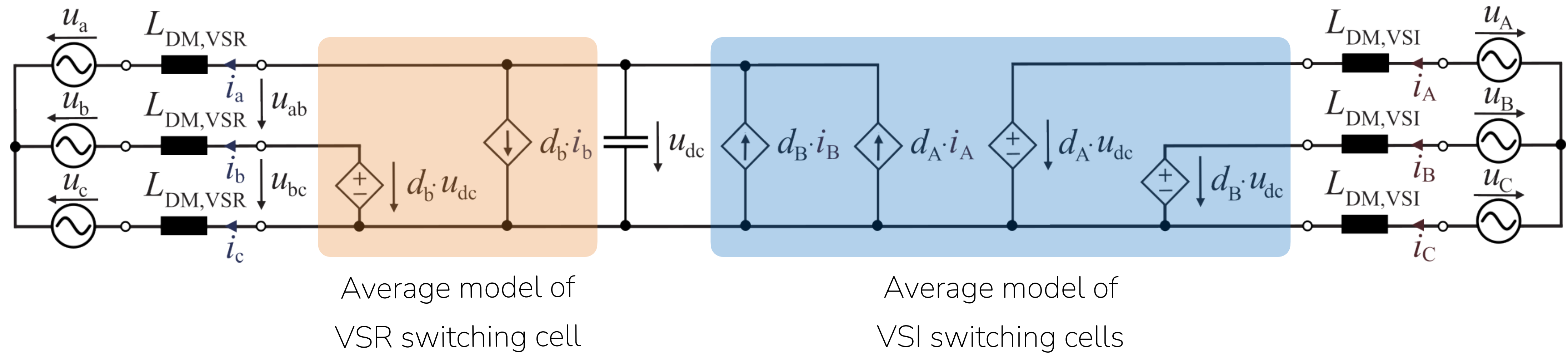
We, power electronics engineers, treat it like two VSC converters, i.e., use the DC-link as a decoupling network.



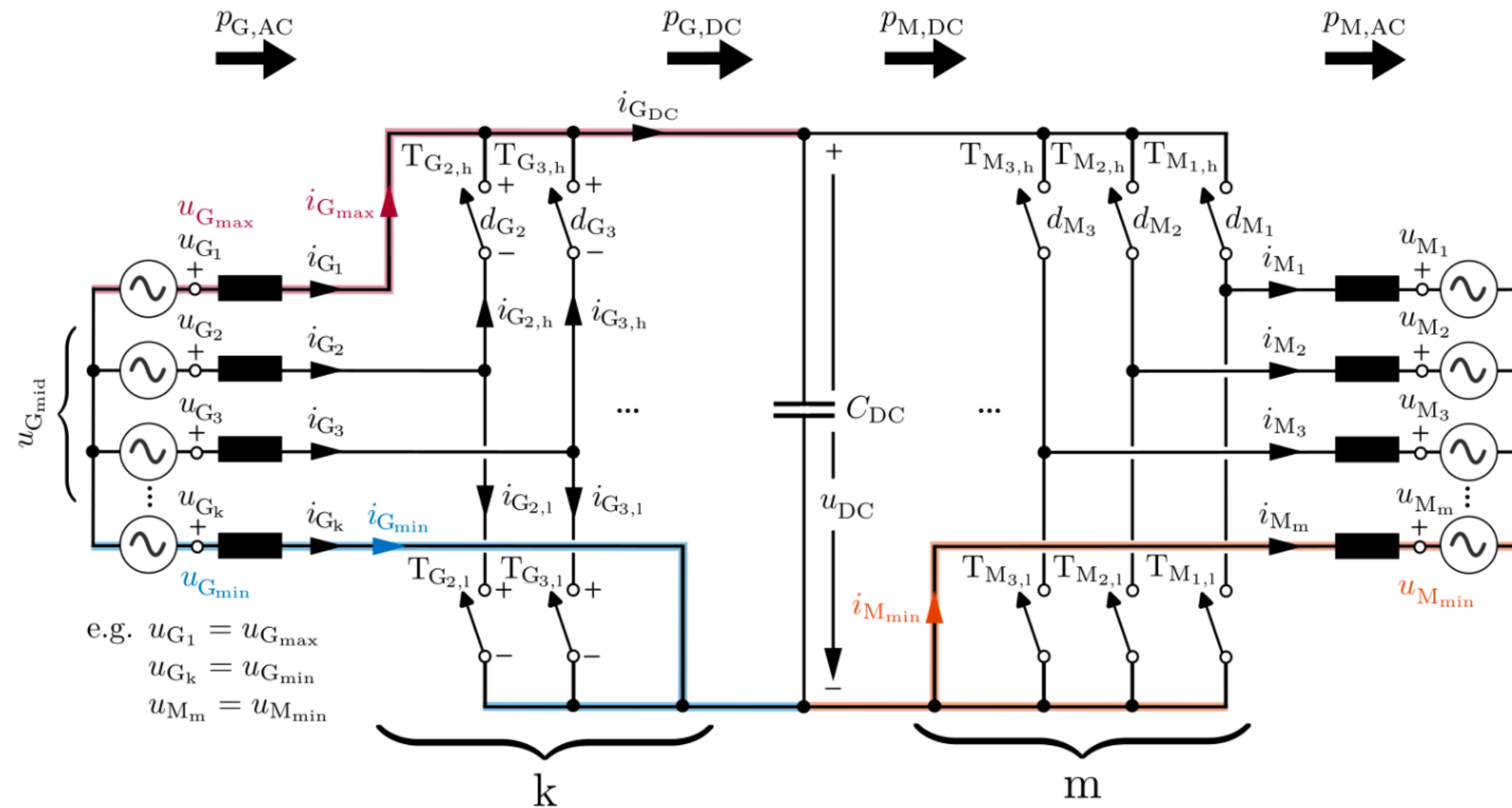
# Basic principle of operating the B2B with just three legs at a time

We start with the idea of using only three legs...

To simplify things, let's consider the **average model of using only three legs**,



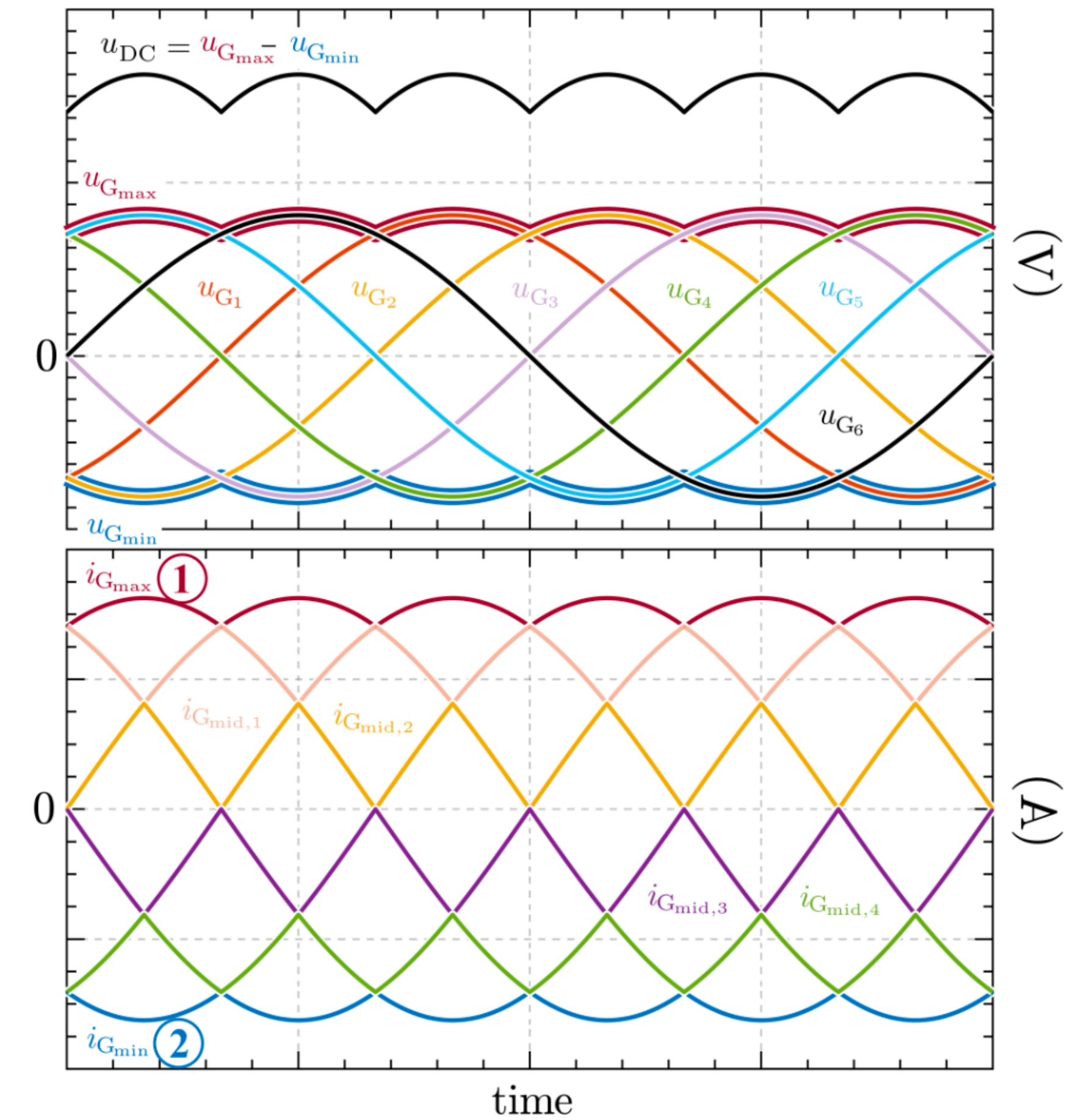
# Generalization to any number of phases



$$d_{G_{2...k-1}} \xRightarrow{\text{controlled}} i_{G_{2...k-1}} \Rightarrow \begin{cases} i_{G_1} = i_{G_{\max}} = \frac{P}{u_{G_{\max}} - u_{G_{\min}}} - \sum_{l=2}^{k-1} \frac{i_{G_l} \cdot (u_{G_l} - u_{G_{\min}})}{u_{G_{\max}} - u_{G_{\min}}} & \textcircled{1} \\ i_{G_k} = i_{G_{\min}} = -\frac{P}{u_{G_{\max}} - u_{G_{\min}}} - \sum_{l=2}^{k-1} \frac{i_{G_l} \cdot (u_{G_{\max}} - u_{G_l})}{u_{G_{\max}} - u_{G_{\min}}} & \textcircled{2} \end{cases}$$

e.g.  $u_{G_1} = u_{G_{\max}}$   
 $u_{G_k} = u_{G_{\min}}$   
 $u_{M_m} = u_{M_{\min}}$

Six-Phase-Rectifier example:





# Modulation principle

Grid side voltages,

$$u_j = \hat{U}_m \sin(\omega_m t - \theta_j), \text{ with } j = a, b, c$$

$$\theta_a = 0, \theta_b = \frac{2\pi}{3}, \theta_c = -\frac{2\pi}{3},$$

Motor side voltages,

$$u_k = \hat{U}_o \sin(\omega_o t - \phi - \theta_k), \text{ with } k = A, B, C$$

$$\theta_A = 0, \theta_B = \frac{2\pi}{3}, \theta_C = -\frac{2\pi}{3},$$

Organizing the voltages according to their amplitudes:

$$u_{VSR,max} = \max(u_a, u_b, u_c)$$

$$u_{VSR,min} = \min(u_a, u_b, u_c)$$

$$u_{VSR,mid} = -(u_{VSR,max} + u_{VSR,min})$$

$$u_{VSI,max} = \max(u_A, u_B, u_C)$$

$$u_{VSI,min} = \min(u_A, u_B, u_C)$$

$$u_{VSI,mid} = -(u_{VSI,max} + u_{VSI,min})$$

# Modulation principle

Grid side voltages,

$$u_j = \hat{U}_m \sin(\omega_m t - \theta_j), \text{ with } j = a, b, c$$

$$\theta_a = 0, \theta_b = \frac{2\pi}{3}, \theta_c = -\frac{2\pi}{3},$$

Motor side voltages,

$$u_k = \hat{U}_o \sin(\omega_o t - \phi - \theta_k), \text{ with } k = A, B, C$$

$$\theta_A = 0, \theta_B = \frac{2\pi}{3}, \theta_C = -\frac{2\pi}{3},$$

The largest line-to-line voltages are defined as,

$$u_{VSR,13} = u_{VSR,max} - u_{VSR,min}$$

$$u_{VSI,13} = u_{VSI,max} - u_{VSI,min}$$

Organizing the voltages according to their amplitudes:

$$u_{VSR,max} = \max(u_a, u_b, u_c)$$

$$u_{VSR,min} = \min(u_a, u_b, u_c)$$

$$u_{VSR,mid} = -(u_{VSR,max} + u_{VSR,min})$$

$$u_{VSI,max} = \max(u_A, u_B, u_C)$$

$$u_{VSI,min} = \min(u_A, u_B, u_C)$$

$$u_{VSI,mid} = -(u_{VSI,max} + u_{VSI,min})$$



# Modulation principle

Grid side voltages,

$$u_j = \hat{U}_m \sin(\omega_m t - \theta_j), \text{ with } j = a, b, c$$

$$\theta_a = 0, \theta_b = \frac{2\pi}{3}, \theta_c = -\frac{2\pi}{3},$$

Motor side voltages,

$$u_k = \hat{U}_o \sin(\omega_o t - \phi - \theta_k), \text{ with } k = A, B, C$$

$$\theta_A = 0, \theta_B = \frac{2\pi}{3}, \theta_C = -\frac{2\pi}{3},$$

Organizing the voltages according to their amplitudes:

$$u_{VSR,max} = \max(u_a, u_b, u_c)$$

$$u_{VSR,min} = \min(u_a, u_b, u_c)$$

$$u_{VSR,mid} = -(u_{VSR,max} + u_{VSR,min})$$

$$u_{VSI,max} = \max(u_A, u_B, u_C)$$

$$u_{VSI,min} = \min(u_A, u_B, u_C)$$

$$u_{VSI,mid} = -(u_{VSI,max} + u_{VSI,min})$$

The largest line-to-line voltages are defined as,

$$u_{VSR,13} = u_{VSR,max} - u_{VSR,min}$$

$$u_{VSI,13} = u_{VSI,max} - u_{VSI,min}$$

A minimum DC-link voltage  $v_{xy}$  will lead to reduced switching losses. We know that  $v_{xy}$  needs to be larger than the maximum overall system voltage, i.e.,

$$u_{xz} = \max(u_{VSR,13}, u_{VSI,13})$$

# Modulation principle

Rewriting,  $u_{xz} = \max(u_{VSR,13}, u_{VSI,13})$

Now, we need modulation/reference voltage signals that would generate proper voltages in both sides. We can assume that the voltage drops across the inverter and rectifier inductances will be low, i.e.,

$$\Delta u_{LDM,j-k} = L_{DM,j-k} \frac{di_{LDM,j-k}}{dt} \approx 0$$

Thus, the modulation signals should be,  $d_{VSR-I,max} = (u_{VSR-I,max}) / (u_{xz}/2) + d_{VSR-I,CM}$

$$d_{VSR-I,mid} = (u_{VSR-I,mid}) / (u_{xz}/2) + d_{VSR-I,CM}$$

$$d_{VSR-I,min} = (u_{VSR-I,min}) / (u_{xz}/2) + d_{VSR-I,CM}$$

+



# Modulation principle

Rewriting,  $u_{xz} = \max(u_{VSR,13}, u_{VSI,13})$

Now, we need modulation/reference voltage signals that would generate proper voltages in both sides. We can assume that the voltage drops across the inverter and rectifier inductances will be low, i.e.,

$$\Delta u_{LDM,j-k} = L_{DM,j-k} \frac{di_{LDM,j-k}}{dt} \approx 0$$

Thus, the modulation signals should be,

$$d_{VSR-I,max} = (u_{VSR-I,max}) / (u_{xz}/2) + d_{VSR-I,CM}$$

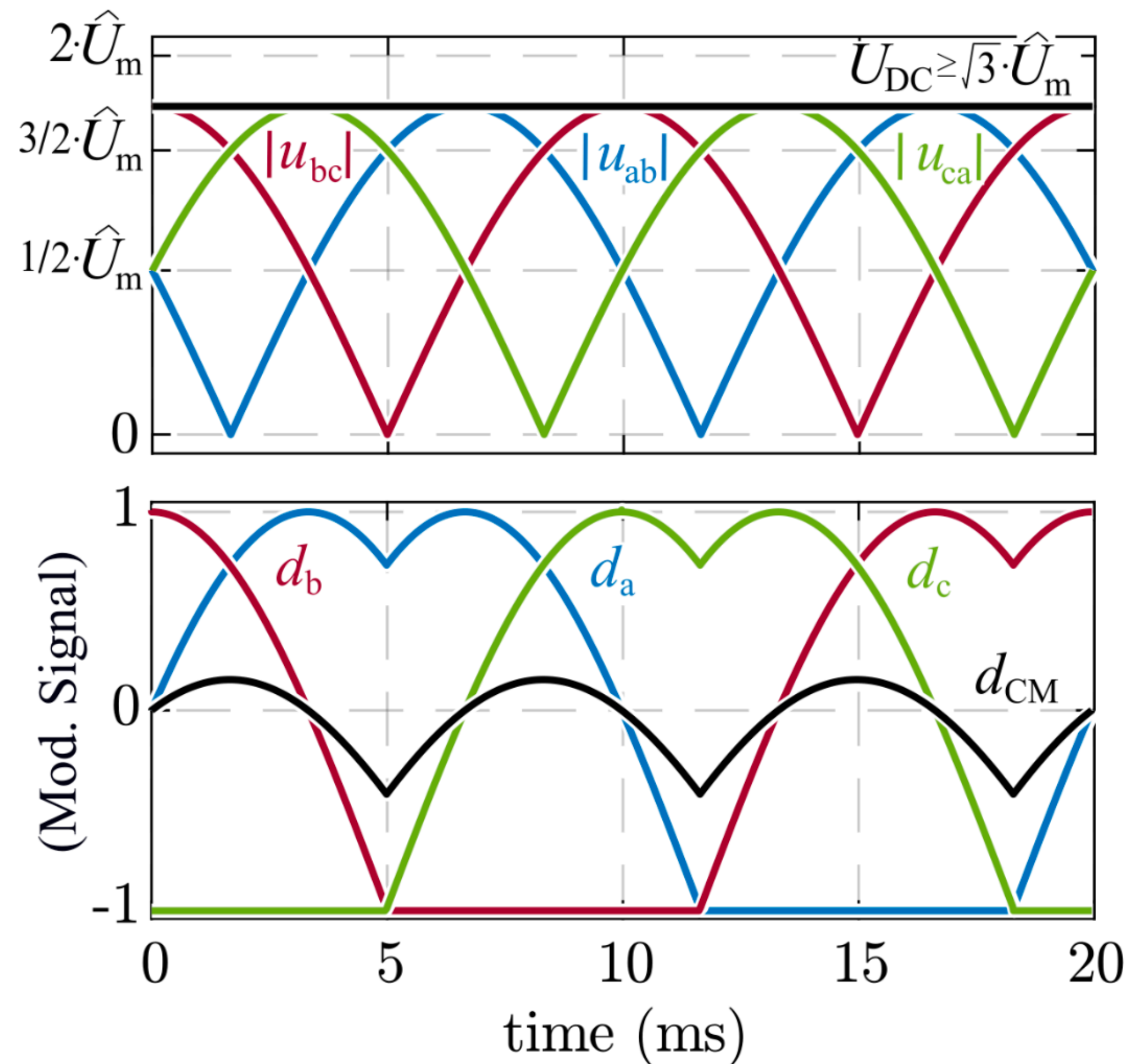
$$d_{VSR-I,mid} = (u_{VSR-I,mid}) / (u_{xz}/2) + d_{VSR-I,CM}$$

$$d_{VSR-I,min} = (u_{VSR-I,min}) / (u_{xz}/2) + d_{VSR-I,CM}$$

A smooth transition between 1/3 and 2/3 modulation modes can be achieved by employing the 0-axis (common mode) signal,

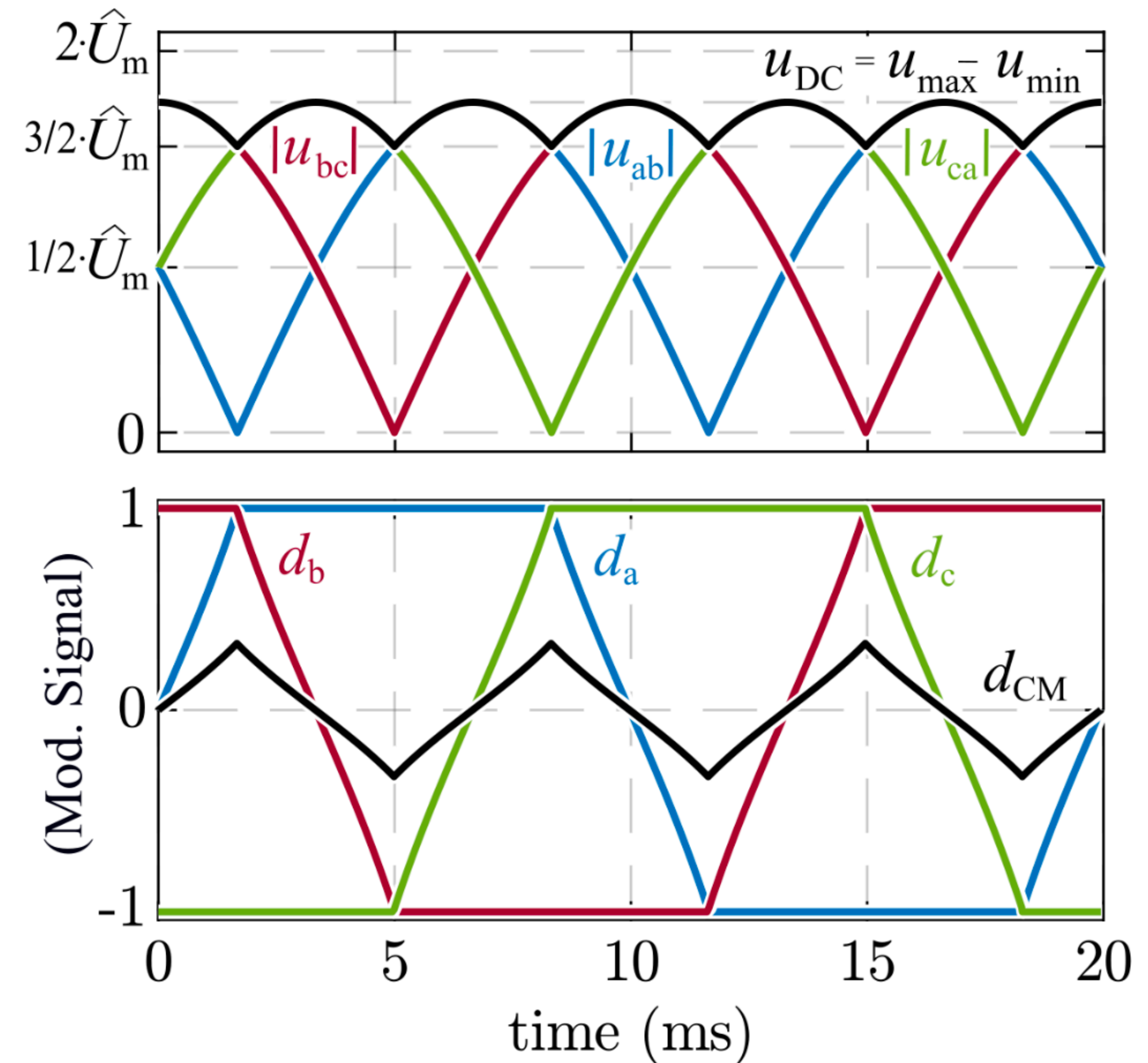
$$d_{VSR-I,CM} = \frac{u_{VSR-I,min}}{u_{xz}/2} + 1.$$

# Principles of discontinuous modulation for a VSC



Signals for conventional discontinuous (2/3) modulation

Remark: Zero modulation margin.

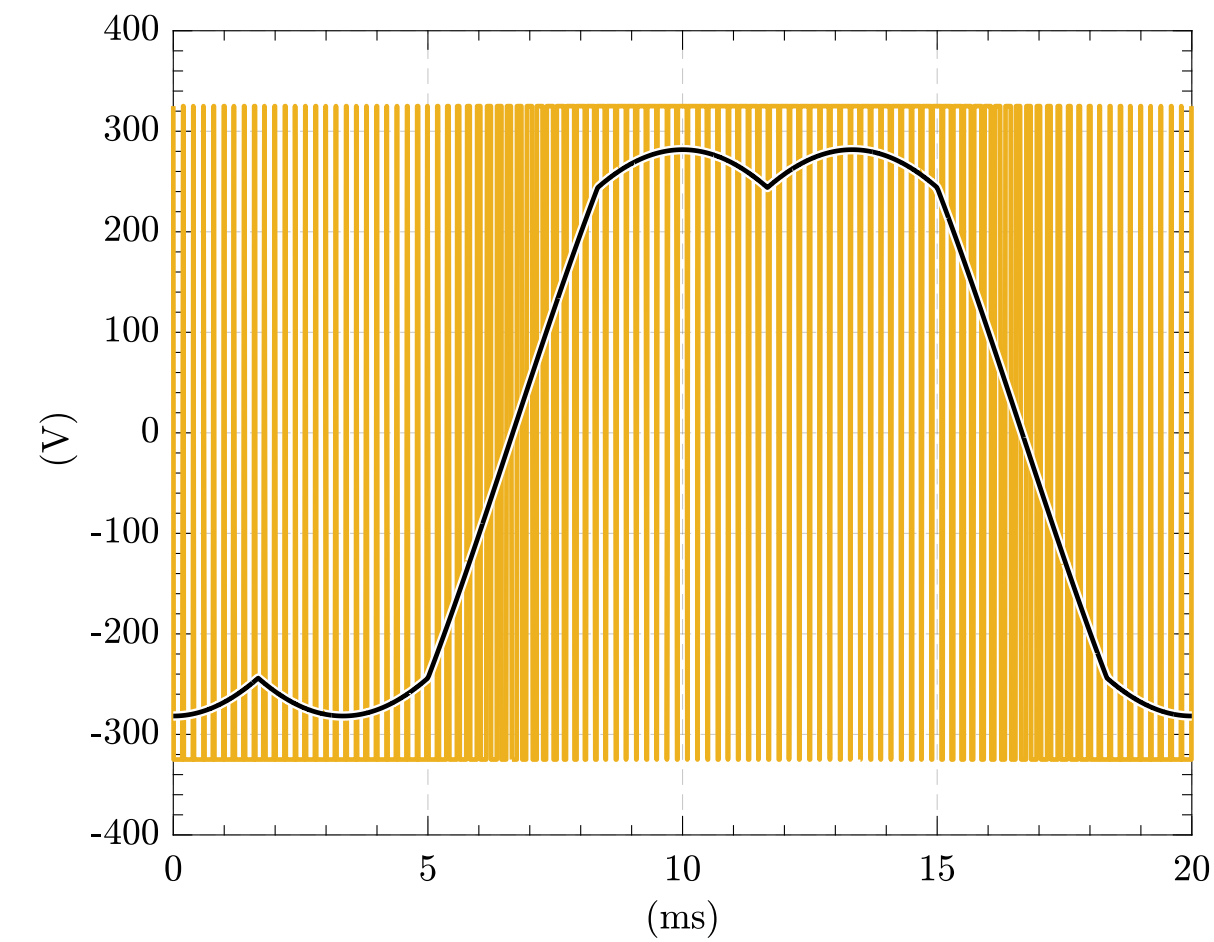
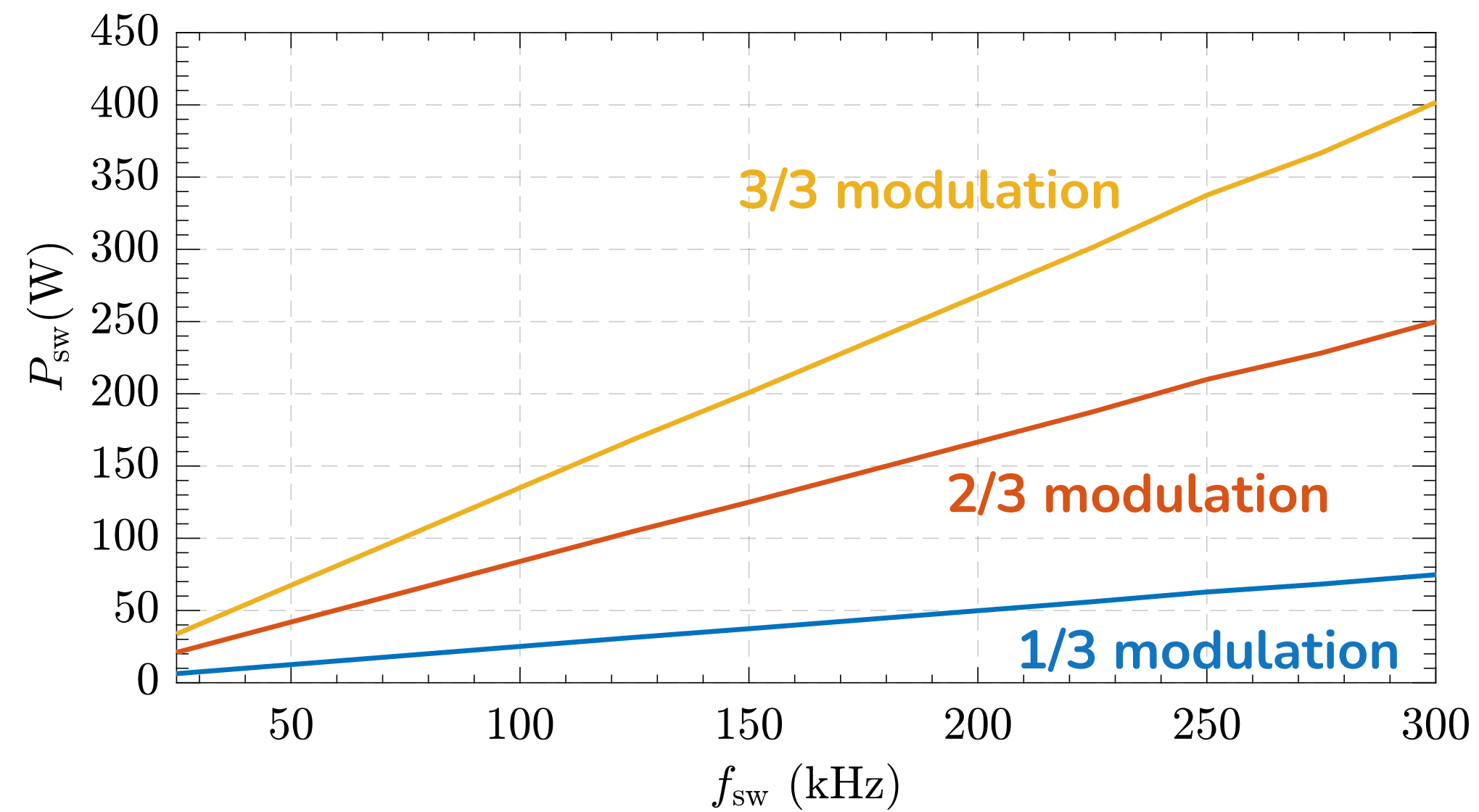


Signals for the 1/3 synergetic modulation

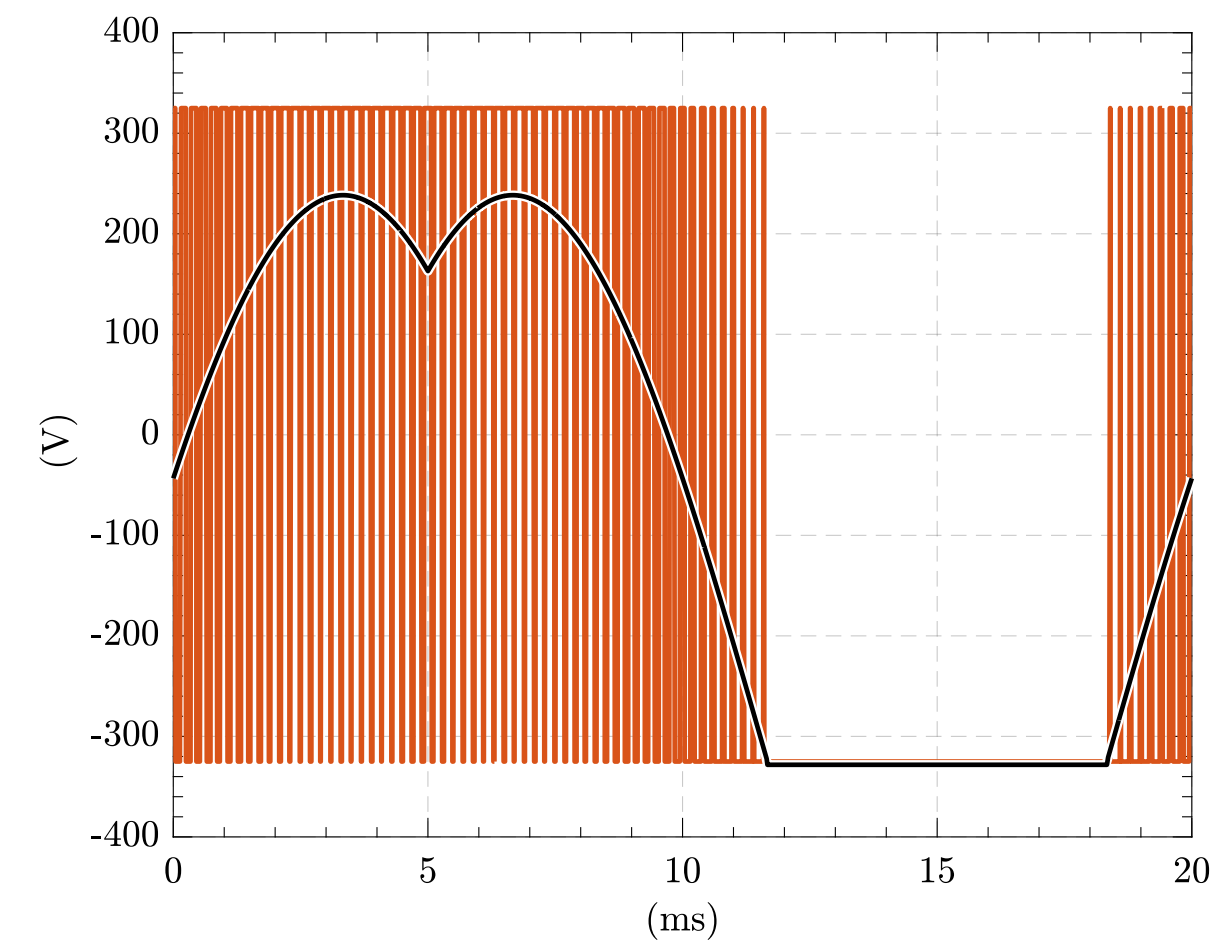


# Principles of discontinuous modulation for a VSC

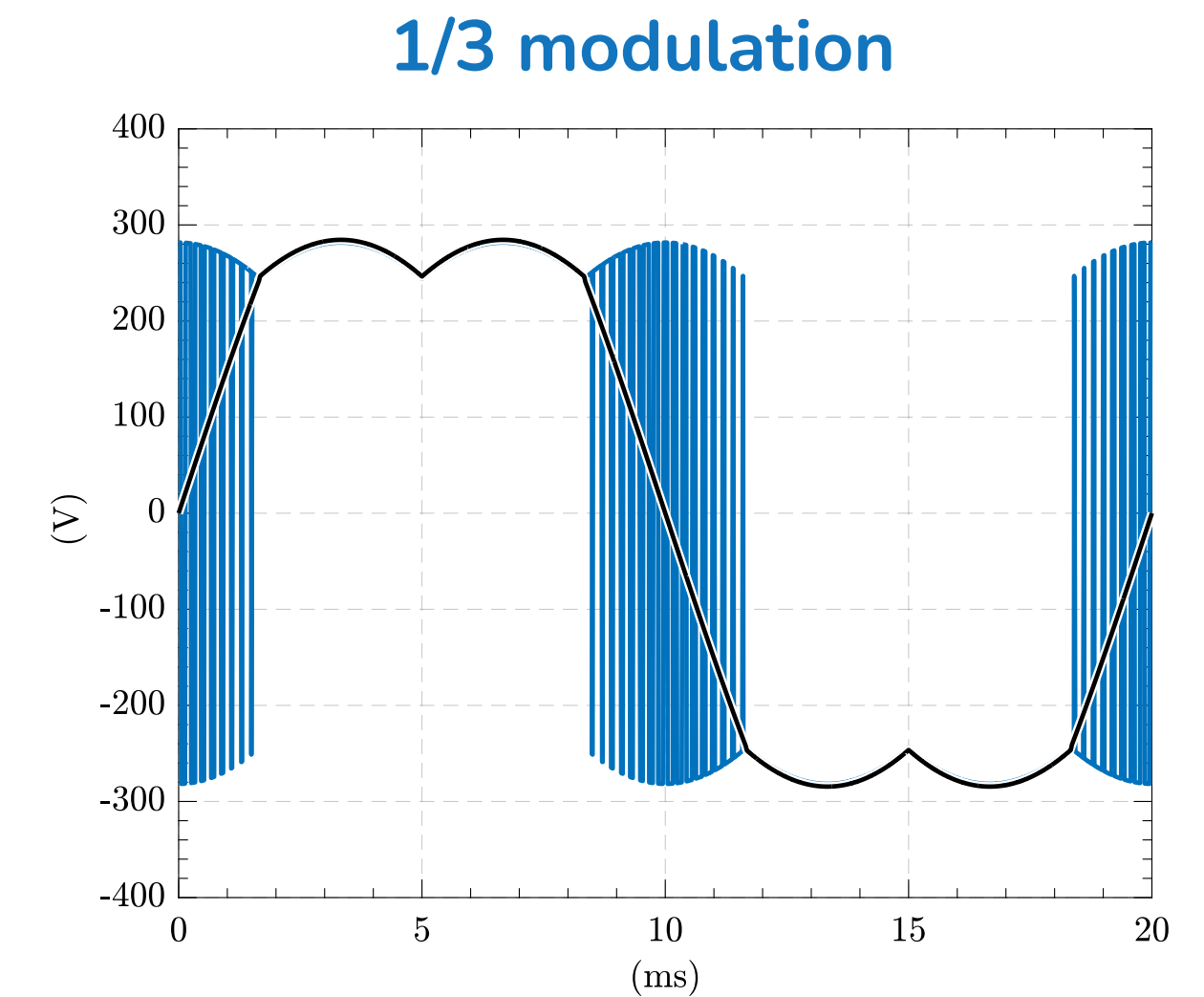
Exemplary switching losses:



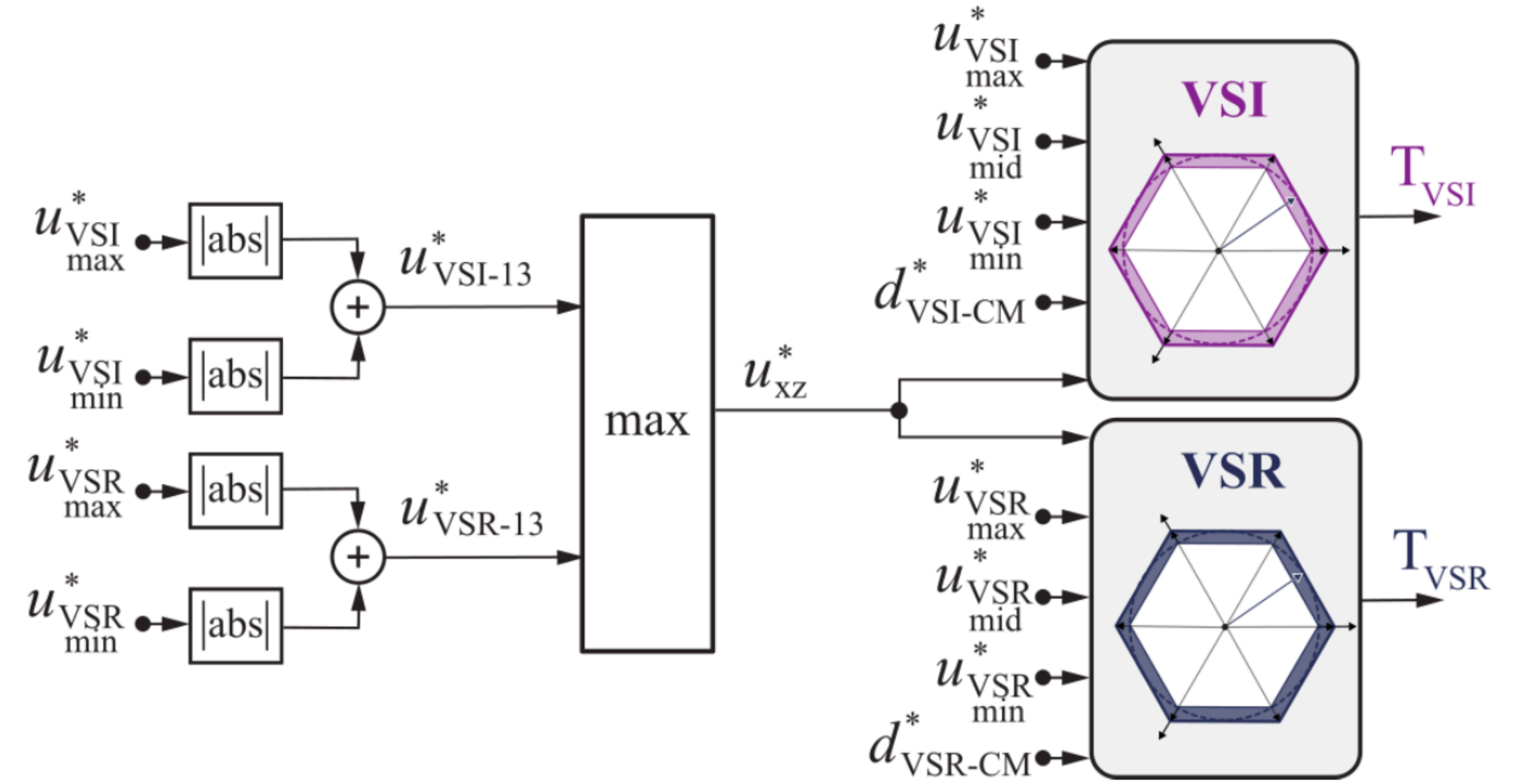
3/3 modulation



2/3 modulation

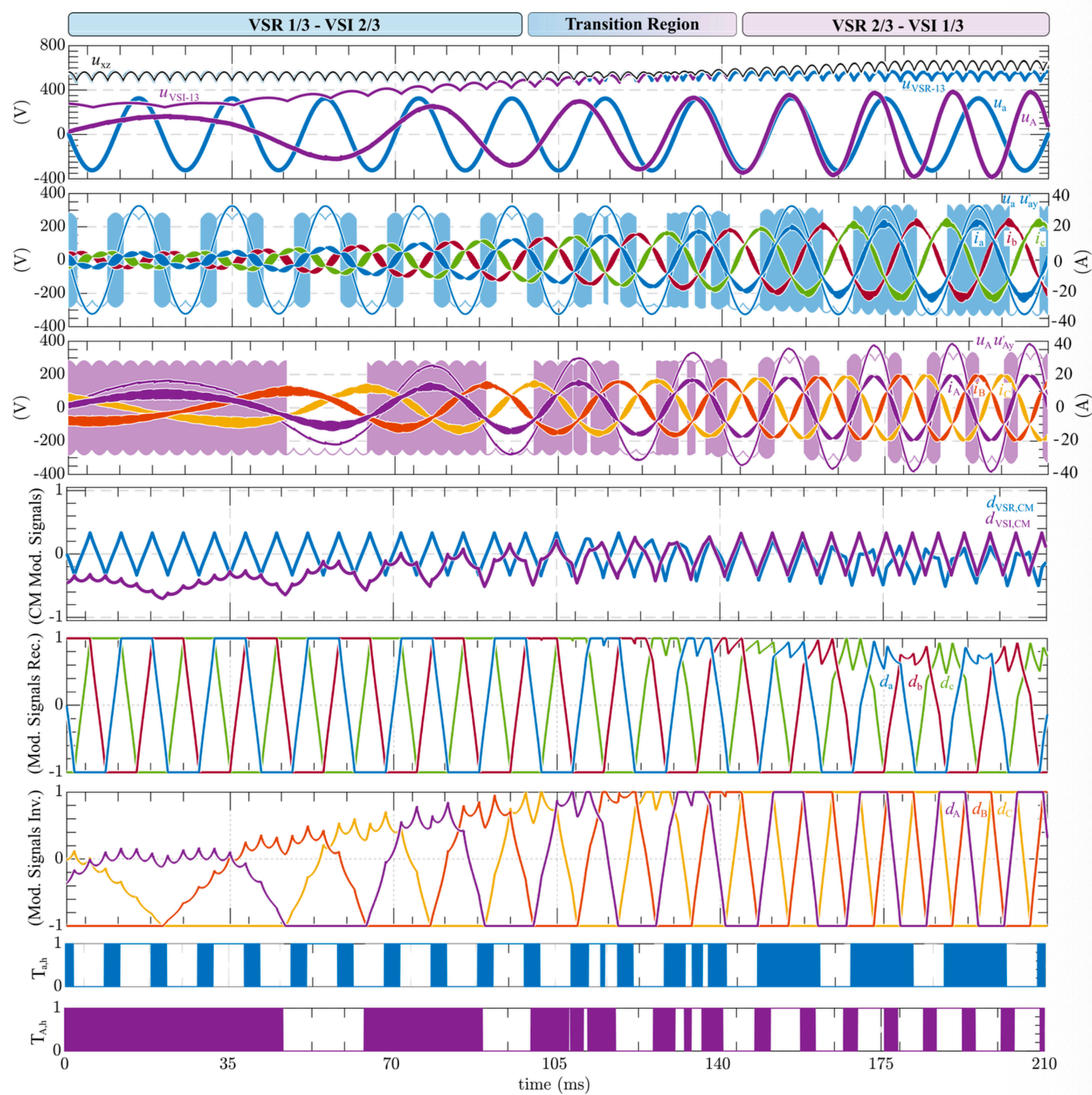


1/3 modulation





# Waveforms





# Design with IGBTs

## Specifications

$$P = 50 \text{ kW}$$

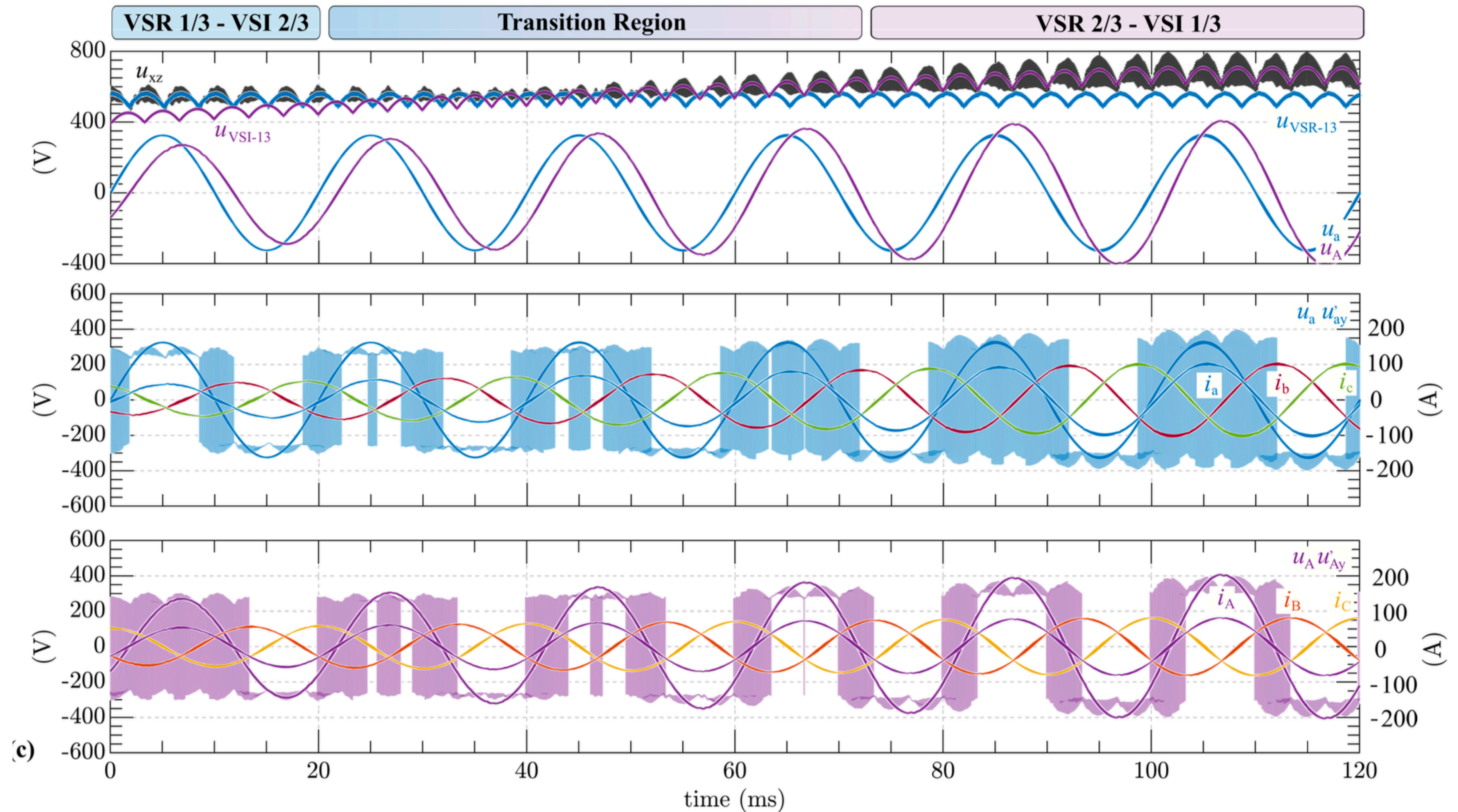
$$V_{\text{grid}} = 380 \text{ V}$$

$$f_{\text{grid}} = 50 \text{ Hz}$$

$$f_o \in \{0..60\} \text{ Hz}$$

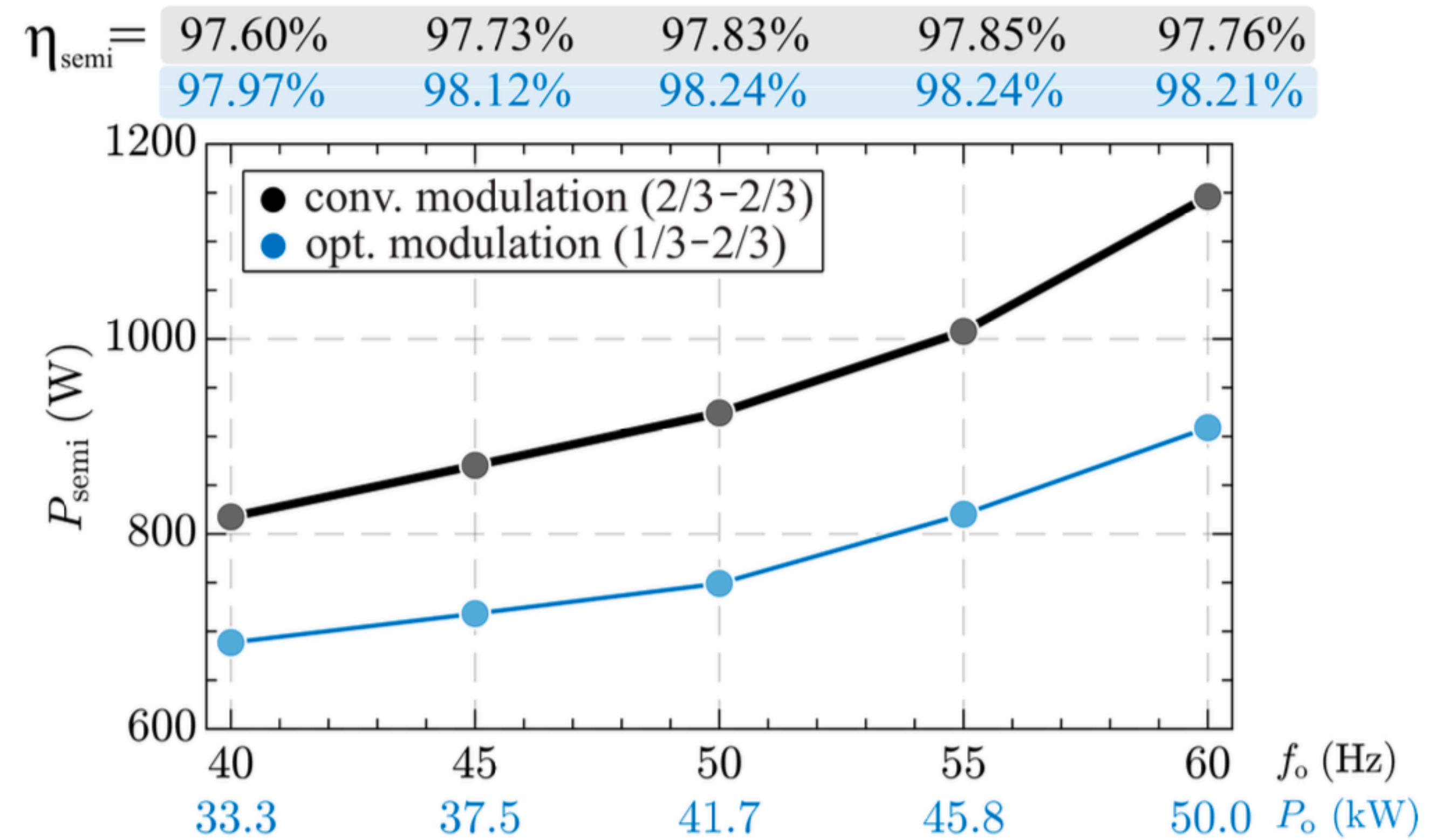
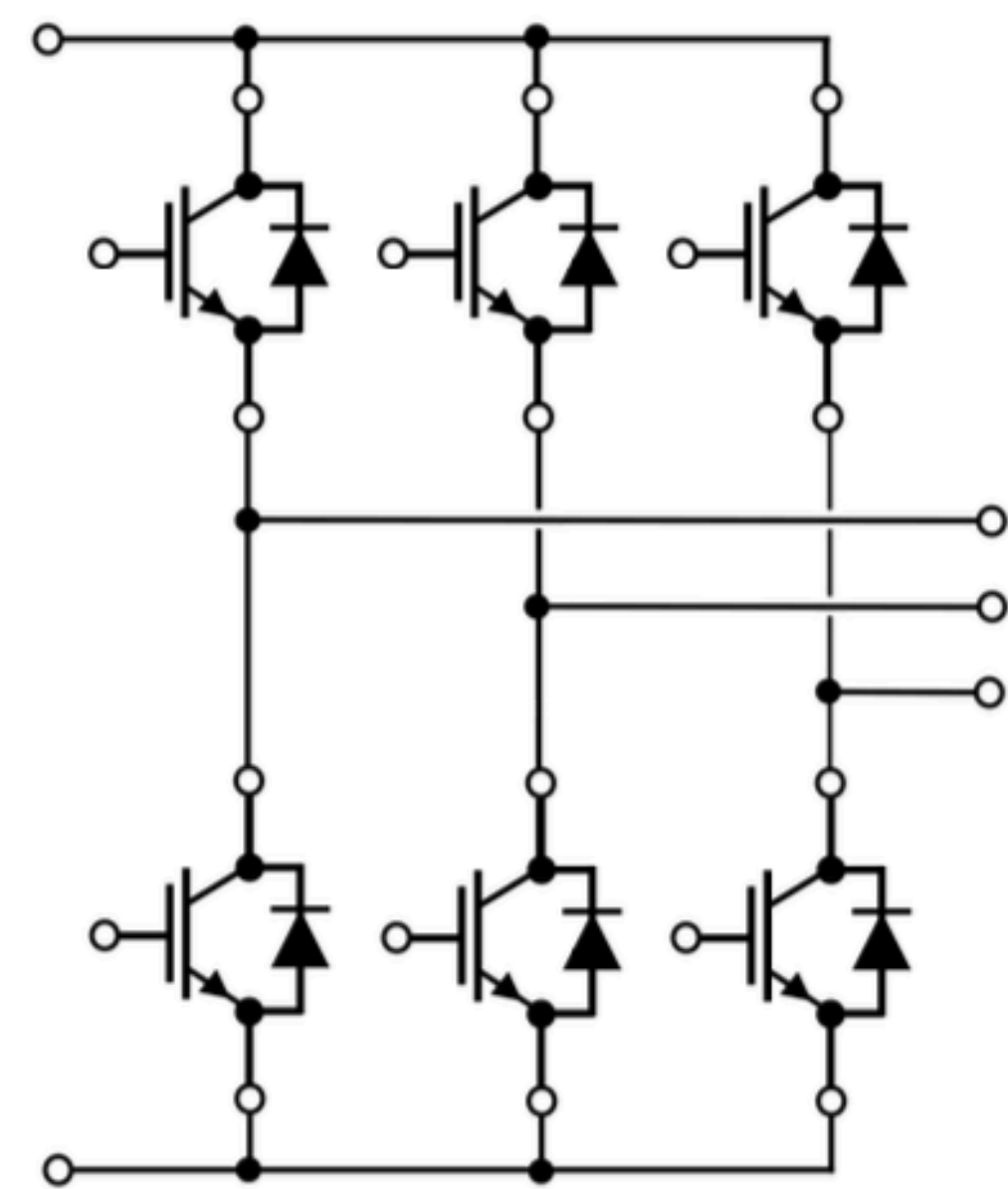
IGBT:

FS75R12W2T7  
(1200 V, 75 A)

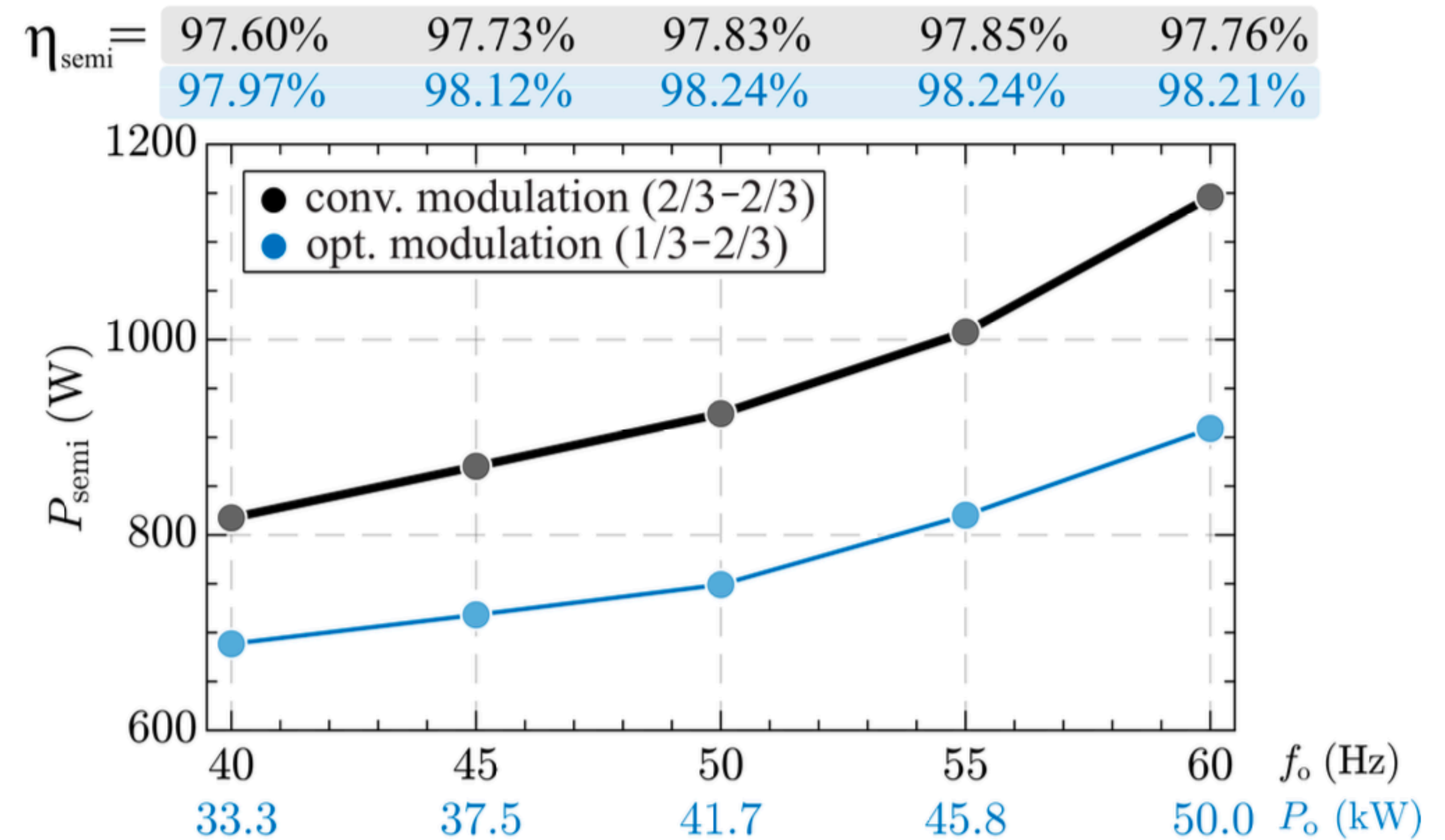
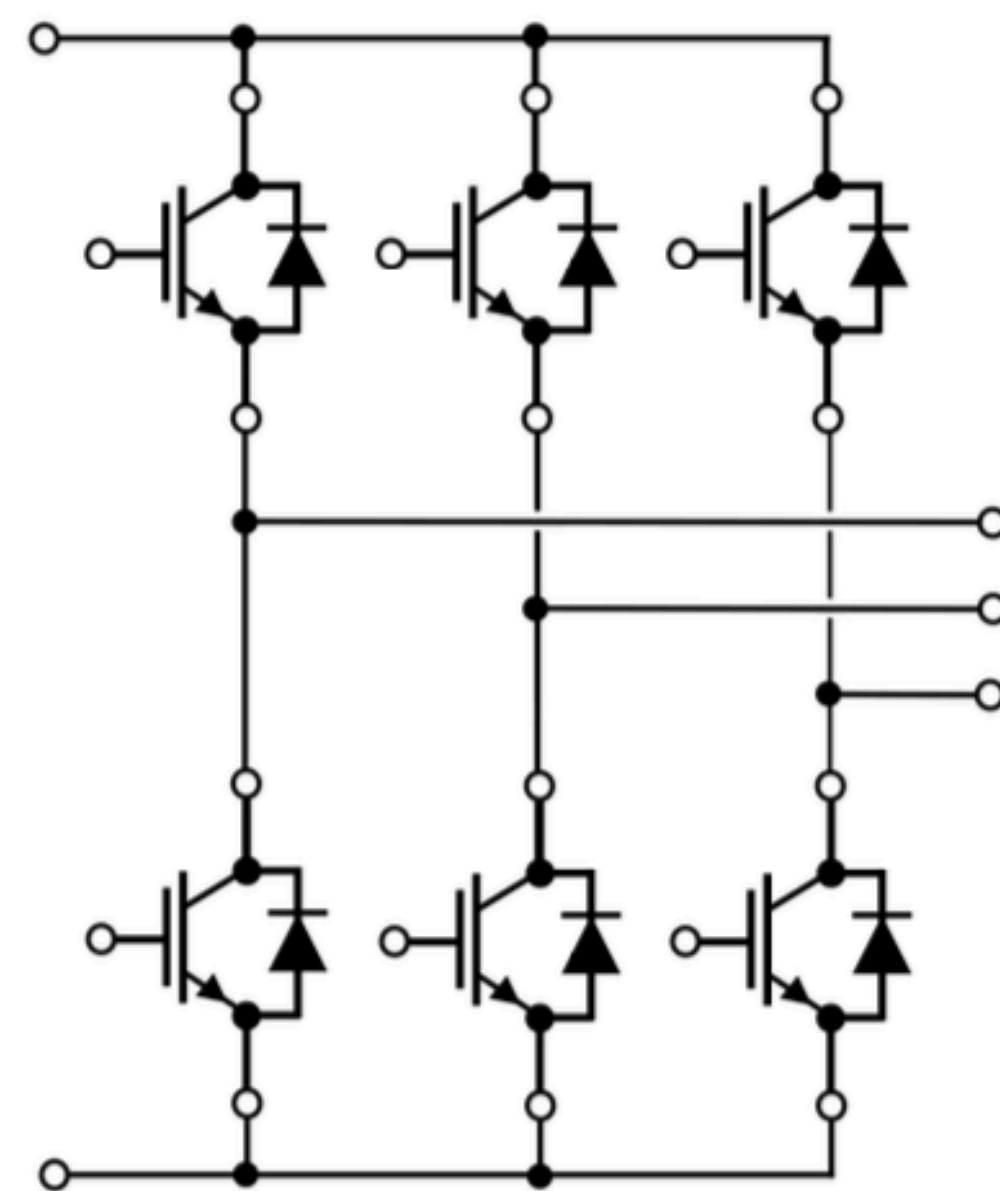




# Design with IGBTs



# Design with IGBTs



Again, 99% was not feasible...

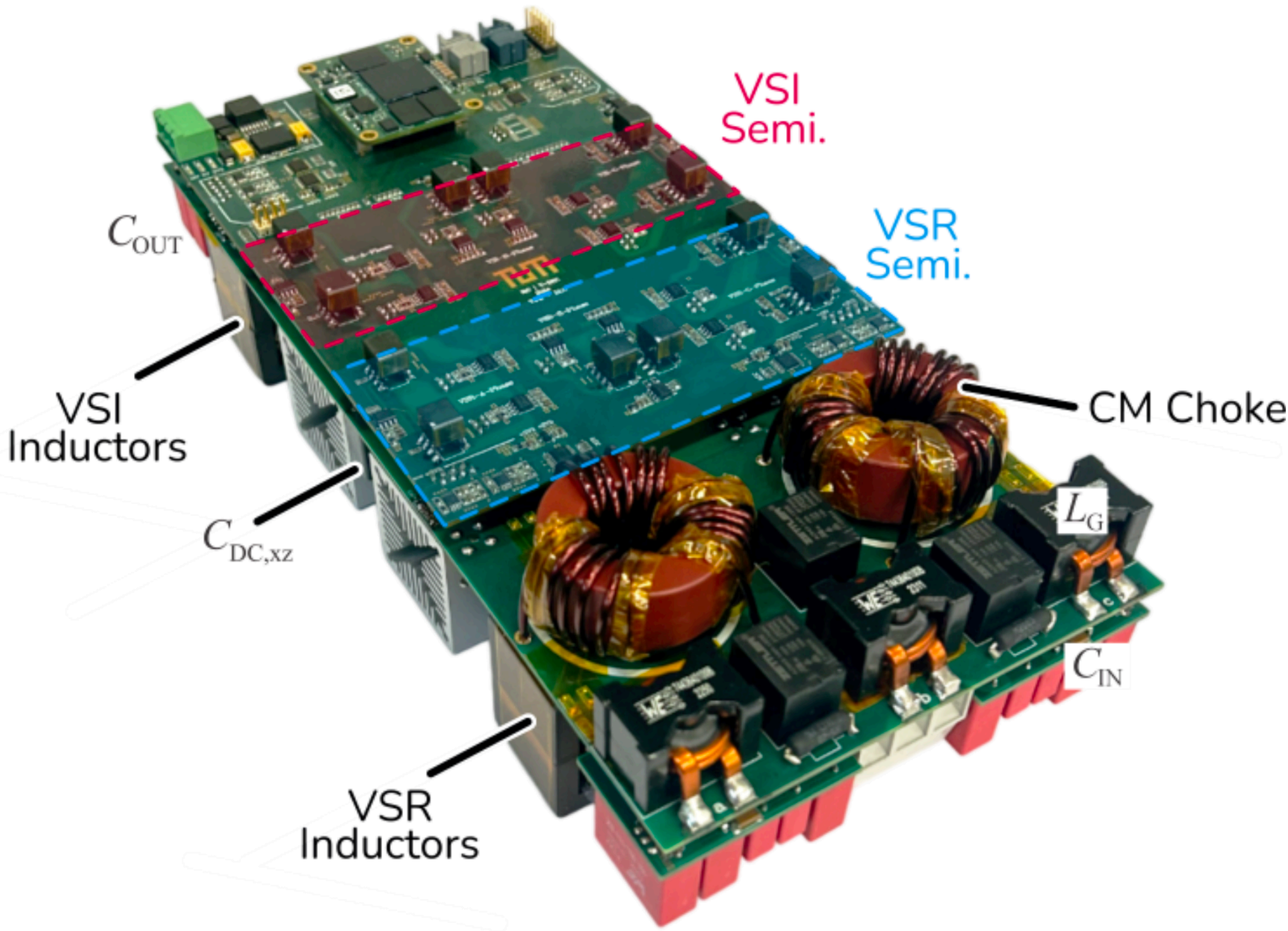


# Prototype

Specifications and parameters:

$$P = 11 \text{ kW} ; V_{\text{grid}} = 380 \text{ V} ; f_{\text{grid}} = 50 \text{ Hz} ; f_o \in \{0..60\} \text{ Hz}$$

|                       | Description   | Value                                    |
|-----------------------|---------------|------------------------------------------|
| $T_{\text{VSR-I}}$    | VSR-I semi.   | C3M0016120K<br>(1200 V, 16 mΩ)           |
| $L_{\text{DM,VSR-I}}$ | VSR-I DM ind. | 140 μH<br>(2×KoolMu-60 E40/20, 22 turns) |
| $L_{\text{CM}}$       | CM ind.       | 1.35 mH<br>(2×VAC 40/25/15, 3×6 turns)   |
| $L_{\text{G}}$        | DM ind.       | 6.8 μH<br>(WE-7443640680B [21])          |
| $C_{\text{IN}}$       | VSR DM cap.   | 3.0 μF                                   |
| $C_{\text{DC,xy-yz}}$ | DC-link cap.  | 2×5.6 μF                                 |
| $C_{\text{OUT}}$      | VSI DM cap.   | 2.2 μF                                   |
| $C_{\text{CM}}$       | CM cap.       | 112 nF                                   |

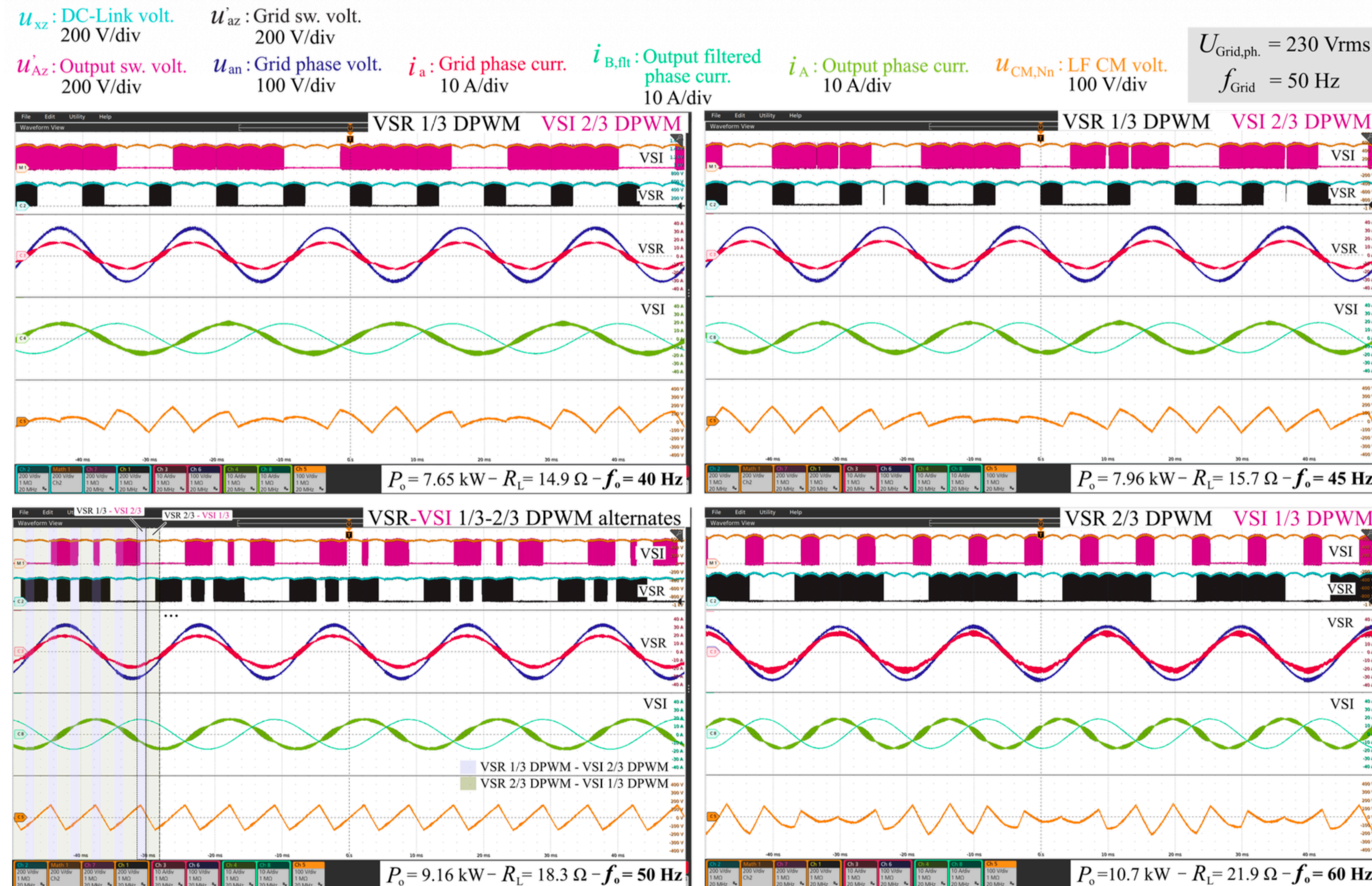


Dimensions: 280 ×132 ×63 mm<sup>3</sup>

Power density:  $\rho \approx 4.7 \text{ kW/dm}^3$

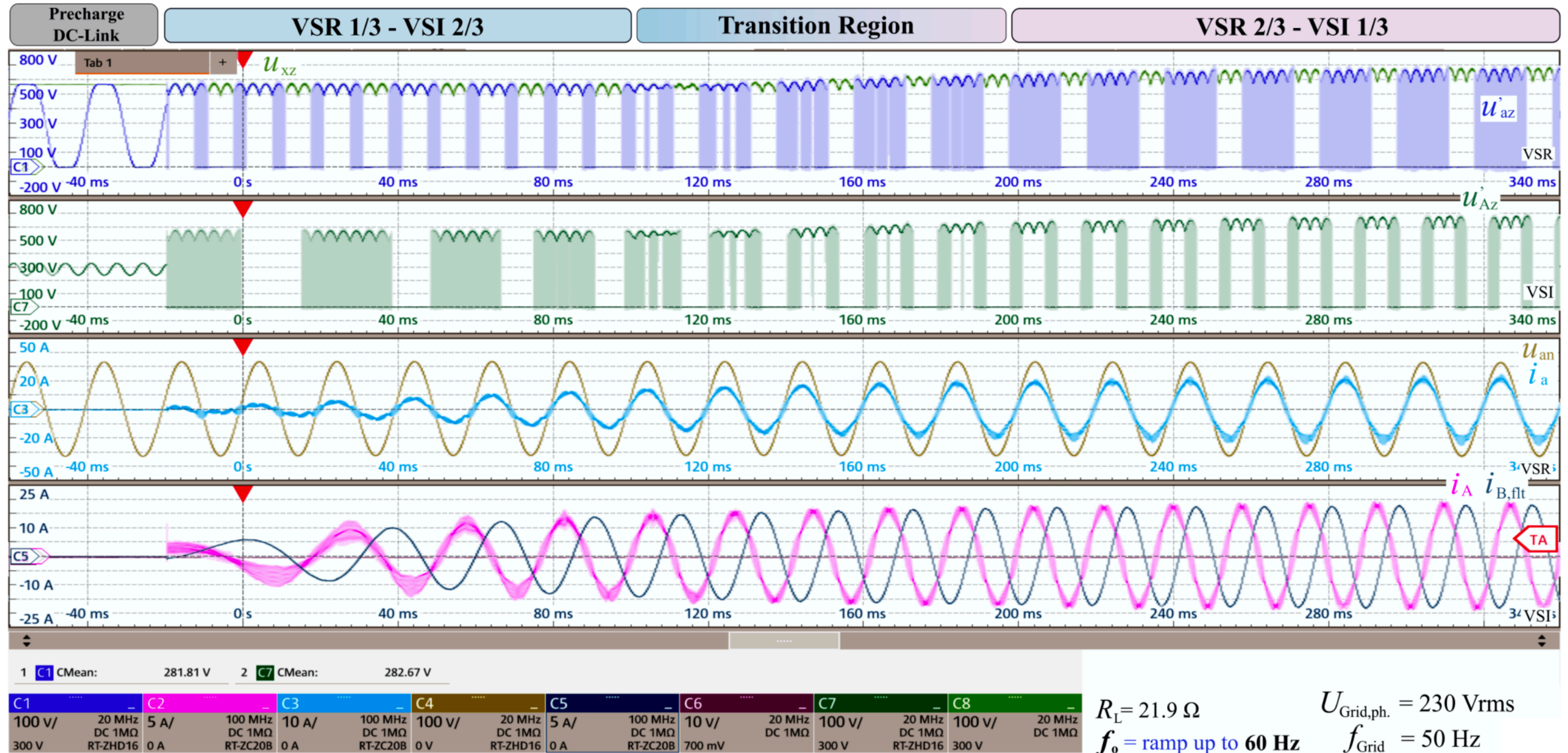


# Experimental waveforms - different steady state conditions



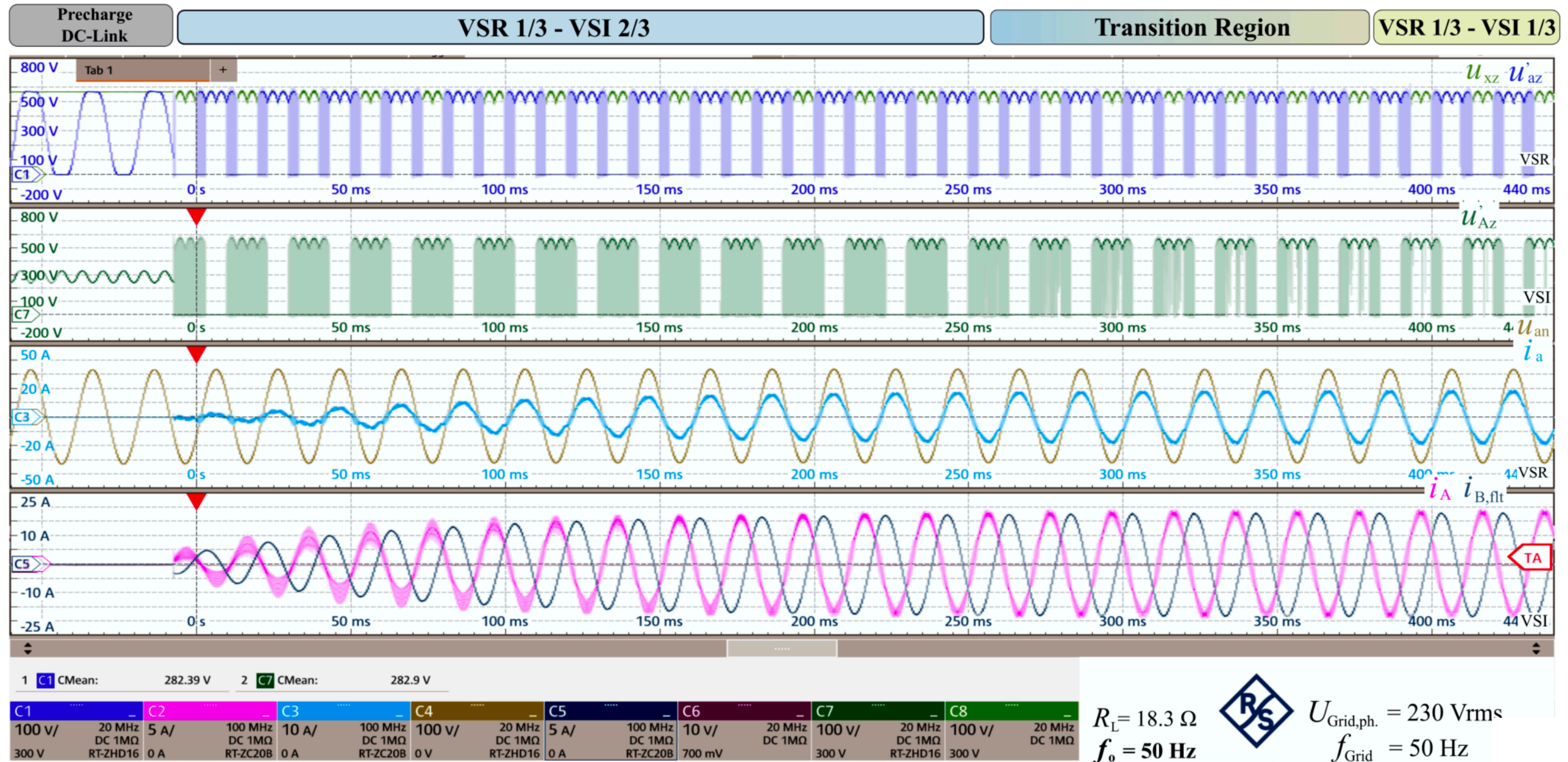


# Experimental waveforms - increasing output frequency



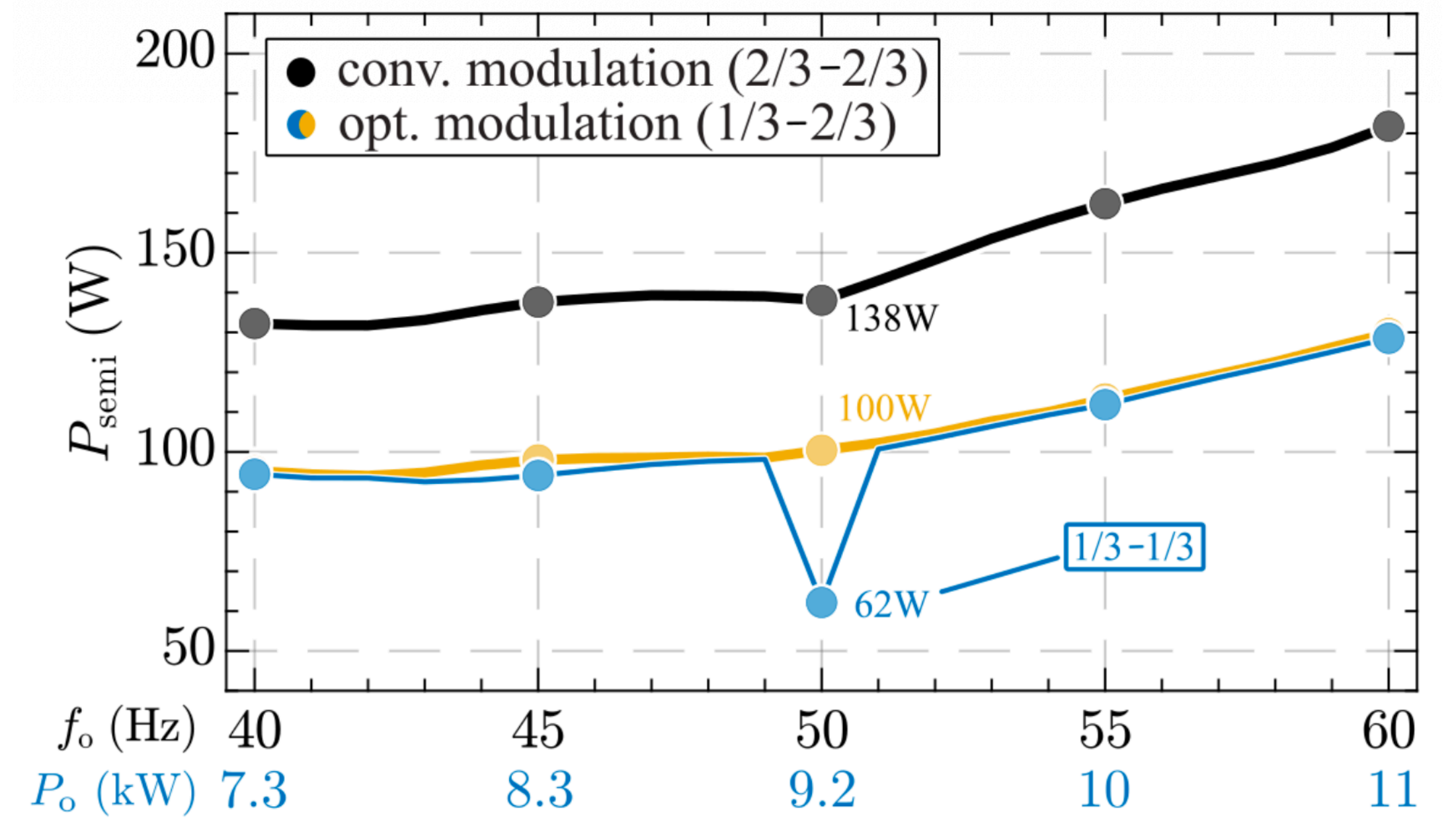
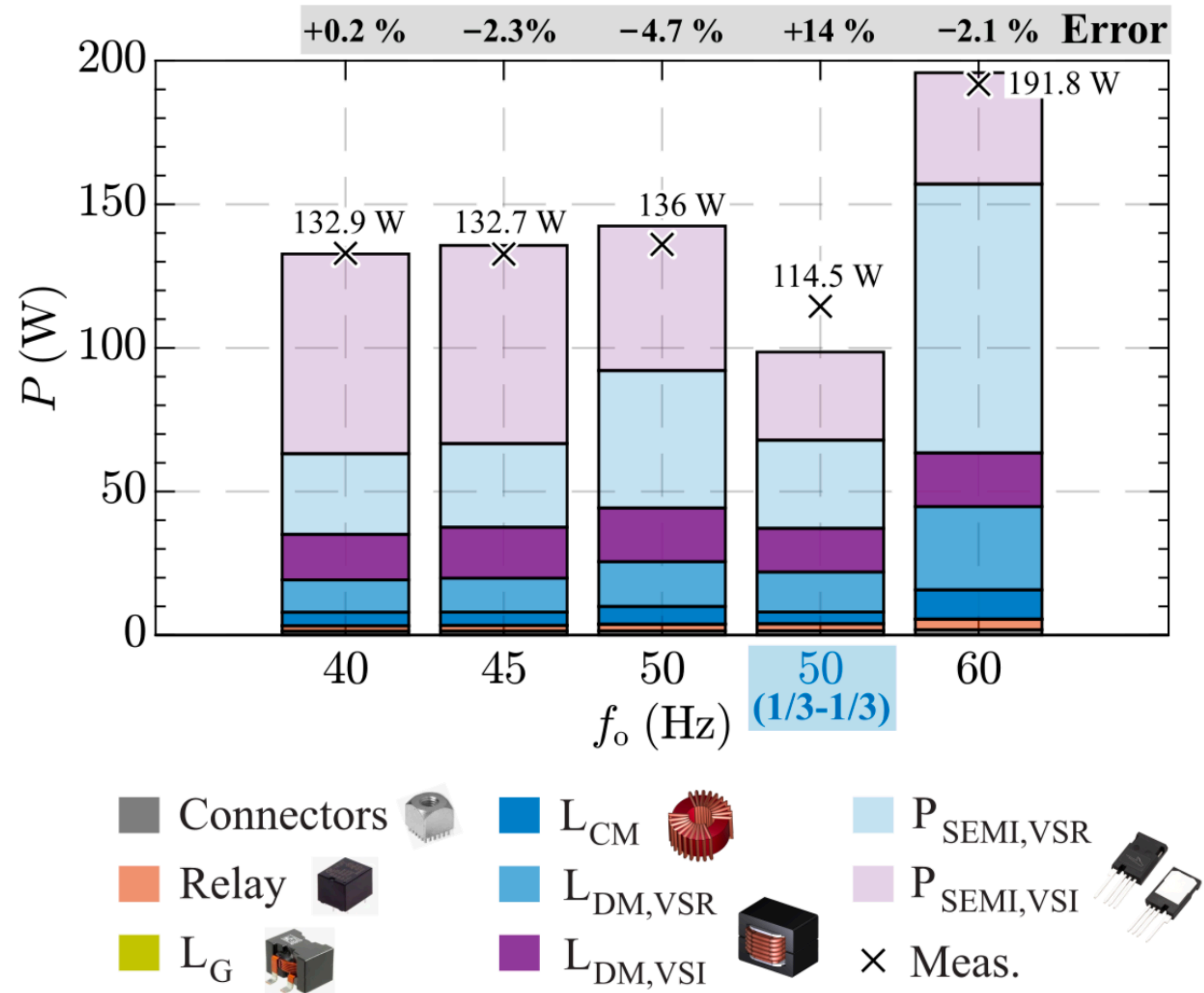


# Experimental waveforms - output frequency = input frequency

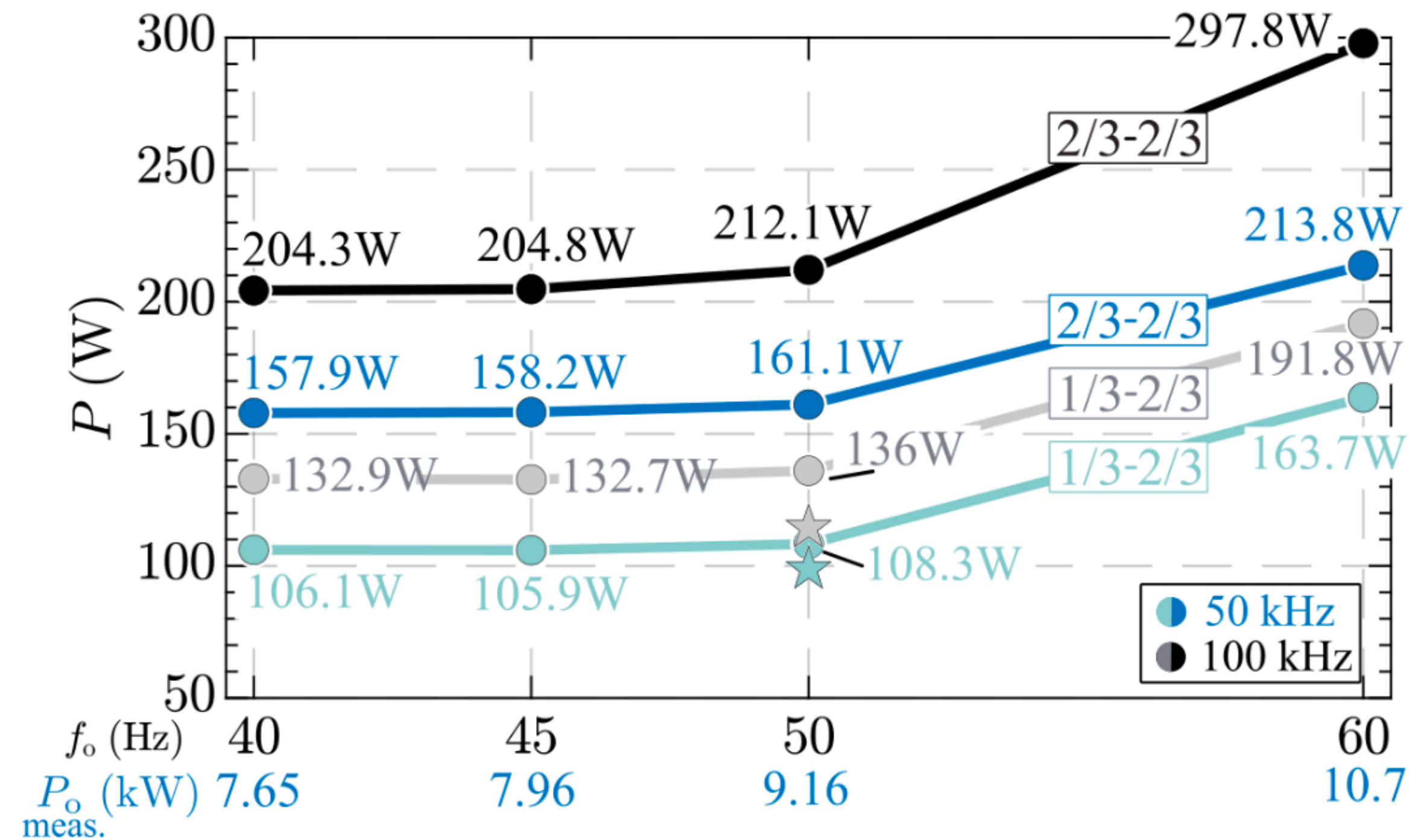
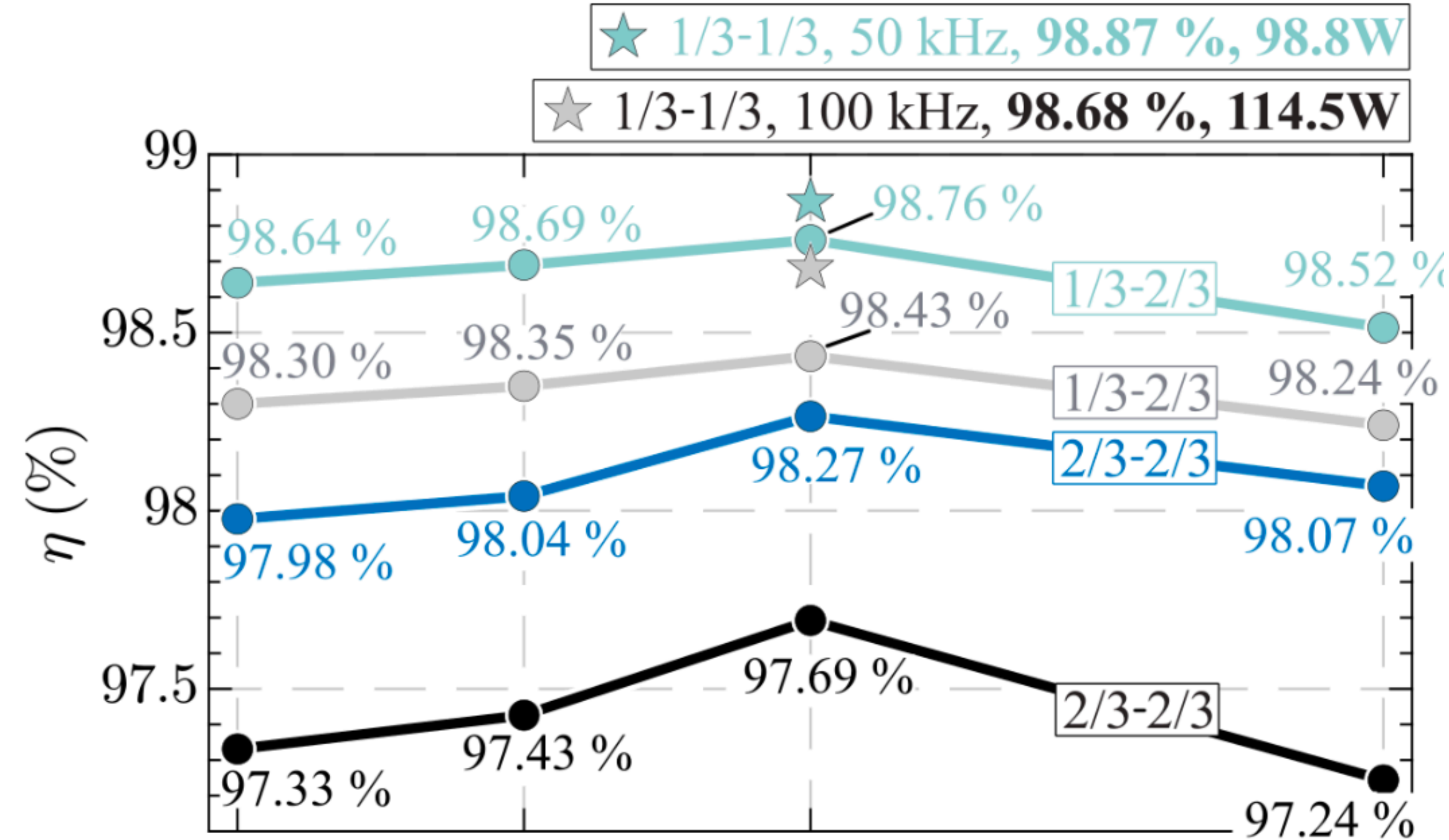




# Loss analysis

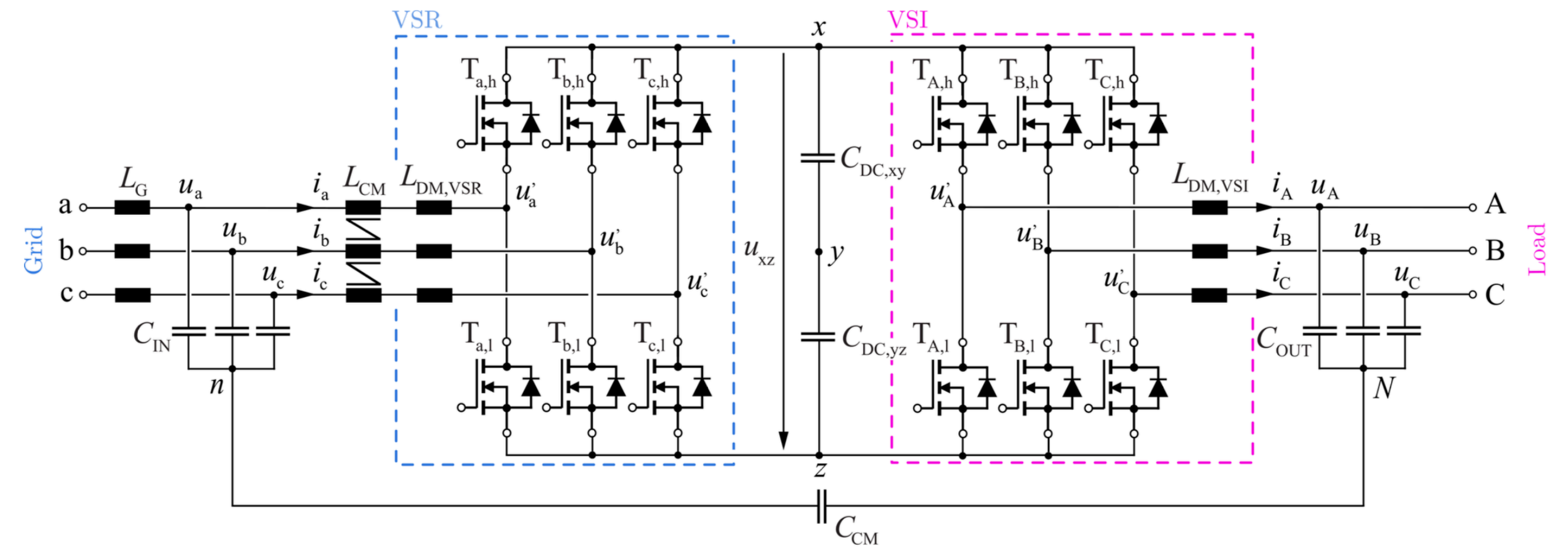


# Measured efficiency values





# Critical evaluation of the three-leg operated VSC-B2B concept



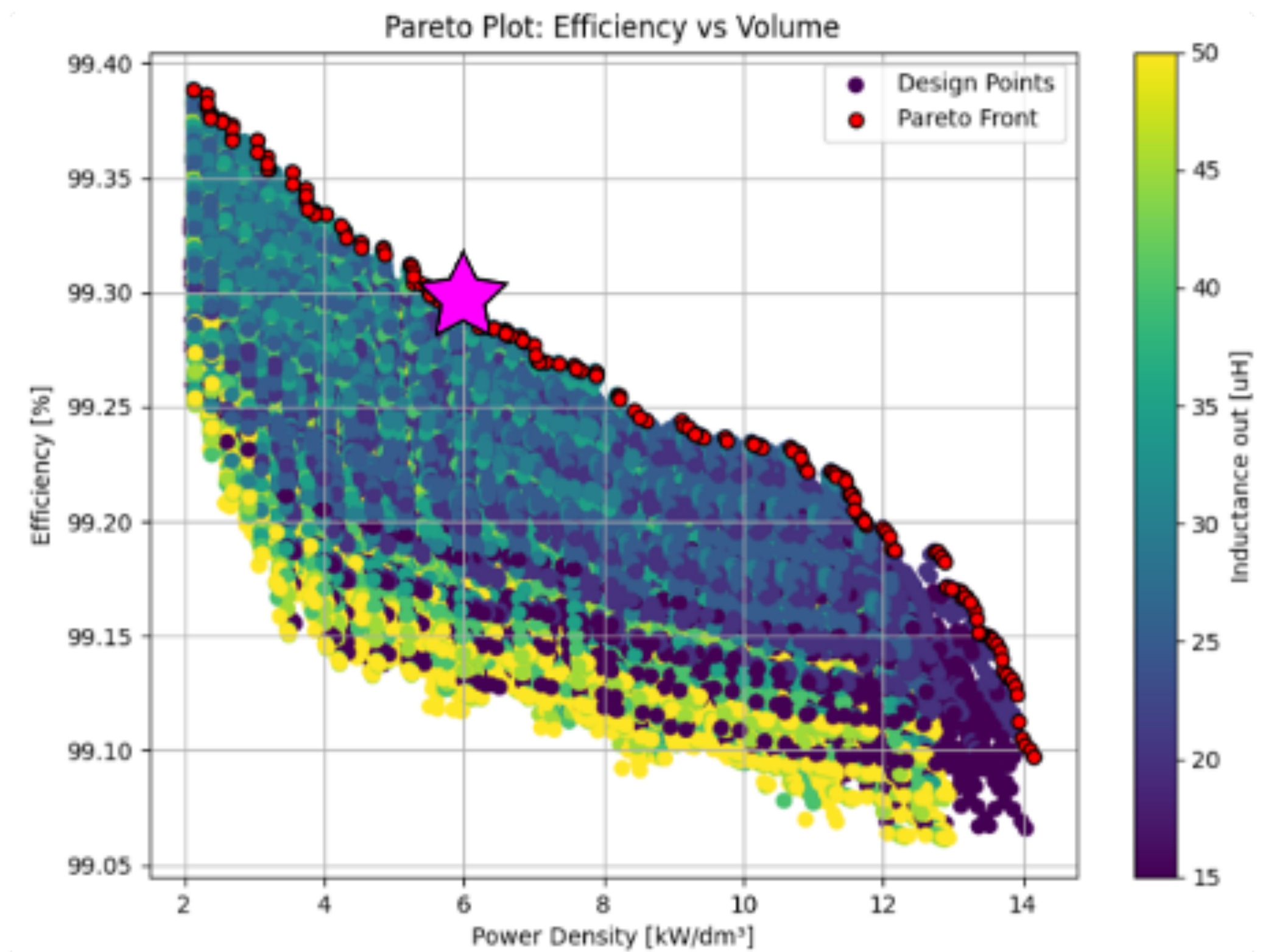
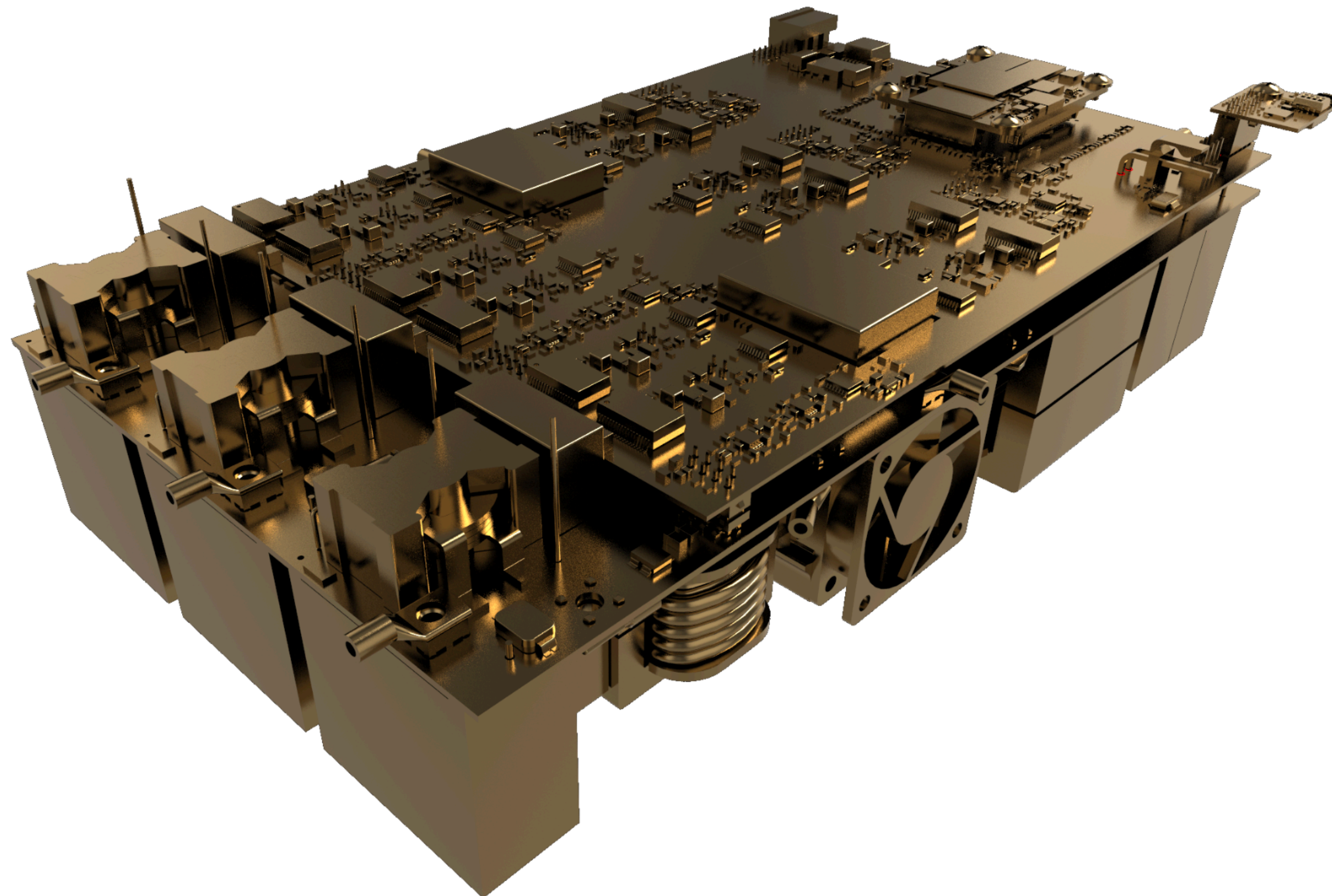
✓ Industry standard topology, can be operated with different switching frequencies and without a filter at the motor side if needed, switching losses are very low, conduction losses are nearly unchanged

✗ Did not achieve 99%

# Final thoughts



We still want to get there... stay tuned!



# References

The slides without references are from these two publications:

[1] C. Leontaris, G. J. M. de Sousa and M. L. Heldwein, "Three-Stage/-Phase Voltage/Current DC-link AC-AC Converter with Synergetic Control," PCIM Europe 2025, 2025, pp. 1321-1330.

doi: <https://doi.org/10.30420/566541172>

[2] C. Leontaris, G. J. M. de Sousa and M. L. Heldwein, "Three-Leg Operation of Back-to-Back Converters," in IEEE Transactions on Power Electronics.

doi: <https://doi.org/10.1109/TPEL.2025.3624327>



The background of the slide is a photograph of a city skyline at sunset. On the left, a prominent clock tower with a green patina and two large golden clock faces stands on a rooftop. The sky is a mix of blue and orange. In the distance, the city skyline includes a church with two large domes and other buildings. The foreground shows a dark, corrugated metal roof.

Thank you!

[marcelo.heldwein@tum.de](mailto:marcelo.heldwein@tum.de)