MODULAR MULTILEVEL CONVERTERS OPERATING PRINCIPLES AND APPLICATIONS

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INTRODUCTION

Non technical one...

Prof. Drazen Dujic

Experience:

2014 – today	École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
2013 – 2014	ABB Medium Voltage Drives, Turgi, Switzerland
2009 – 2013	ABB Corporate Research, Baden-Dättwil, Switzerland
2006 – 2009	Liverpoool John Moores University, Liverpool, United Kingdom
2003 – 2006	University of Novi Sad, Novi Sad, Serbia

Education:

2008	PhD, Liverpoool John Moores University, Liverpool, United Kingdom
2005	M.Sc., University of Novi Sad, Novi Sad, Serbia
2002	Dipl. Ing., University of Novi Sad, Novi Sad, Serbia

Mr. Stefan Milovanovic

Education:

2020	PhD, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
2016	M.Sc., School of Electrical Engineering, University of Belgrade, Belgrade, Serbia

École Polytechnique Fédérale de Lausanne

School of Engineering

EPFL — STI — IEL — PEL

Institute of Electrical Engineering

- Online since February 2014
- 12 PhD, 1 Scientist, 1 Postdoc, 1 Secretary
- `http://pel.epfl.ch`

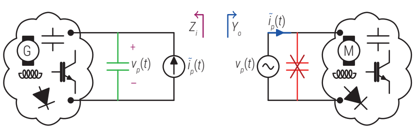
ECPE Competence Centre

RESEARCH FOCUS

MVDC Technologies and Systems

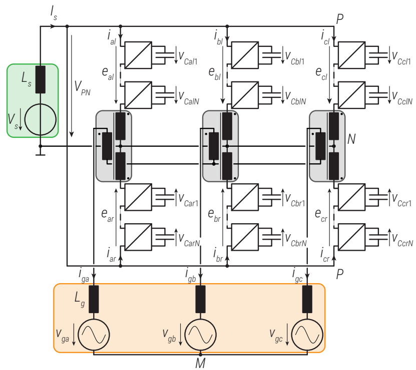
- System Stability
- Protection Coordination
- Power Electronic Converters

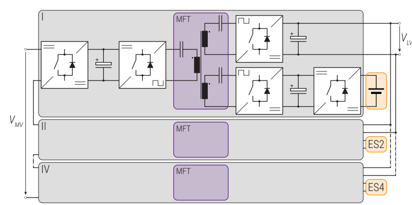
MVDC
ENERGY CONVERSION TECHNOLOGIES AND SYSTEMS



High Power Electronics

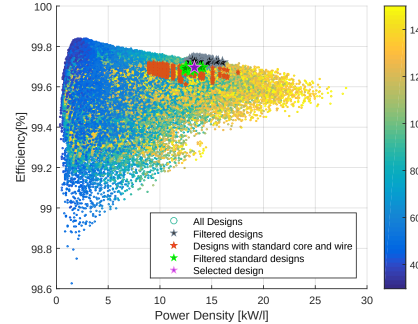
- Multilevel Converters
- Solid State Transformers
- Medium Frequency Conversion

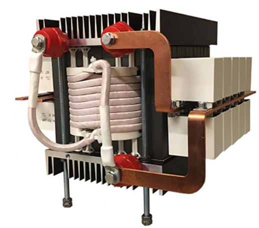




Components

- Semiconductor devices
- Magnetics
- Modeling, Characterization





MVDC POWER DISTRIBUTION NETWORKS

MVDC Power Distribution Networks

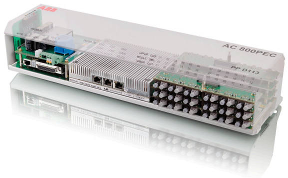
- Feasibility (Applications)
- System Level Gains
- Dynamic Stability

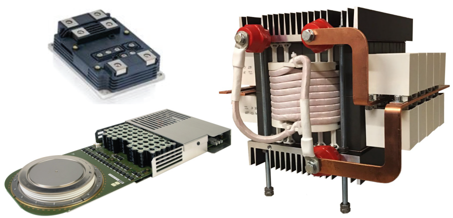
Conversion

- Passive, Efficient and Stable
- Flexible, Modular and Scalable
- Efficient

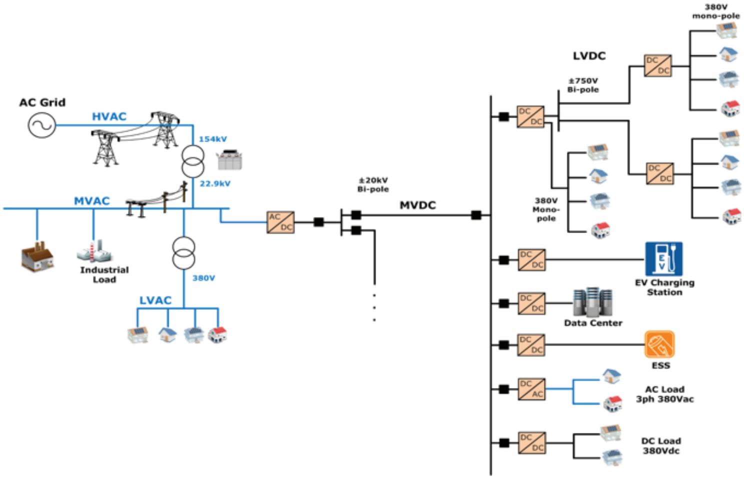
Protection

- DC Breaker?
- Fault Current Limiting by Converters
- Protection Coordination





▲ Power electronics constituents



▲ Possible future MVDC grids and its links with existing grids

SCHEDULE

Before the Coffee

1) Introduction and Motivation - MVDC
- MVDC Applications and Technologies
- MVDC Conversion Technologies
- Solid State Transformers

2) Modular Multilevel Converter Fundamentals
- Operating principles
- Modeling and Control
- Performance Benchmark

3) MMC Modulation Methods
- Carrier-based PWM, SVPWM
- Centralized vs. Distributed PWM
- SHE and OPPs

After the Coffee

4) High Power MMCs
- Branch Energy Balancing
- Power Extension
- Pulse Width Modulation

5) High Power DC-DC Conversion
- MMC-based DAB Topologies
- Quasi-Two-Level Converters
- Design and Control

6) MMC Research Platform
- MMC system level design
- MMC RT-HIL development
- Questions and Discussion

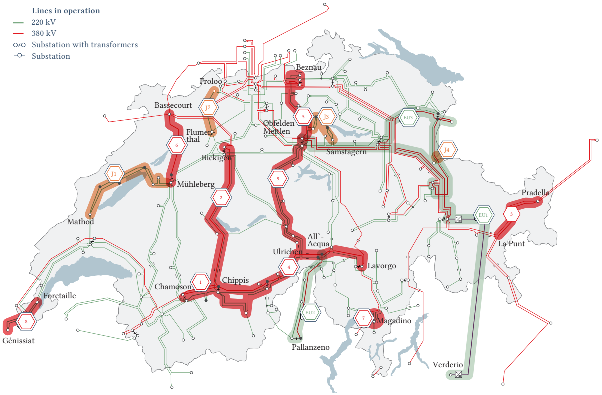
⇒ Tutorial pdf can be downloaded from: *(Source: `https://pel.epfl.ch/publications_talks_en`)*

MVDC TECHNOLOGIES AND SYSTEMS

Future electrical energy generation, conversion and storage technologies

SwissGrid infrastructure

- Existing infrastructure (220 – 380kV, 50 Hz) is ageing (2/3 built ~ 1960)
- Large PHSPs commissioned ⇒ sufficient capacity required
- Lengthy procedures for new overhead lines construction (low social acceptance, impact on landscape)

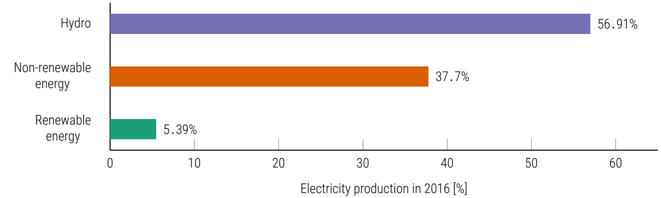


MVDC grids

- Might be a good candidate w/ underground cable
- Suited for medium-scale energy collection

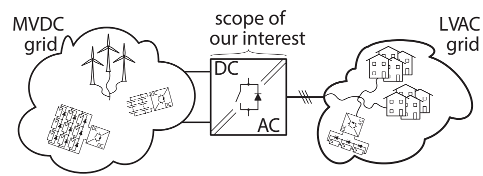
Swiss energy landscape

- Annual consumption 60 TWh
- Nuclear phase out by 2050



Swiss Competence Centers for Energy Research (SCCERs)

- Government supported initiative
- SCCER-FURIES for future grids
- Explore ways to interconnect a MVDC grid w/ a LVAC grid



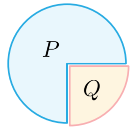
▲ Future energy systems with MVDC and LVAC grids

WHY DC?

- No reactive power

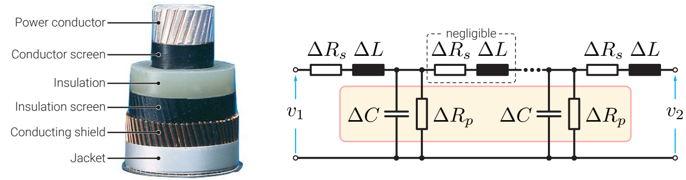
  Example: @ $cos(\varphi) = 0.95$

  $$\frac{P}{Q} \approx \frac{3}{1}$$

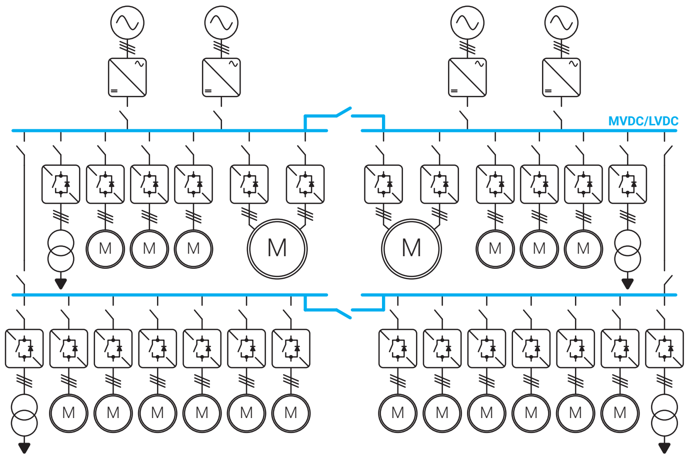


  - No constraints imposed upon transmission distance
  - Transmission capacity increase
  - Lower transmission losses
  - Alleviated stability problems

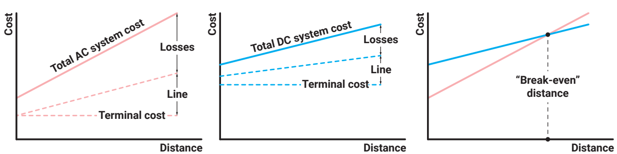
- No skin effect ($R_{\gamma} \downarrow \Rightarrow P_{\gamma} \uparrow$)
- Cheaper solution ("Break-even distance")
- Underwater cable transmission
- No need for synchronization (Marine applications)
- Direct integration of Renewable Energy Sources
- Challenges ⇒ DC Transformer/Protection?



▲ High voltage cable



▲ DC Ship distribution system - frequency decoupling through a DC distribution



▲ Cost comparison between AC and DC systems

TREND TOWARDS DC

Bulk power transmission

- Break even distance against AC lines
- ~ 50 km for subsea cables or 600 km for overhead lines
- Long history since 1950s
- Interconnection of asynchronous grids

▲ From mercury arc rectifiers to modern HVDC systems

LVDC ships

- Variable frequency generators ⇒ maximum efficiency of the internal combustion engines
- Commercial products by ABB & Siemens

▲ Specialized vessels with LVDC distribution

Datacenters

- 380 V_{dc}
- DC loads (including UPS)
- Expected efficiency increase

Large PV powerplants

- 1500 V_{dc} PV central inverters
- Higher number of series-connected panels per string

▲ 1500V PV inverter - step towards the MVDC

Open challenges

- DC breaker
- Conversion blocks missing
- Protection coordination

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▲ 1500V PV inverter - step t… s the MVDC

⇒ dc beneficial for medium / high power applications

Open challenges

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EMERGING MVDC APPLICATIONS

Installations

- ABB HVDC Light demo: 4.3 km/$\pm$9 kV$_{dc}$ [1]
- Tidal power connection: 16 km/10 kV$_{dc}$ (based on MV3000 & MV7000) [2]

- Unidirectional oil platform connection in China: 29.2 km/$\pm$15 kV$_{dc}$ [3]

Projects

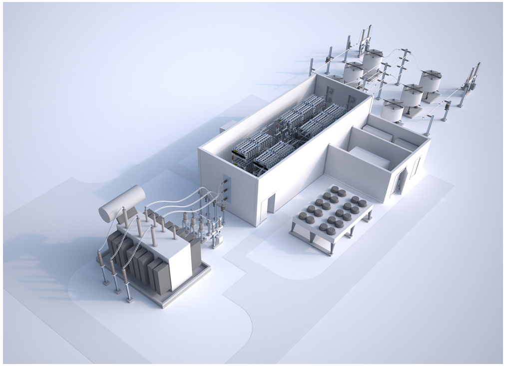
- Angle DC: conversion of 33 kV MVac line to $\pm$27 kV MVdc [4]

Universities

- Increased number of laboratories active in high power domain
- China, Europe, USA,...

Products

- Siemens MVDC Plus
  - 30 - 150 MW
  - < 200 km
  - < $\pm$50 kV$_{dc}$



- RXPE Smart VSC-MVDC
  - 1 - 10 MVAr
  - $\pm$5 - $\pm$50 kV$_{dc}$
  - 40 - 200 km

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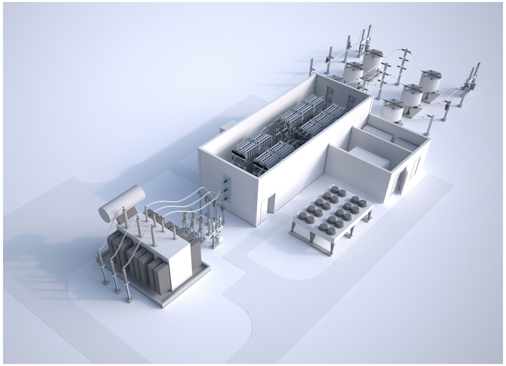


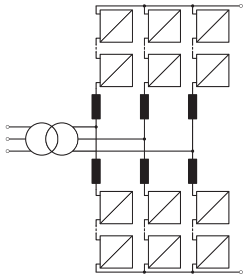
- RXPE Smart VSC-MVDC
  - 1 - 10 MVAr
  - ±5 - ±50 kV_{dc}
  - 40 - 200 km

⇒ MVDC is gaining momentum!

TREND TOWARDS HIGHLY MODULAR CONVERTER TOPOLOGIES

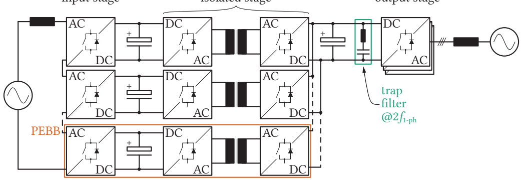
HVDC

- Decoupled semiconductor switching frequency from converter apparent switching frequency
- Improved harmonic performance ⇒ less / no filters
- Series-connection of semiconductors still possible
- Fault blocking capability depending on cell type



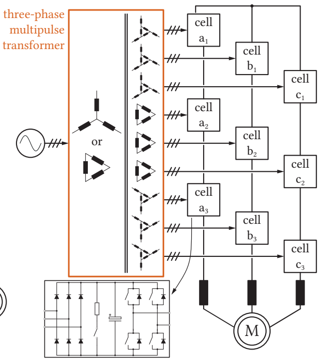
Solid-state transformers (SSTs)

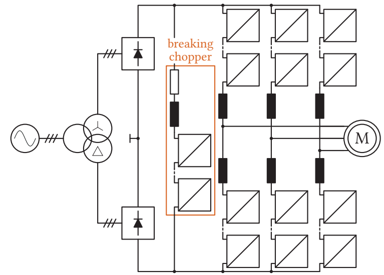
- Power density increase w/ conversion & isolation at higher frequency
- Grid applications / traction transformer w/ different optimization objectives
- MFT design / isolation are the bottlenecks



MV drives

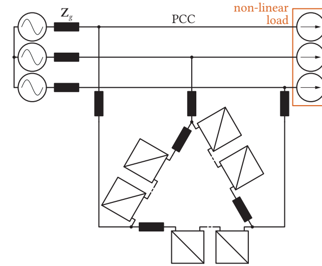
- Monolithic ML topologies (NPC, NPP, FC, ANPC) are not scalable
- Robicon drive → everyone offers it
- Siemens & Benshaw: MMC drive
- Low dv/dt ⇒ motor friendly





FACTS

- SFC for railway interties (direct catenary connection)
- STATCOM
- BESS (split batteries)



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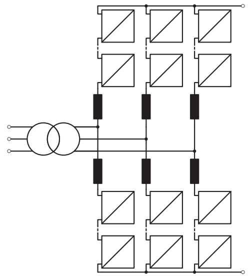

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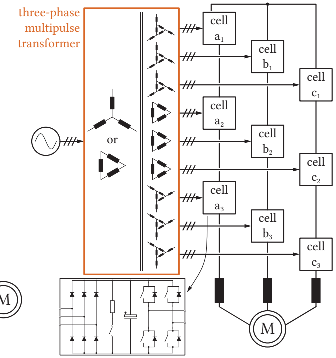

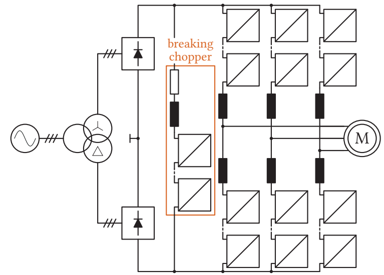

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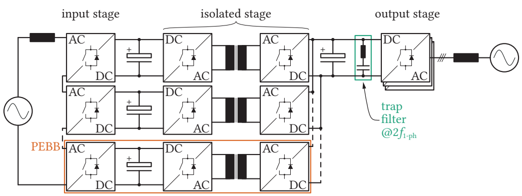

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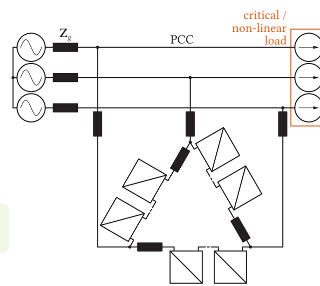


⇒ Modularity provides obvious benefits in high power applications!

SOLID STATE TRANSFORMER FOR TRACTION (ABB - 1.2MW PETT)

Characteristics

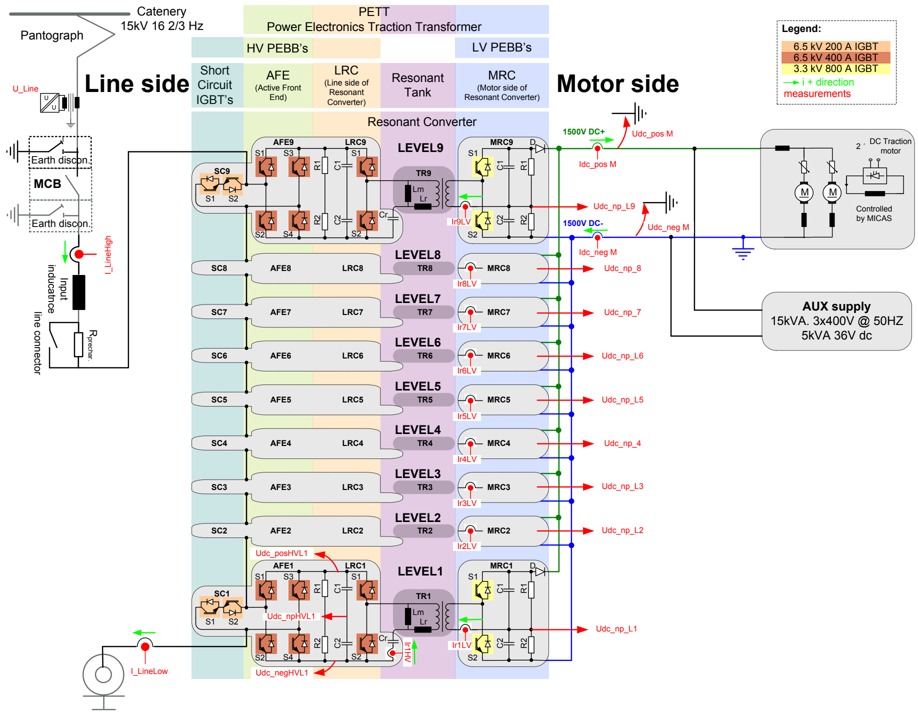
- 1-Phase MVAC to MVDC
- Power: 1.2MVA
- Input AC voltage: 15kV, 16.7Hz
- Output DC voltage: 1500 V
- 9 cascaded stages (n + 1)
- input-series output-parallel
- double stage conversion

99 Semiconductor Devices

- HV PEBB: 9 x (6 x 6.5kV IGBT)
- LV PEBB: 9 x (2 x 3.3kV IGBT)
- Bypass: 9 x (2 x 6.5kV IGBT)
- Decoupling: 9 x (1 x 3.3kV Diode)

9 MFTs

- Power: 150kW
- Frequency: 1.75kHz
- Core: Nanocrystalline
- Winding: Litz
- Insulation / Cooling: oil



▲ ABB PETT scheme [5], [6]

SOLID STATE TRANSFORMER FOR TRACTION - DESIGN

Retrofitted to shunting locomotive

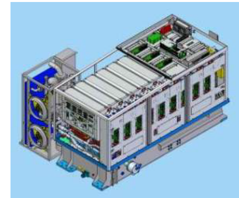
- Replaced LFT + SCR rectifier
- Propulsion motor - 450kW
- 12 months of field service
- No power electronic failures
- Efficiency around 96%
- Weight: ≈ 4.5 t

Technologies

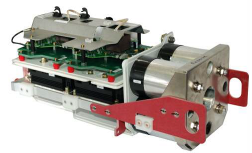
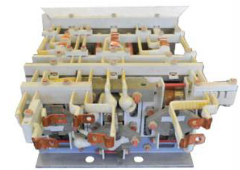
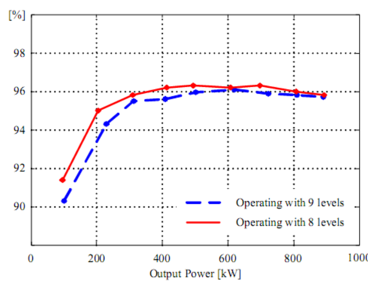
- Standard 3.3kV and 6.5kV IGBTs
- De-ionized water cooling
- Oil cooling/insulation for MFTs
- n + 1 redundancy
- IGBT used for bypass switch

Displayed at:

- Swiss Museum of Transport
- https://www.verkehrshaus.ch





▲ ABB PETT prototype [5], [6]

MEDIUM OR LOW FREQUENCY CONVERSION?

MVDC integration challenge

- MVDC-LVAC galvanically isolated conversion system

Desired conversion features

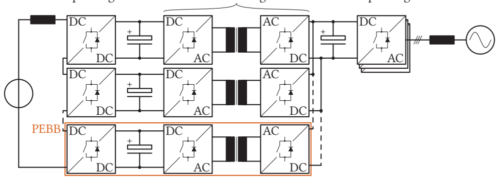
- High efficiency
- Galvanic isolation
- Modularity
- Scalability
- Reliability
- Availability

Laboratory prototype ratings

- $S = 0.5\,\text{MVA}$
- $N_{\text{cells}} = 6 \times 16$
- $V_{\text{dc}} = 10\,\text{kV}$
- $V_{\text{ac}} = 400\,\text{V}$

SST approach

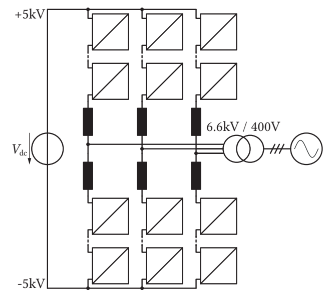
- VSI on LVAC side of SST reduces efficiency by ≈ 2 % (!) [7]
- Drawn solution is not the unique possibility

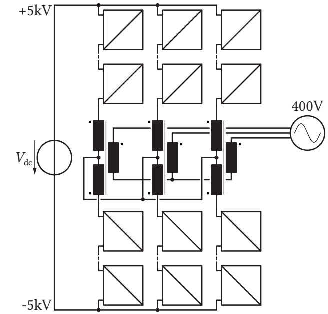


▲ Generic SST illustration for MVDC-LVAC conversion

MMC

- Solution with MMC + LFT has higher efficiency





Research opportunities

1. MMC topological variations and control methods
2. Modulation and branch balancing methods
3. Integration of branch inductances into the transformer structure: **GIMC**
4. Virtual Submodule Concept for fast cell loss estimation method [8]
5. MMC cell design optimization [9]

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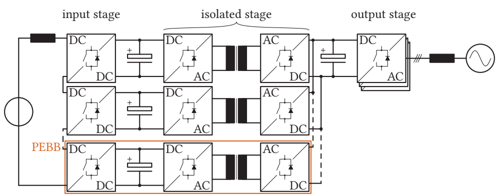

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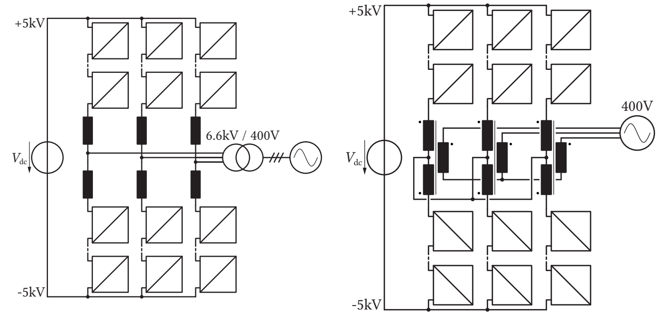

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⇒ The choice is not always obvious and greatly depends on the application requirements and constraints!

MODULAR MULTILEVEL CONVERTER

Fundamental operating principles, modeling, power equations

NOMENCLATURE

Cell (Submodule)

- Controllable devices (semiconductors)
- Energy storage element (capacitor)

Branch

- Controllable current / voltage source
- A string of cells (submodules)
- One reactor

Phase-leg

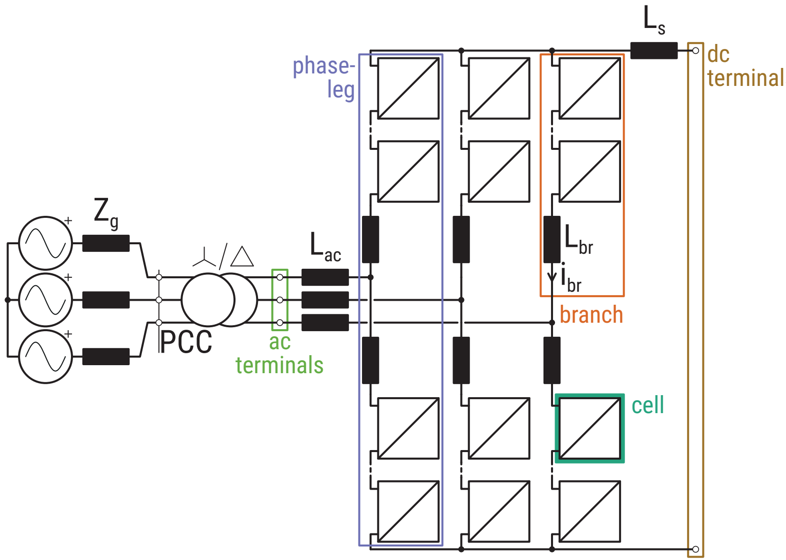
- Comprising two branches

AC terminals

- Connection to a grid (with or without transformer) or a load (e.g., ac machine)

DC terminals

- Connection to transmission line (overhead line or cable), load or other converter (back-to-back)



▲ Modular multilevel converter connected to an ac grid through a transformer

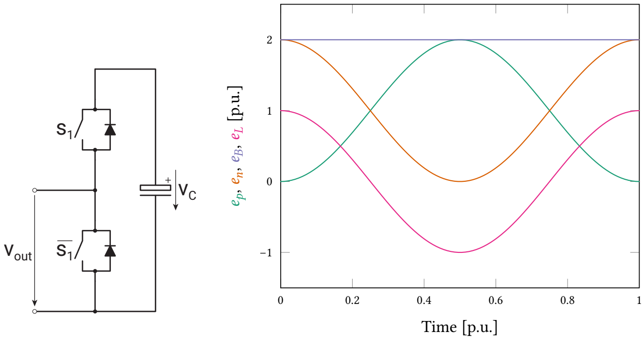
Functionality wise, only L_{br} is required!

Unipolar cell

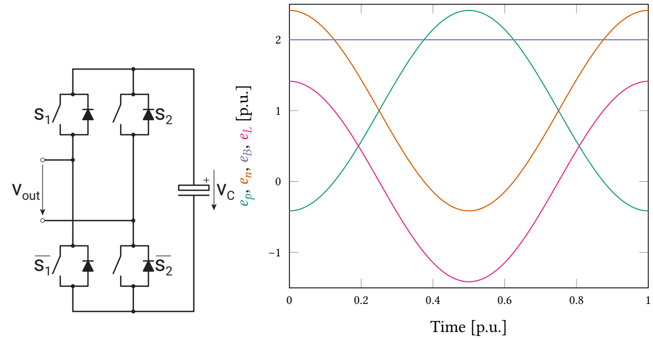
- Best for efficiency
- No fault blocking capability
- 2-level output voltage

Bipolar cell

- Fault blocking capability
- Conduction losses double
- 3-level output voltage



▲ Unipolar (half-bridge) Submodule



▲ Bipolar (full-bridge) Submodule

Many other variations and advanced cell types have been reported...

KVL equations

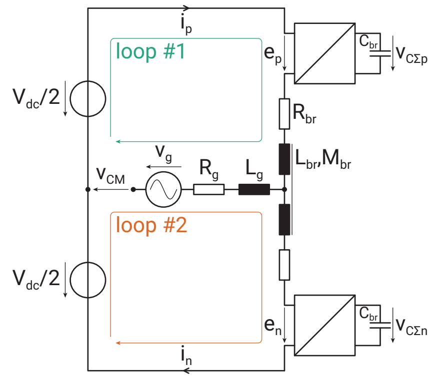
$$\frac{V_{\mathrm{dc}}}{2} = e_p + L_{\mathrm{br}}\frac{\mathrm{d}}{\mathrm{d}t}i_p - M_{\mathrm{br}}\frac{\mathrm{d}}{\mathrm{d}t}i_n + R_{\mathrm{br}}i_p + L_g\frac{\mathrm{d}}{\mathrm{d}t}(i_p - i_n) + R_g(i_p - i_n) + v_g + v_{\mathrm{CM}}$$

$$\frac{V_{\mathrm{dc}}}{2} = e_n + L_{\mathrm{br}}\frac{\mathrm{d}}{\mathrm{d}t}i_n - M_{\mathrm{br}}\frac{\mathrm{d}}{\mathrm{d}t}i_p + R_{\mathrm{br}}i_n - L_g\frac{\mathrm{d}}{\mathrm{d}t}(i_p - i_n) - R_g(i_p - i_n) - v_g - v_{\mathrm{CM}}$$

where $e_x = \sum_{i=1}^{N_{\mathrm{cells}}} s_{xi}v_{Cxi}$ (switched model) or $e_x = m_x v_{C\Sigma x}$ (average model)

Submodule capacitor voltages

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} v_{C\Sigma p} \\ v_{C\Sigma n} \end{bmatrix} = \frac{1}{C_{\mathrm{br}}}\begin{bmatrix} m_p & 0 \\ 0 & m_n \end{bmatrix}\begin{bmatrix} i_p \\ i_n \end{bmatrix}$$



▲ Single-phase MMC for modeling

First transformation

$$\begin{bmatrix} i_{\mathrm{circ}} \\ i_g \end{bmatrix} = \begin{bmatrix} 1/2 & 1/2 \\ 1 & -1 \end{bmatrix}\begin{bmatrix} i_p \\ i_n \end{bmatrix} \leftrightarrow \begin{bmatrix} i_p \\ i_n \end{bmatrix} = \begin{bmatrix} 1 & 1/2 \\ 1 & -1/2 \end{bmatrix}\begin{bmatrix} i_{\mathrm{circ}} \\ i_g \end{bmatrix}$$

$$\begin{bmatrix} e_B \\ e_L \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ -1/2 & 1/2 \end{bmatrix}\begin{bmatrix} e_p \\ e_n \end{bmatrix} \leftrightarrow \begin{bmatrix} e_p \\ e_n \end{bmatrix} = \begin{bmatrix} 1/2 & -1 \\ 1/2 & 1 \end{bmatrix}\begin{bmatrix} e_B \\ e_L \end{bmatrix}$$

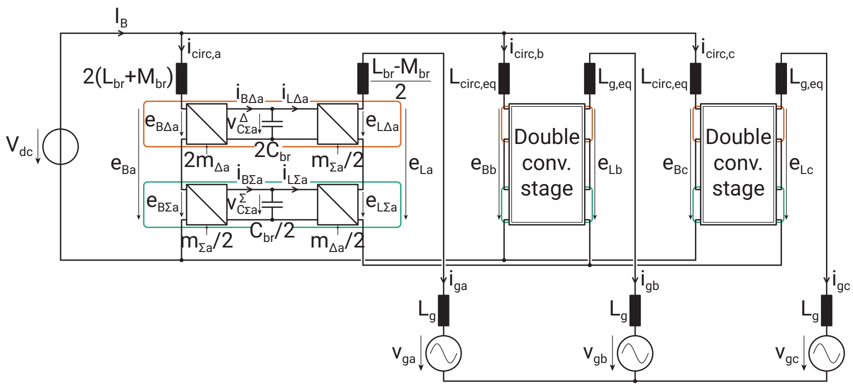
Second transformation

$$\begin{bmatrix} v_{C\Sigma}^{\Sigma} \\ v_{C\Sigma}^{\Delta} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ -1/2 & 1/2 \end{bmatrix}\begin{bmatrix} v_{C\Sigma p} \\ v_{C\Sigma n} \end{bmatrix} \leftrightarrow \begin{bmatrix} v_{C\Sigma p} \\ v_{C\Sigma n} \end{bmatrix} = \begin{bmatrix} 1/2 & -1 \\ 1/2 & 1 \end{bmatrix}\begin{bmatrix} v_{C\Sigma}^{\Sigma} \\ v_{C\Sigma}^{\Delta} \end{bmatrix}$$

$$\begin{bmatrix} m_{\Sigma} \\ m_{\Delta} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ -1/2 & 1/2 \end{bmatrix}\begin{bmatrix} m_p \\ m_n \end{bmatrix} \leftrightarrow \begin{bmatrix} m_p \\ m_n \end{bmatrix} = \begin{bmatrix} 1/2 & -1 \\ 1/2 & 1 \end{bmatrix}\begin{bmatrix} m_{\Sigma} \\ m_{\Delta} \end{bmatrix}$$

DECOUPLED MODEL

$$
\frac{d}{dt}\begin{bmatrix} i_{\mathrm{circ}} \\ i_g \\ v_{C\Sigma}^{\Sigma} \\ v_{C\Sigma}^{\Delta} \end{bmatrix} =
\begin{bmatrix}
-\frac{R_{\mathrm{br}}}{L_{\mathrm{br}}-M\mathrm{br}}\mathbb{I}_3 & -\frac{R_{\mathrm{br}}/2+R_g}{L_{\mathrm{br}}+M_{\mathrm{br}}+2L_g}\mathbb{I}_3 & \frac{(L_{\mathrm{br}}+L_g)\mathbb{M}_p+(M_{\mathrm{br}}+L_g)\mathbb{M}_n}{2(L_{\mathrm{br}}-M_{\mathrm{br}})(L_{\mathrm{br}}+2L_g+M_{\mathrm{br}})} & -\frac{(L_{\mathrm{br}}+L_g)\mathbb{M}_p-(L_g+M_{\mathrm{br}})\mathbb{M}_n}{(L_{\mathrm{br}}-M_{\mathrm{br}})(L_{\mathrm{br}}+2L_g+M_{\mathrm{br}})} \\
-\frac{R_{\mathrm{br}}}{L_{\mathrm{br}}-M_{\mathrm{br}}}\mathbb{I}_3 & \frac{R_{\mathrm{br}}/2+R_g}{L_{\mathrm{br}}+2L_g+M_{\mathrm{br}}}\mathbb{I}_3 & \frac{(L_{\mathrm{br}}+L_g)\mathbb{M}_n+(L_g+M_{\mathrm{br}})\mathbb{M}_p}{2(L_{\mathrm{br}}-M_{\mathrm{br}})(L_{\mathrm{br}}+2L_g+M_{\mathrm{br}})} & \frac{(L_{\mathrm{br}}+L_g)\mathbb{M}_n-(L_g+M_{\mathrm{br}})\mathbb{M}_p}{(L_{\mathrm{br}}-M_{\mathrm{br}})(L_{\mathrm{br}}+2L_g+M_{\mathrm{br}})} \\
\frac{1}{C_{\mathrm{br}}}\mathbb{M}_p & \frac{1}{2C_{\mathrm{br}}}\mathbb{M}_p & -\frac{1}{2C_{\mathrm{br}}R_{\mathrm{esr}}}\mathbb{I}_3 & \frac{1}{C_{\mathrm{br}}R_{\mathrm{esr}}}\mathbb{I}_3 \\
\frac{1}{C_{\mathrm{br}}}\mathbb{M}_n & -\frac{1}{2C_{\mathrm{br}}}\mathbb{M}_n & -\frac{1}{2C_{\mathrm{br}}R_{\mathrm{esr}}}\mathbb{I}_3 & -\frac{1}{C_{\mathrm{br}}R_{\mathrm{esr}}}\mathbb{I}_3
\end{bmatrix}
\begin{bmatrix} i_{\mathrm{circ}} \\ i_g \\ v_{C\Sigma}^{\Sigma} \\ v_{C\Sigma}^{\Delta} \end{bmatrix} +
\begin{bmatrix}
\frac{3}{4(L_{\mathrm{br}}-M_{\mathrm{br}})}\mathbb{I}_{3\times1} & -\frac{1}{2(L_{\mathrm{br}}+2L_g+M_{\mathrm{br}})}\mathbb{I}_3 \\
\frac{1}{4(L_{\mathrm{br}}-M_{\mathrm{br}})}\mathbb{I}_{3\times1} & -\frac{3}{2(L_{\mathrm{br}}+2L_g+M_{\mathrm{br}})}\mathbb{I}_3 \\
\mathbb{O}_{3\times1} & \mathbb{O}_3 \\
\mathbb{O}_{3\times1} & \mathbb{O}_3
\end{bmatrix}
\begin{bmatrix} V_{\mathrm{dc}} \\ v_g + v_{\mathrm{CM}}\mathbb{I}_{3\times1} \end{bmatrix}
$$



▲ Decoupled MMC model with main and secondary paths

POWER EQUATIONS (I)

$$e_{p/n}(t) = \frac{V_{dc}}{2} \mp \left(v_g(t) + v_{CM}(t)\right) - \left(R_{br} i_{p/n}(t) + L_{br}\frac{d}{dt} i_{p/n}(t) - M_{br}\frac{d}{dt} i_{n/p}(t)\right)$$

$$i_{p/n}(t) = \frac{I_{dc}}{3} \pm \frac{i_g(t)}{2} + i_{circ}(t)$$

where

V_{dc}	the dc-link voltage
$v_g(t) = k_{ac}\frac{V_{dc}}{2}\cos\left(\omega t - \frac{2\pi(k-1)}{3}\right)$	the ac grid voltage
$v_{CM}(t) = \sum_i \hat{v}_{CM,i}\cos(i3\omega t)$	the CM voltage
I_{dc}	the dc-link current
$i_g(t) = \hat{i}_g \cos\left(\omega t + \varphi - \frac{2\pi(k-1)}{3}\right)$	the ac grid current
$i_{circ}(t) = \sum_{6 \nmid l} \hat{i}_{circ,l}\cos\left(l2\omega t + \theta_l - \frac{2\pi(k-1)}{3}\right)$	the circulating current

with $k \in \{1, 2, 3\}$ the phase number.

POWER EQUATIONS (II)

Generic formulation $p_{p/n}(t) = e_{p/n}(t) i_{p/n}(t)$

$$p_{p/n}(t) = \frac{V_{dc} I_{dc}}{6} \pm \frac{V_{dc} i_g(t)}{4} + \frac{V_{dc} i_{circ}(t)}{2} \mp \frac{I_{dc}\left(v_g(t) + v_{CM}(t)\right)}{3} - \frac{i_g(t)\left(v_g(t) + v_{CM}(t)\right)}{2} \mp i_{circ}(t)\left(v_g(t) + v_{CM}(t)\right) - \left(R_{br} i_{p/n}(t)^2 + L_{br} i_{p/n}(t) \frac{d}{dt} i_{p/n}(t) - M_{br} i_{p/n}(t) \frac{d}{dt} i_{n/p}(t)\right)$$

Transformation

$$\begin{bmatrix} p_\Sigma \\ p_\Delta \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ -1/2 & 1/2 \end{bmatrix} \begin{bmatrix} p_p \\ p_n \end{bmatrix}$$

- p_Σ only contains even harmonics
- p_Δ only contains odd harmonics

$$p_\Sigma(t) = \frac{V_{dc} I_{dc}}{3} + V_{dc} i_{circ}(t) - i_g(t)\left(v_g(t) + v_{CM}(t)\right) - 2\left[R_{br}\left(i_p(t)^2 + i_n(t)^2\right) + L_{br}\left(i_p(t)\frac{d}{dt} i_p(t) + i_n(t)\frac{d}{dt} i_n(t)\right) - M_{br}\left(i_p(t)\frac{d}{dt} i_n(t) + i_n(t)\frac{d}{dt} i_p(t)\right)\right]$$

$$p_\Delta(t) = -\frac{V_{dc} i_g(t)}{8} + \frac{I_{dc}\left(v_g(t) + v_{CM}(t)\right)}{6} + \frac{i_{circ}(t)\left(v_g(t) + v_{CM}(t)\right)}{2}$$

Reminder

Zero net energy balance $\int_0^T p_\Sigma \mathrm{d}t = 0$

Insight provided

- Circulating current optimization (in steady state!)
- Converter energy requirement
- Converter safe operating area (a bit optimistic though)

CIRCULATING CURRENT OPTIMIZATION (I)

- First discussed in [10].
- Without passives!

W/o circulating current

$$p_\Sigma(t) = \frac{I_{dc}V_{dc}}{3} - \hat{i}_g \cos(\omega t + \varphi) v_{CM}(t) - \frac{\hat{i}_g \hat{v}_g \cos(\varphi)}{2} - \frac{\hat{i}_g \hat{v}_g \cos(2\omega t + \varphi)}{2} + \underbrace{i_{circ}(t)}_{=0} V_{dc}$$

$$\Rightarrow I_{dc} = \frac{3\hat{i}_g \hat{v}_g \cos(\varphi)}{2V_{dc}}$$

W/o common mode

$$p_\Sigma(t) = \frac{V_{dc}I_{dc}}{3} + V_{dc} i_{circ}(t) - \frac{\hat{i}_g \hat{v}_g \cos(\varphi)}{2} - \frac{\hat{i}_g \hat{v}_g \cos(2\omega t + \varphi)}{2} = 0$$

$$\Rightarrow I_{dc} = \frac{3\hat{i}_g \hat{v}_g \cos(\varphi)}{2V_{dc}}$$

$$\Rightarrow i_{circ}(t) = \frac{\hat{i}_g \hat{v}_g \cos(2\omega t + \varphi)}{2V_{dc}}$$

W/ common mode

$$p_\Sigma(t) = -\hat{i}_g \cos(\omega t + \varphi) v_{CM}(t) - \frac{\hat{i}_g \hat{v}_g \cos(\varphi)}{2} - \frac{\hat{i}_g \hat{v}_g \cos(2\omega t + \varphi)}{2} + i_{circ}(t) V_{dc} + \frac{I_{dc}V_{dc}}{3} = 0$$

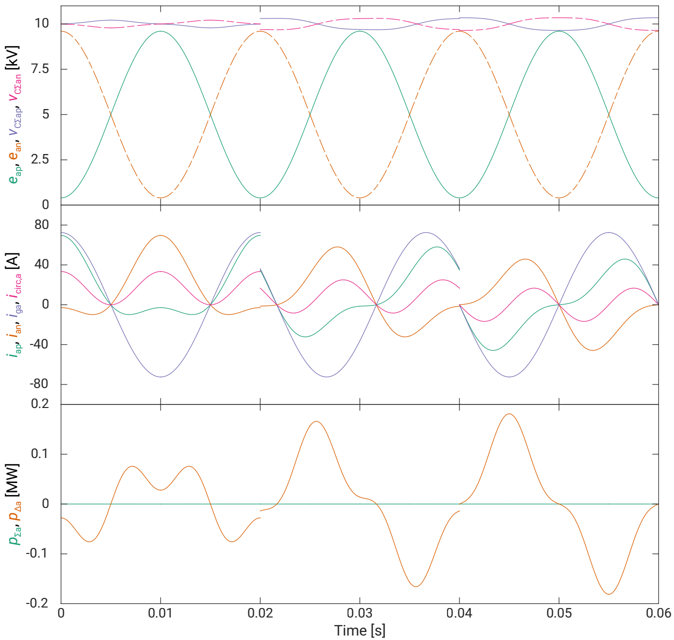
$$\Rightarrow I_{dc} = \frac{3\hat{i}_g \hat{v}_g \cos(\varphi)}{2V_{dc}}$$

$$\Rightarrow i_{circ}(t) = \frac{\hat{i}_g \left[2\cos(\omega t + \varphi) v_{CM}(t) + \hat{v}_g \cos(2\omega t + \varphi)\right]}{2V_{dc}}$$

which means 2^{nd} and 4^{th} harmonics (at least!)

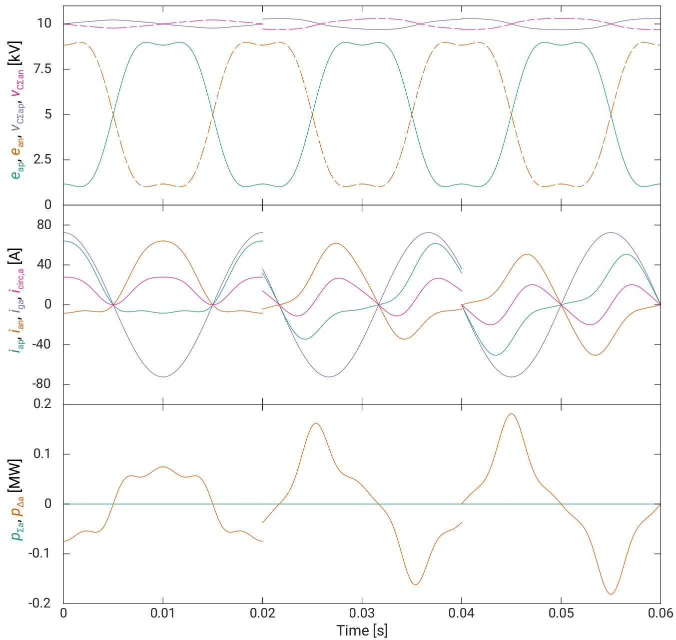
CIRCULATING CURRENT OPTIMIZATION (II)

W/o common mode



▲ MMC relevant waveforms without injection of the common mode voltage

W/ common mode



▲ MMC relevant waveforms with injection of the common mode voltage

Branch energy ripples

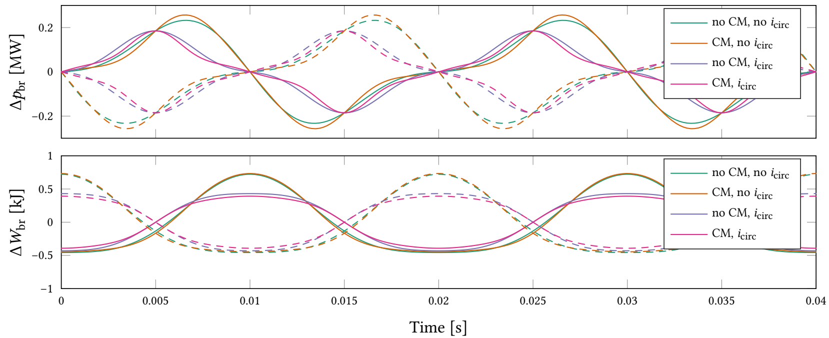
$$\Delta W_{\mathrm{br},+} = \frac{1}{2}C_{\mathrm{br}}v_{C\Sigma,\max}^{2} - \frac{1}{2}C_{\mathrm{br}}v_{C\Sigma 0}^{\star 2} \quad \rightarrow \quad C_{\mathrm{br}} = \frac{2\Delta W_{\mathrm{br},+}}{\left[(1+\varepsilon_{v_{C\Sigma}})^2 - 1\right] v_{C\Sigma 0}^{\star 2}}$$

$$\Delta W_{\mathrm{br},-} = \frac{1}{2}C_{\mathrm{br}}v_{C\Sigma 0}^{\star 2} - \frac{1}{2}C_{\mathrm{br}}v_{C\Sigma,\min} \quad \rightarrow \quad C_{\mathrm{br}} = \frac{2\Delta W_{\mathrm{br},-}}{\left[1 - (1-\varepsilon_{v_{C\Sigma}})^2\right] v_{C\Sigma 0}^{\star 2}}$$

Energy requirement $k_{\mathrm{ac}} = 0.9$, $v_{C\Sigma 0}^{\star} = V_{\mathrm{dc}}$ and $\varepsilon_{v_{C\Sigma}} = 10\,\%$

Case #	CM	2nd (+ 4th) harmonic	Energy requirement [kJ/MVA]
1	○	○	45.6
2	○	●	46.3
3	●	○	27.2
4	●	●	24.8

Time domain waveforms $\varphi = -\pi/2$ (worst case)



MMC CONTROL METHODS

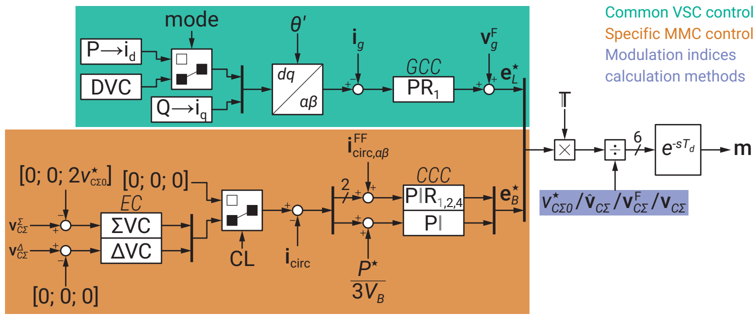
Similarities and differences with other voltage source converters

Two modes of operation:

1. Current source mode (also called inverter mode): transferring active power from the dc terminals to the ac terminals
2. Voltage source mode (also called rectifier mode): transferring active power from the ac terminals to the dc terminals

Two sets of state variables:

1. **External** state variables (dc-link voltage, grid currents, etc.): knowledge from VSC control is reused
2. **Internal** state variables (capacitor voltages, circulating currents): specific MMC control

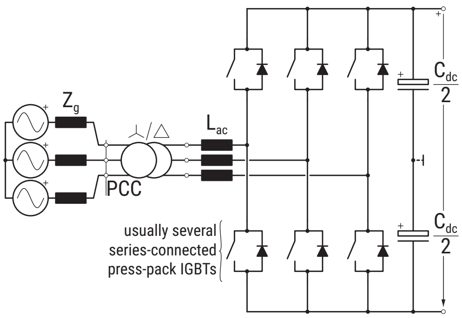


▲ Overall MMC control structure

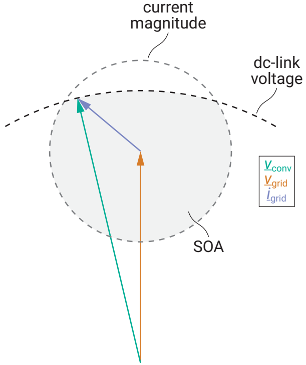
COMMON CONTROL LOOPS WITH OTHER VSC'S

HVDC light

- 2-level or 3-level
- Series-connected StakPak IGBTs
- Low switching frequency (no multiplication factor since it is a macro switch)
- Large filters for grid code compliance

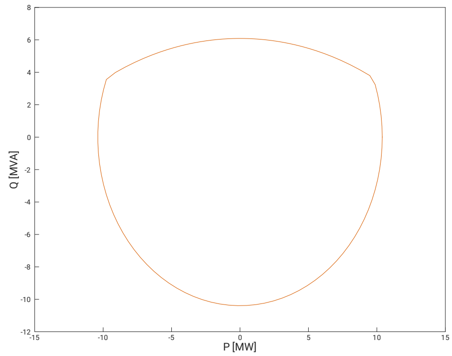


SOA derivation



P/Q diagram for the considered design

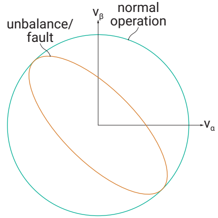
- $|V_{conv}| \leq V_{dc}/\sqrt{3}$ (CM injection)
- $I_{g,max} = 1$ kA (semi. devices)



Details about the control loops and their tuning can be found in: Amirnaser Yazdani and Reza Iravani. *Voltage-Sourced Converters in Power Systems:Modeling, Control, and Applications*. Wiley-IEEE Press, 2010

Aim

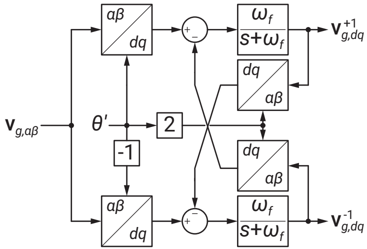
- Retrieve the positive and negative grid voltage sequences (in order to handle grid unbalances/faults)



▲ Unbalanced grid conditions

Decoupled Double Synchronous Reference Frame (DDSRF) [12]

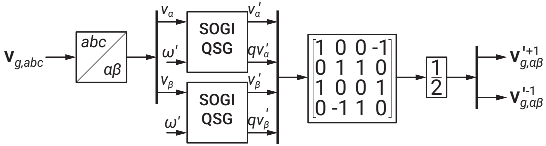
- Implementation in *dq* frame
- LPF to remove oscillations at twice the frequency



▲ Decoupled Double Synchronous Reference Frame

Double Second-Order Generalized Integrator (DSOGI)

- Implementation in $\alpha\beta$ frame
- No additional filters required (with SOGI, LPF on α and notch on β)



▲ Double Second-Order Generalized Integrator

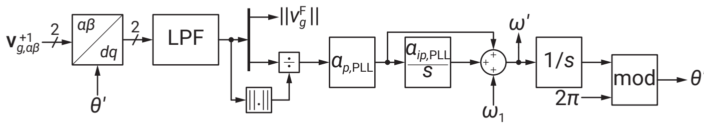
COMMON CONTROL LOOPS WITH OTHER VSC'S: PHASE-LOCKED LOOP (PLL)

Aim

- Retrieve the grid frequency
- Retrieve the grid angle (esp. for control in *dq* frame)

dq **PLL**

- Align with *d* axis by setting *q* component to 0
- Slow tuning to avoid instabilities

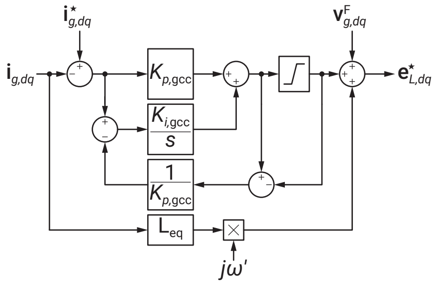


▲ Simple Phase Locked Loop scheme for 3-phase system

COMMON CONTROL LOOPS WITH OTHER VSC'S: GRID CURRENT CONTROL (GCC)

PI in *dq* **frame**

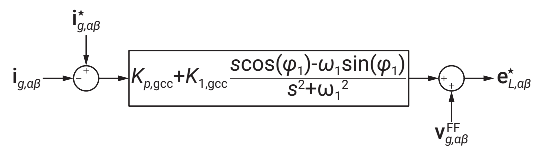
- Track dc components in a rotating reference frame
- Delay compensation by phase advance in the inverse Park transform



▲ Proportional Integral regulator in *dq* frame

PR in *αβ* **frame [13]**

- Track ac components in a stationary reference frame
- Delay compensation with $\varphi_h = h\omega_1 T_d$

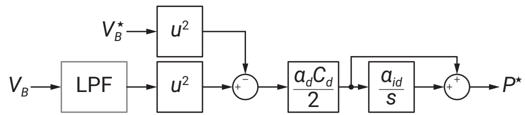


▲ Proportional Resonant regulator in *αβ* frame

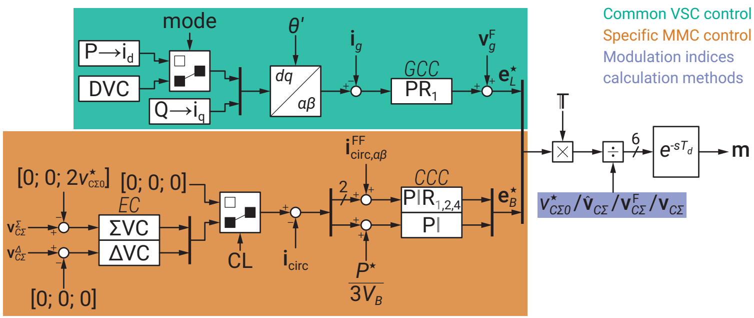
COMMON CONTROL LOOPS WITH OTHER VSC'S: DIRECT VOLTAGE CONTROL (DVC)

Voltage control

- Based on the energy rather than the voltage information to be linear
- Sets the active power reference to the converter controlling the dc voltage
- Energy instead of voltage control in order to be linear



▲ DC voltage control

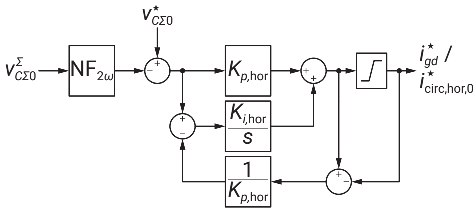


▲ Overall MMC control structure

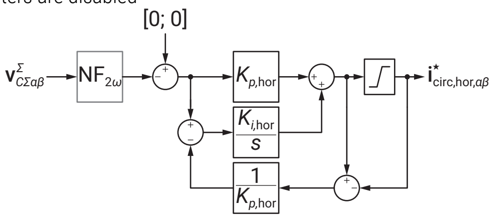
1. **Horizontal balancing**: shift energy between phase-legs using a CM current component
2. **Vertical balancing**: shift energy between branches using a fundamental ac current component

Horizontal balancing

- Redistribution the CM component (i.e., the dc current for a dc/ac MMC) with the zero component

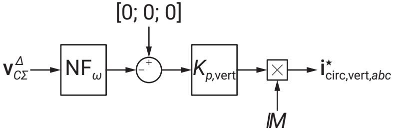


- Optimization of the capacitor voltage ripple with the $\alpha\beta$ components in case notch filters are disabled



Vertical balancing

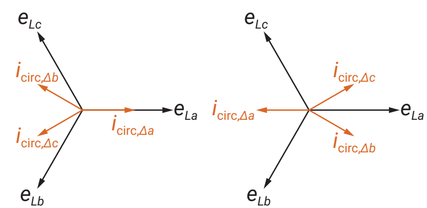
- Using a fundamental ac component



- Major contribution by [14] to cancel the circulating currents from vertical balancing at the dc terminals

$$\mathbb{M} = \begin{bmatrix} \cos(\theta_L) & \frac{-\sin(\theta_L)}{\sqrt{3}} & \frac{\sin(\theta_L)}{\sqrt{3}} \\ \frac{\sin(\theta_L - 2\pi/3)}{\sqrt{3}} & \cos(\theta_L - 2\pi/3) & \frac{-\sin(\theta_L - 2\pi/3)}{\sqrt{3}} \\ \frac{-\sin(\theta_L + 2\pi/3)}{\sqrt{3}} & \frac{\sin(\theta_L + 2\pi/3)}{\sqrt{3}} & \cos(\theta_L + 2\pi/3) \end{bmatrix}$$

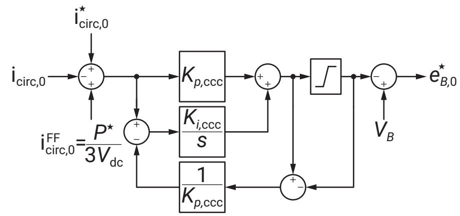
where θ_L is the load current angle



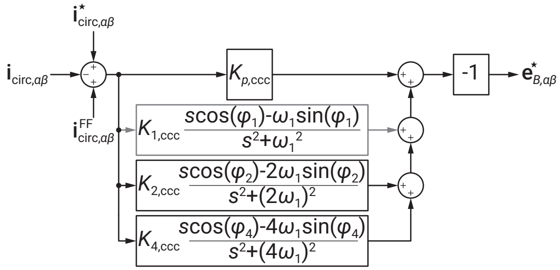
It has been shown in the power equations that the circulating current contains multiple low harmonic frequency components:

- **DC**: power exchange with the dc terminal, i.e., horizontal balancing
- **Fundamental AC**: vertical balancing
- **Second harmonic**: main component to be suppressed / controlled for capacitor voltage ripple reduction in steady-state
- **Fourth harmonic**: for capacitor voltage ripple reduction in steady-state with CM injection

PI and multiple R controllers are the best suited candidates to deal with these multiple harmonic components [15]



▲ Zero-sequence control



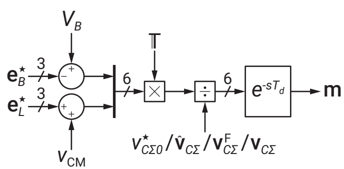
▲ $\alpha\beta$-sequence control

MODULATION INDEX CALCULATION METHODS (I): DIRECT MODULATION

- The modulation indices are calculated from the *desired* dc average value
- The energy controllers **are disabled**
- The odd harmonics and integrator on dc component in the circulating current control **are disabled**
- Rely on self balancing of the branch energies [16]

$$m_p = \frac{V_B/2 - e_B^\star/2 - e_L^\star}{v_{C\Sigma 0}^\star}$$

$$m_n = \frac{V_B/2 - e_B^\star/2 + e_L^\star}{v_{C\Sigma 0}^\star}$$



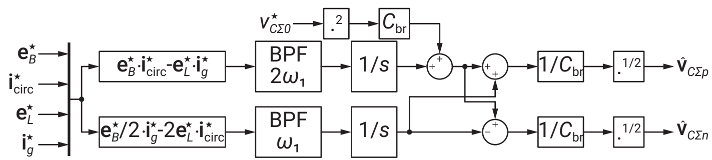
▲ Direct modulation principles

MODULATION INDEX CALCULATION METHODS (II): OPEN-LOOP CONTROL

- The modulation indices are calculated from *estimates* of the summed branch capacitors in steady-state [17]
- The energy controllers **are disabled**
- The odd harmonics and integrator on dc component in the circulating current control **are disabled**
- Self energy balance achieved [18]

$$m_p = \frac{V_B/2 - e_B^\star/2 - e_L^\star}{\hat{v}_{C\Sigma p}}$$

$$m_n = \frac{V_B/2 - e_B^\star/2 + e_L^\star}{\hat{v}_{C\Sigma n}}$$



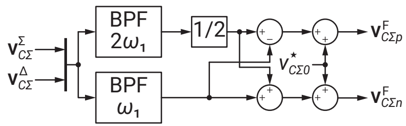
▲ Open-loop control

MODULATION INDEX CALCULATION METHODS (III): HYBRID VOLTAGE CONTROL

- The modulation indices are calculated from *filtered values* of the summed branch capacitors measurements
- The energy controllers **are disabled**
- The odd harmonics and integrator on dc component in the circulating current control **are disabled**
- Self energy balance achieved [19]

$$m_p = \frac{V_B/2 - e_B^\star/2 - e_L^\star}{v_{C\Sigma p}^F}$$

$$m_n = \frac{V_B/2 - e_B^\star/2 + e_L^\star}{v_{C\Sigma n}^F}$$



▲ Hybrid voltage control

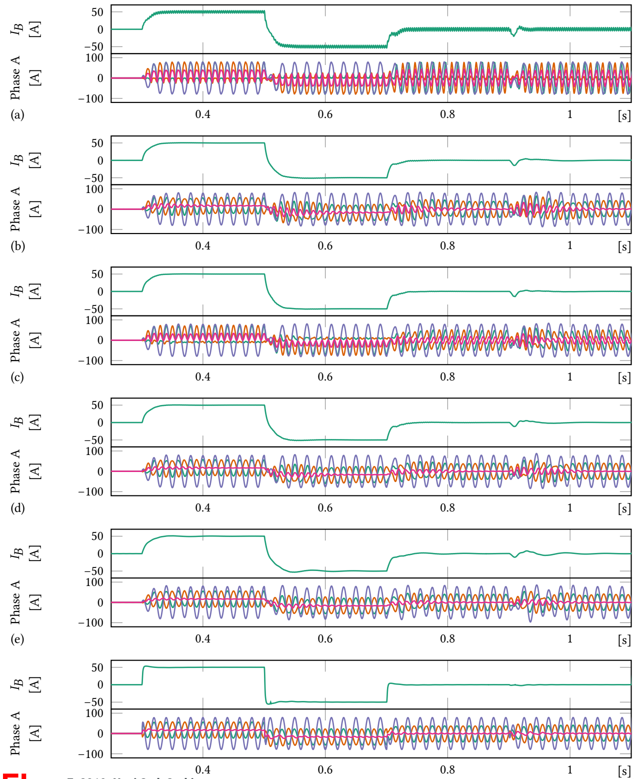
MODULATION INDEX CALCULATION METHODS (IV): CLOSED-LOOP CONTROL

- The modulation indices are calculated from the *actual measurements* of the summed branch capacitors
- The energy controllers **are enabled**
- The odd harmonics in the circulating current control **are enabled**

> ϟ This is by far the most complex control implementation, but at the same time the only method suitable for reaching the best dynamics.

MMC CONTROL PERFORMANCE BENCHMARK

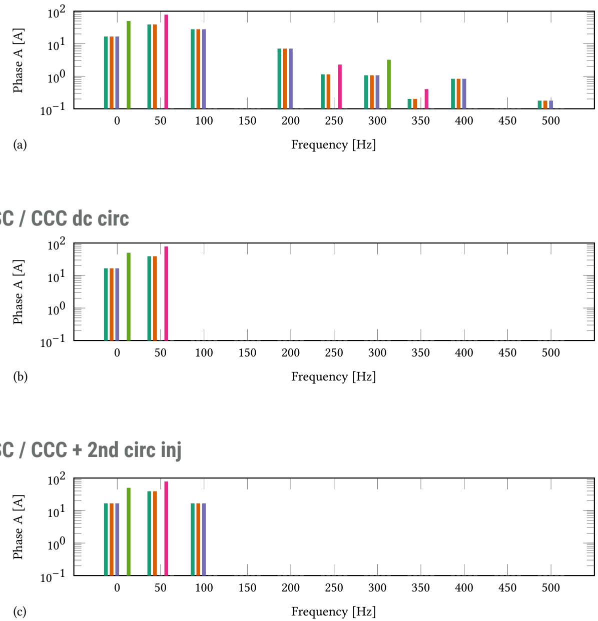
Inverter and Rectifier modes of operation...



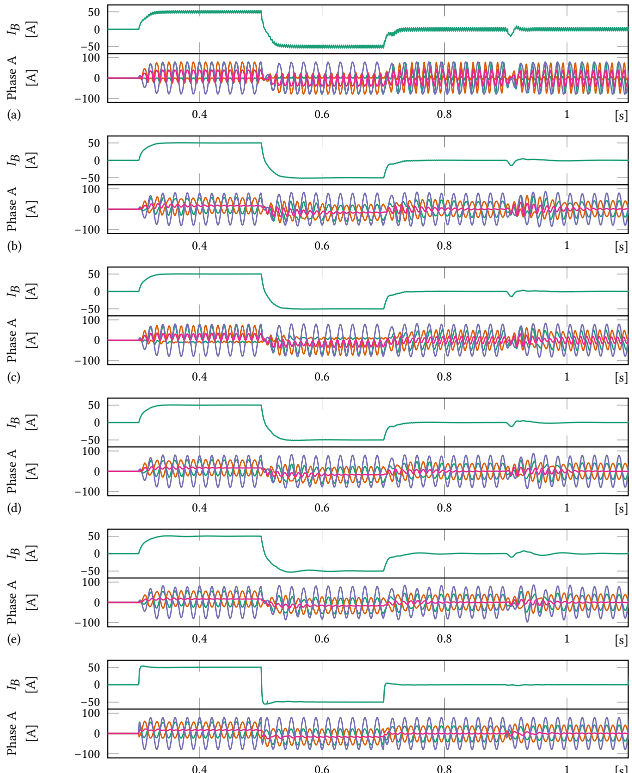
No CCC

CCSC / CCC dc circ

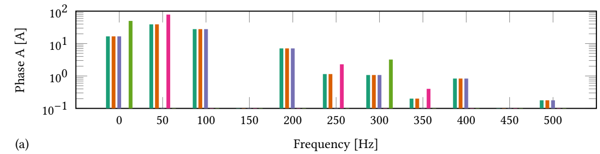
CCSC / CCC + 2nd circ inj



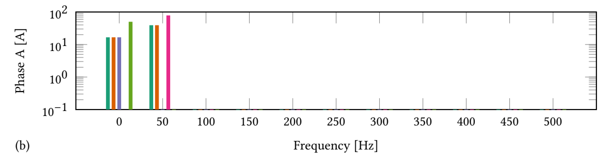
CURRENTS IN INVERTER MODE



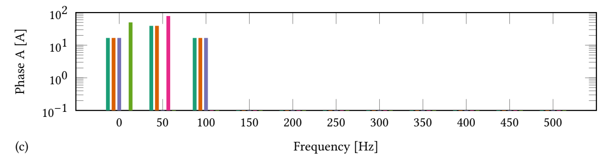
No CCC



CCSC / CCC dc circ

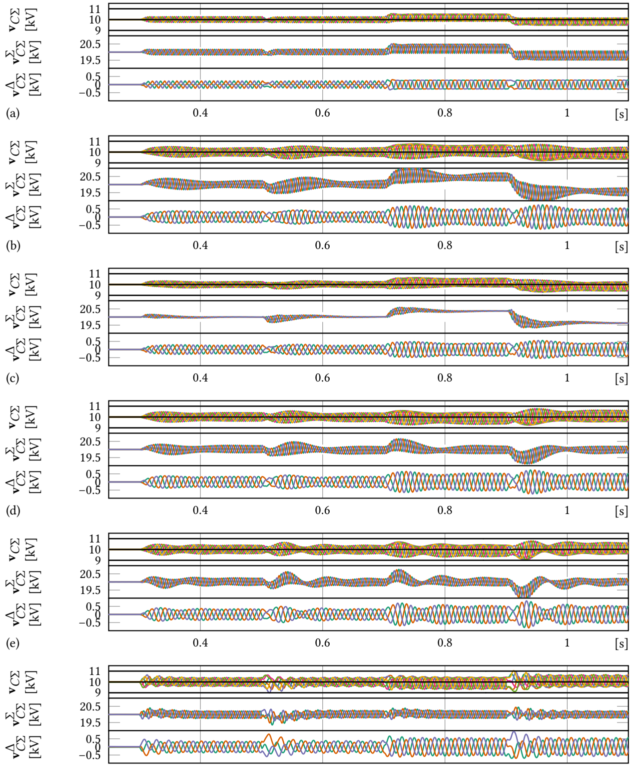


CCSC / CCC + 2nd circ inj



⇒ CCSC / CCC **mandatory** to cancel low order harmonics

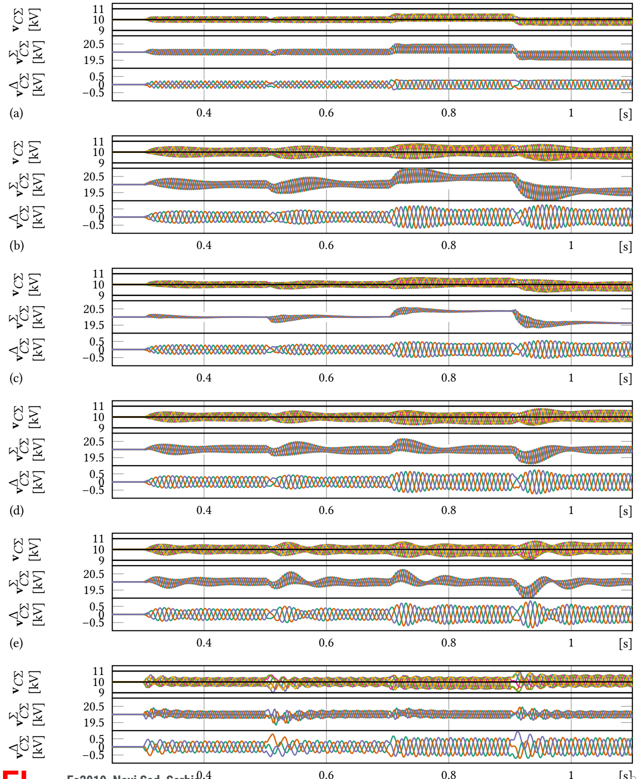
SUMMED CAPACITOR VOLTAGES IN INVERTER MODE



Few comments:

- With the direct modulation, $\mathbf{v}_{C\Sigma}^{\Sigma}$ is not properly controller on reactive power steps (it settles to a value close to $V_{C\Sigma 0}^{\star}$)
- With the direct modulation w/o CCSC, the energies are shifted between the phase-legs (thanks to the uncontrolled circulating current) $\Rightarrow$ smallest capacitor voltage ripples are observed
- The self-balancing is more performant than the closed-loop energy balancing (it takes 3 fundamental periods to rebalance the voltages), however consequence is that $\mathbf{v}_{C\Sigma}^{\Sigma}$ dynamics are sluggish (increased voltage variation & lightly damped oscillatory response)
- BPFs tuning is affecting the performance of the hybrid voltage control method

SUMMED CAPACITOR VOLTAGES IN INVERTER MODE



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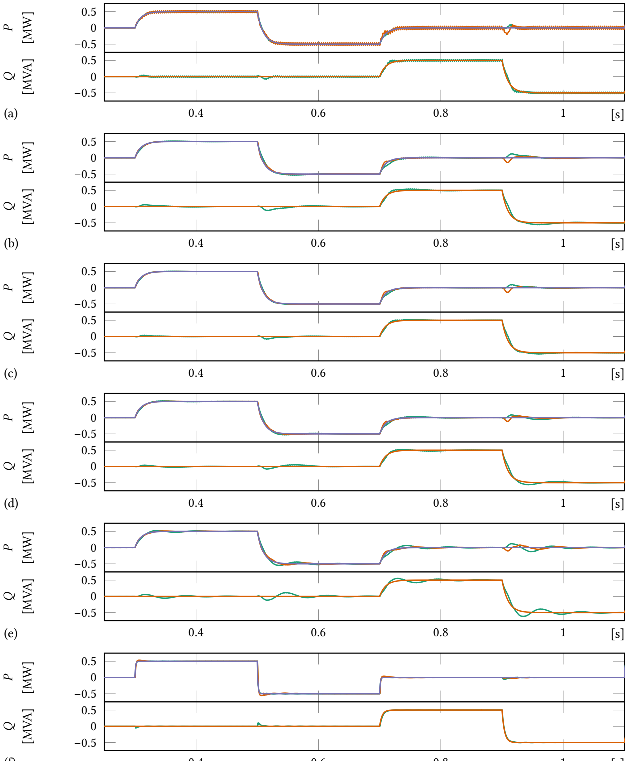
⇒ the branch energy control offers mitigated performances

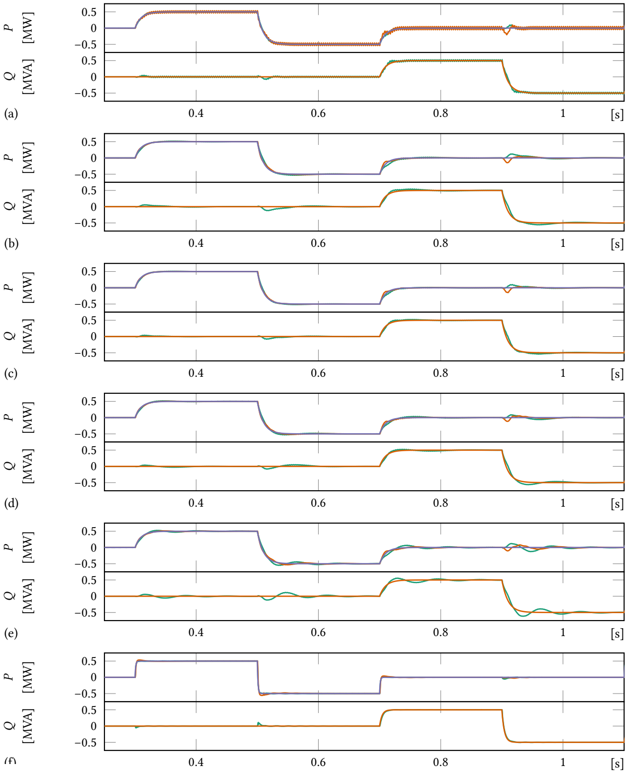
PQ TRACKING IN INVERTER MODE



Few comments:

- LPF filter bandwith 100 rad/s for self-balancing methods
- Low-order harmonics with direct modulation w/o CCSC
- Lightly damped oscillatory response with the hybrid voltage control method
- Dynamics are increased to 300 rad/s for the closed-loop control method without controller optimization
- Power decoupling is not perfect

PQ TRACKING IN INVERTER MODE



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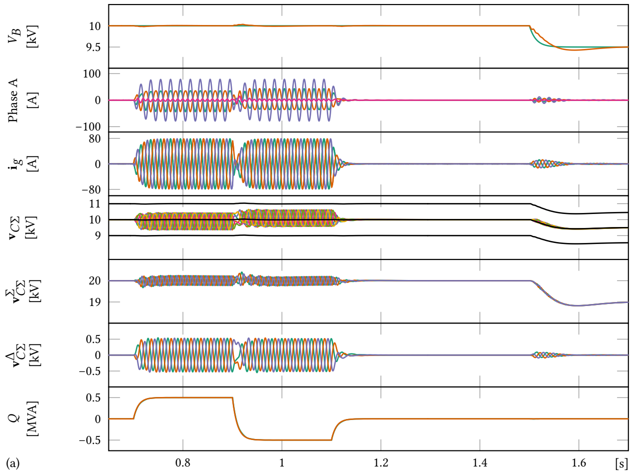
- Lightly damped oscillatory response with the hybrid voltage control method
- Dynamics are increased to 300 rad/s for the closed-loop control method without controller optimization
- Power decoupling is not perfect

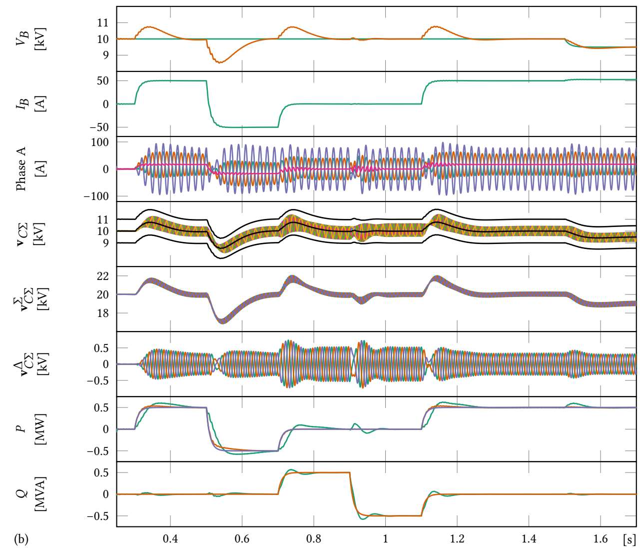
⇒ clear advantage of the closed-loop control method for highly dynamic applications

OPERATION IN RECTIFIER MODE

Open-circuit

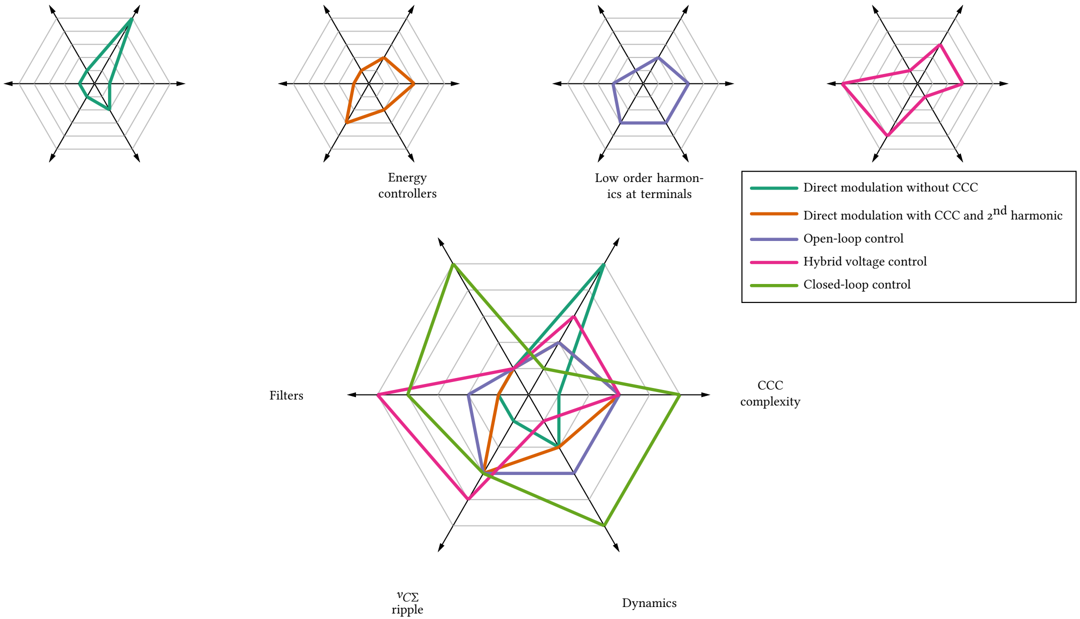


Current source



- Circulating currents are canceling out at the terminals

CONTROL METHOD PERFORMANCE RATING



⇒ the final choice depends on the application requirements / acceptable compromises between complexity and performance

MMC MODULATION METHODS

Variety of options are available...

CLASSIFICATION

- Choice and motivations for the choice completely different for an HVDC design compared to MVDC!

Carrier-based
- PS-PWM [20]
- LS-PWM (PD-PWM, etc.)
- SVM [21]

Programmed
- SHE [22]
- OPP [23], [24]

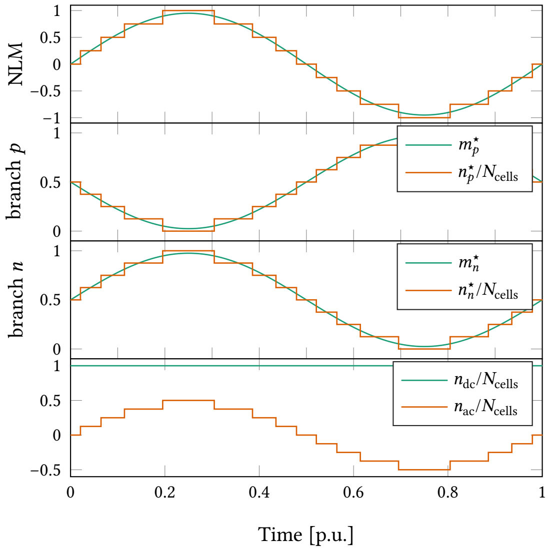
Decision based
- NLM
- FTB [25]

NUMBER OF VOLTAGE LEVELS PER BRANCH

- Assuming no required action from circulating current control!
- Unipolar cells as base case

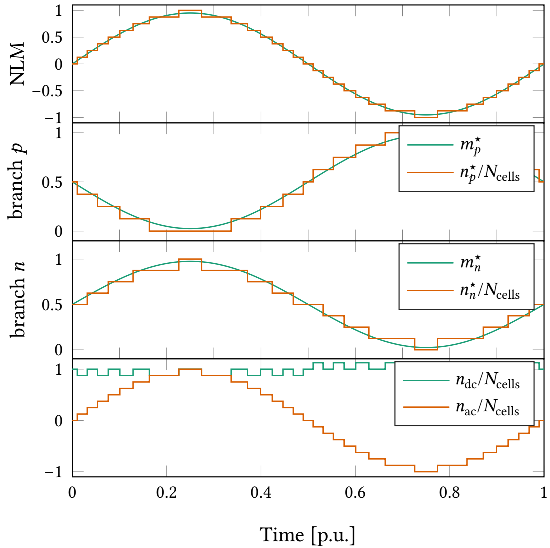
$N + 1$ modulation

- Synchronous switching of the branches within the same phase-leg



$2N + 1$ modulation

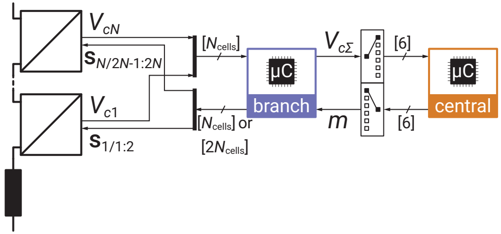
- Asynchronous switching of the branches within the same phase-leg



MAXIMUM LEVEL OF CONTROL DECENTRALIZATION

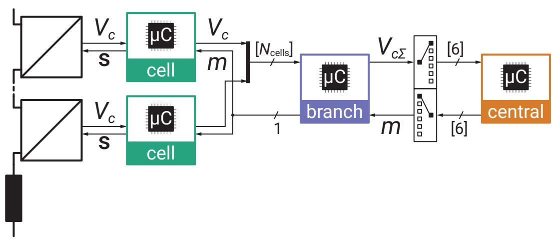
Branch level modulation

- Each branch handled separately



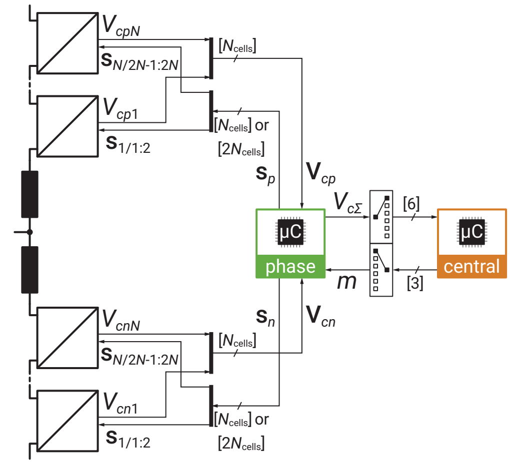
Cell level modulation

- Each cell has its own modulator



Phase-leg level modulation

- Aim at improving ac-side spectrum and unlocking full modulation method harmonic performance
- Compromises in the circulating current control
- SHE / OPP / SVM with $2N_{cells} + 1$ modulation



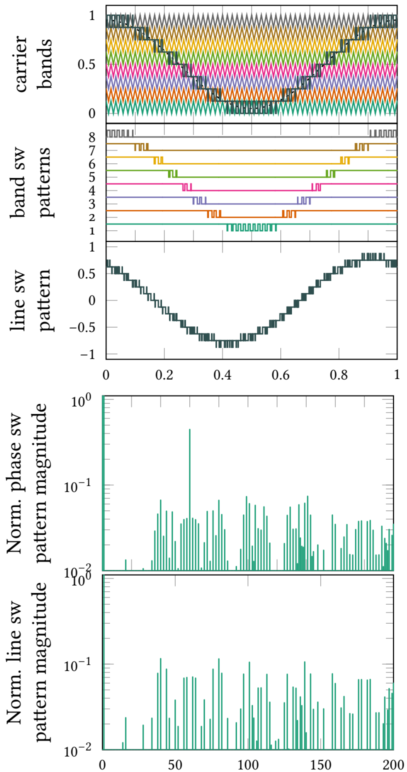
Remark µC denotes either a microcontroller, an FGPA, or a combination of both.

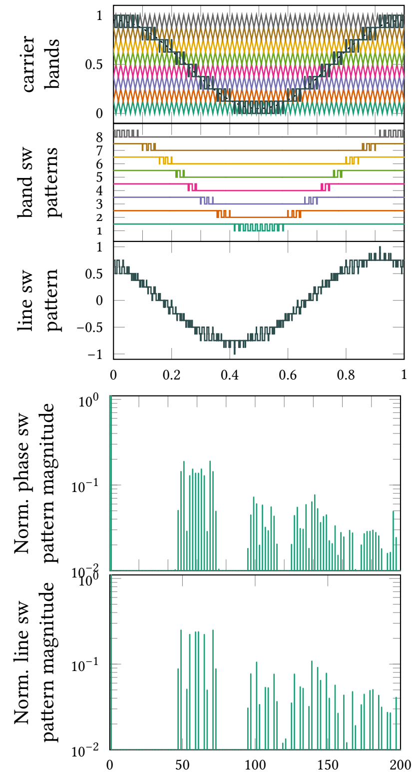
PD-PWM

- Phase switching pattern with high harmonic at switching frequency
- Line switching pattern with low harmonic peak
- Lower THD

APOD-PWM

- Phase switching pattern without strong harmonic at switching frequency
- Line switching pattern with distinctive carrier side bands
- Higher THD





SHE AND OPPS

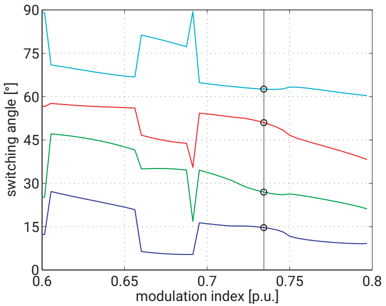
Selective Harmonic Elimination

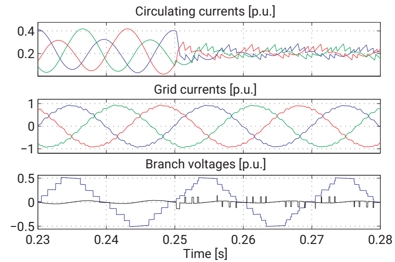
- Cancel one harmonic per switching angle plus 1 angle to set the modulation index over a quarter fundamental period
- Results in continuous switching angles ⇒ linear grid current controller
- $2N + 1$ modulation preferred when it comes to the circulating current control [26]

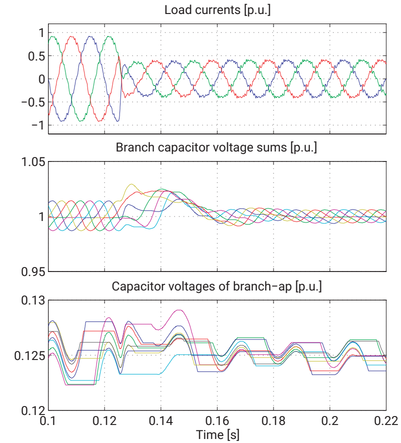
Optimized Pulse Patterns

- Cancel low order harmonics and incorporate user settable constraints on individual harmonics for a given number of switching angles over a quarter fundamental period
- Results in discontinuous switching angles ⇒ non-linear grid current controller
- Different circulating current control methods for $N + 1$ and $2N + 1$ modulation [24]

Results with OPPs from [24]



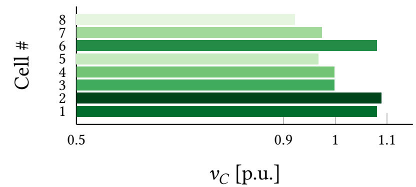


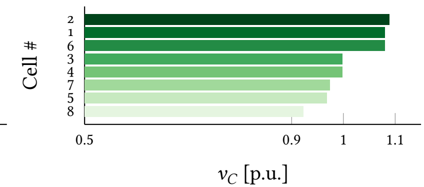


⇒ maximum performance without compromising the switching frequency

Principle

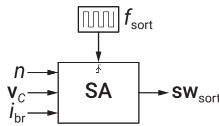
- Depending on the branch current polarity (and switching state), the inserted cells are either charged or discharged

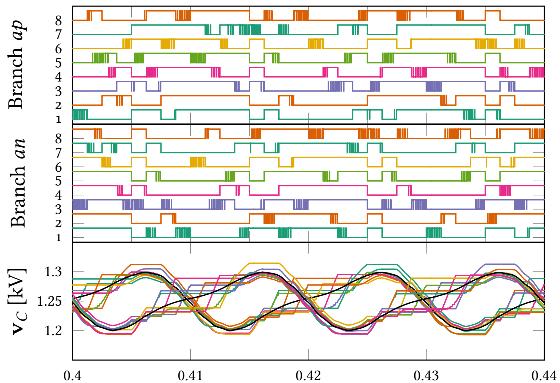




Simple sorting

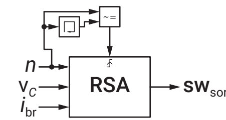
- The sorting algorithm is triggered at f_{sort}
- All switching signals can be modified

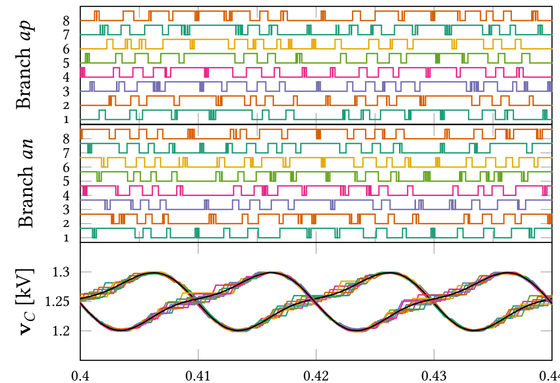




Restricted sorting [27]

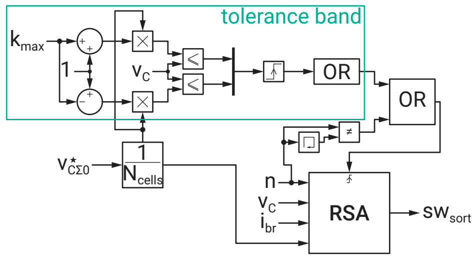
- The sorting algorithm is triggered when a switching transition occur
- No additional switching events!





Tolerance band [25]

- With very low switching frequency, the restricted algorithm cannot maintain the cell capacitor voltages within their limits
- Another condition forces the swapping of two cells when the bands are exceeded



▲ Restricted Sorting Algorithm with tolerance band

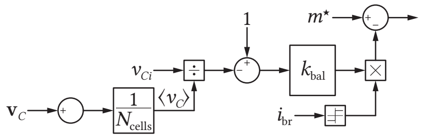
CELL BALANCING WITH DISTRIBUTED MODULATORS

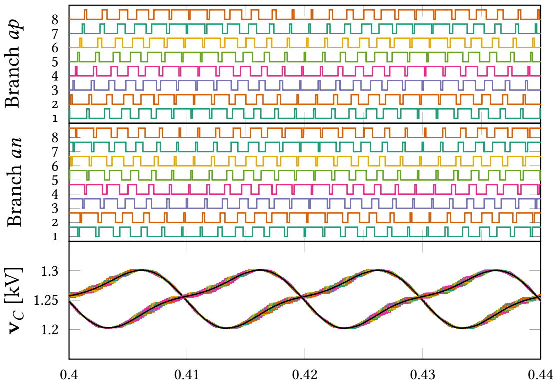
Principle

- The proportional control action cancel out at the branch level

Branch average based

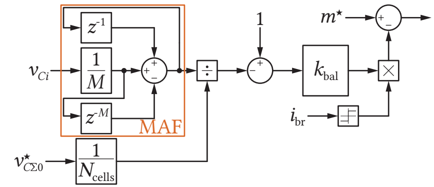
- The *instantaneous* summed branch capacitor average is sent by the branch controller [20]

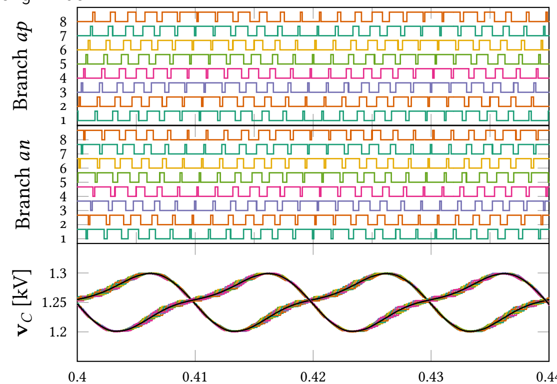


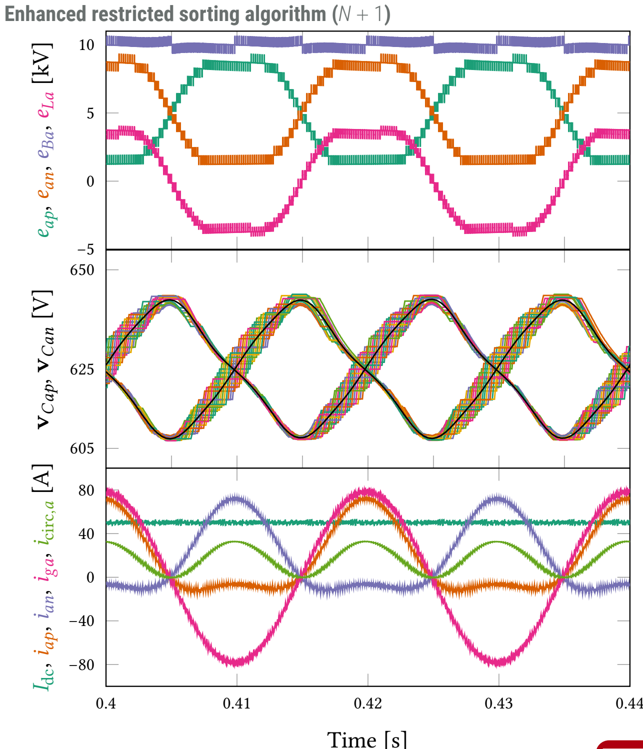


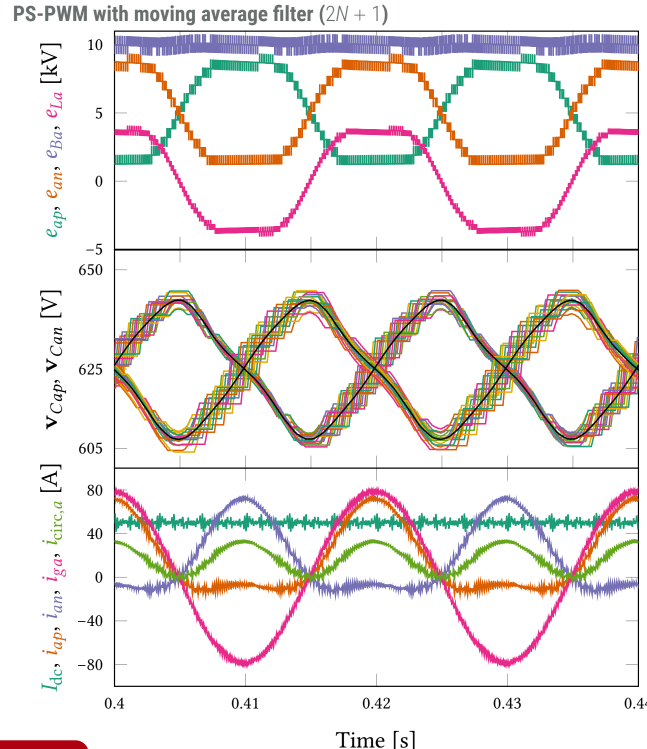
Moving average filter based

- The summed branch capacitor average is retrieved by a moving average filter with a long window



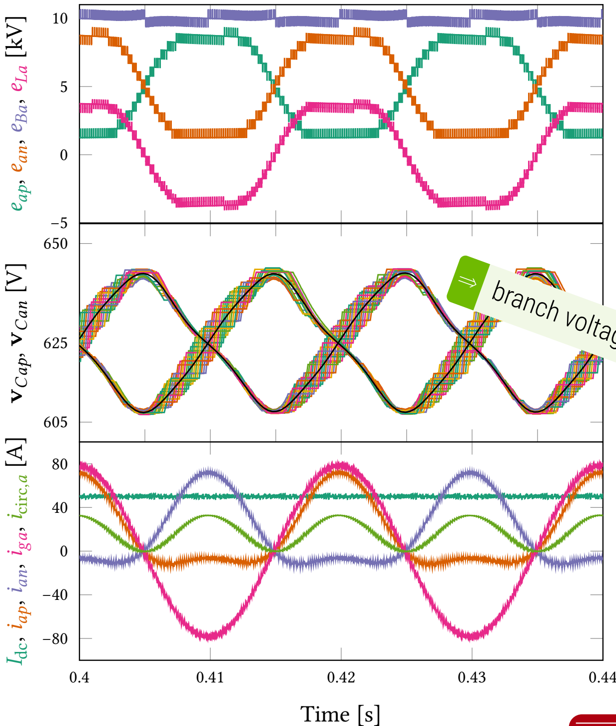




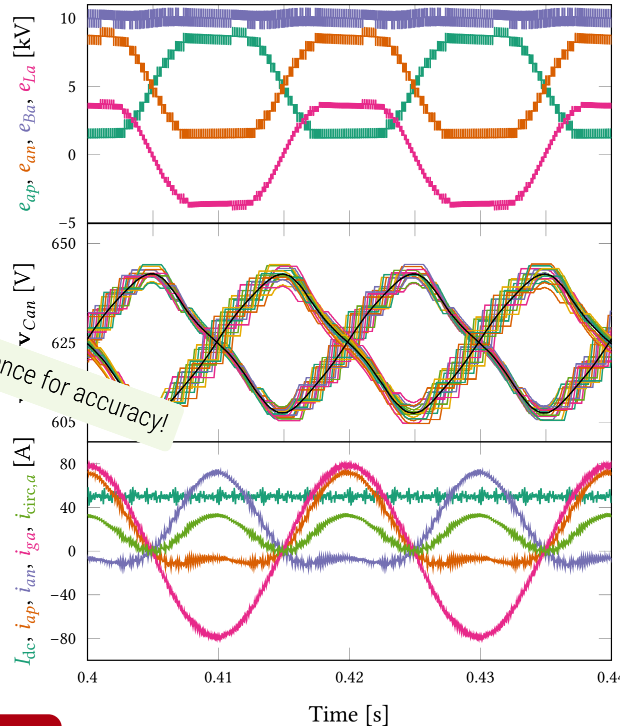


$\overline{f_{\text{sw,cell}}} = 375\,\text{Hz}$

Enhanced restricted sorting algorithm ($N + 1$)



PS-PWM with moving average filter ($2N + 1$)



⇒ branch voltage reference for accuracy!

$\overline{f_{sw,cell}} = 375\,\text{Hz}$

COFFEE BREAK

Well deserved...

COFFEE BREAK

Before the Coffee

1) Introduction and Motivation - MVDC
- MVDC Applications and Technologies
- MVDC Conversion Technologies
- Solid State Transformers

2) Modular Multilevel Converter Fundamentals
- Operating principles
- Modeling and Control
- Performance Benchmark

3) MMC Modulation Methods
- Carrier-based PWM, SVPWM
- Centralized vs. Distributed PWM
- SHE and OPPs

After the Coffee

4) High Power MMCs
- Branch Energy Balancing
- Power Extension
- Pulse Width Modulation

5) High Power DC-DC Conversion
- MMC-based DAB Topologies
- Quasi-Two-Level Converters
- Design and Control

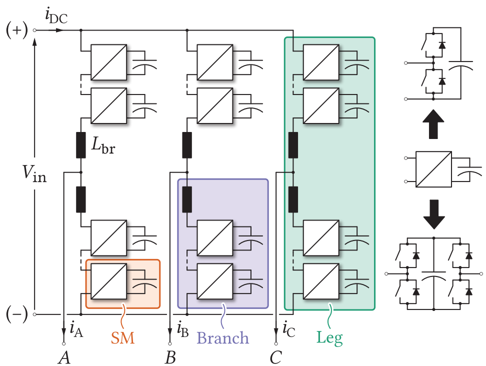
6) MMC Research Platform
- MMC system level design
- MMC RT-HIL development
- Questions and Discussion

⇒ Tutorial pdf can be downloaded from: *(Source:* `https://pel.epfl.ch/publications_talks_en`*)*

MMC POWER CAPACITY EXTENSION

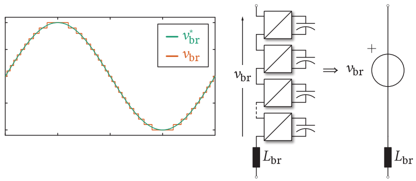
Boosting the power through branch paralleling...

MODULAR MULTILEVEL CONVERTER POWER SCALING



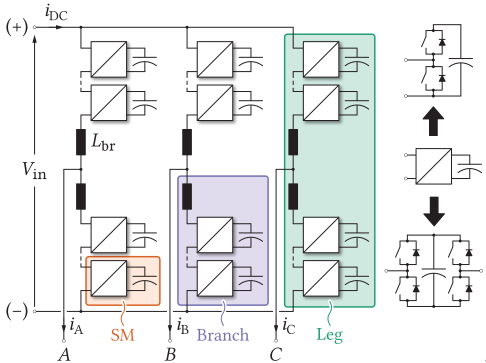
▲ Modular Multilevel Converter

- Series connection of HB/FB Submodules (SMs)
- Flexible in terms of voltage scaling
- High quality voltage waveforms



▲ Branch equivalent circuit with its voltage waveform

MODULAR MULTILEVEL CONVERTER POWER SCALING



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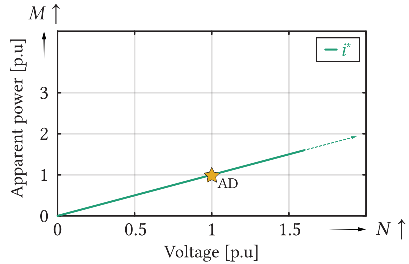
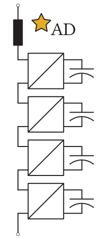


▲ MMC power scaling



▲ MMC branch voltage scaling

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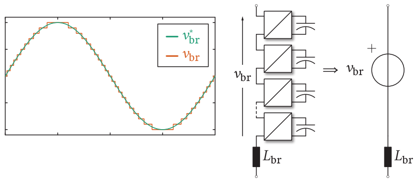
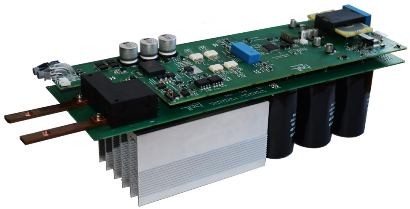


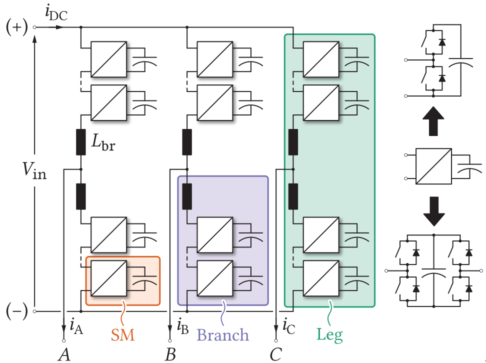
▲ Branch equivalent circuit with its voltage waveform

- Existing SM design is assumed

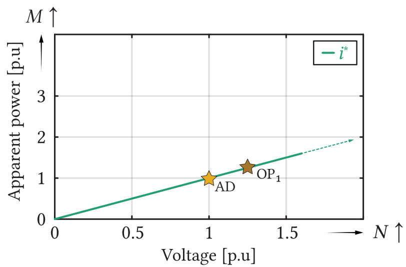


▲ SM designed at PEL

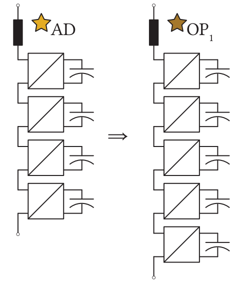
MODULAR MULTILEVEL CONVERTER POWER SCALING



▲ Modular Multilevel Converter



▲ MMC power scaling



▲ MMC branch voltage scaling

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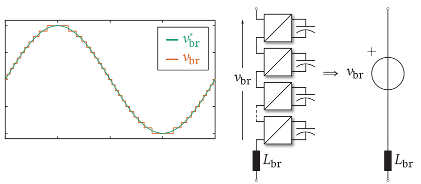
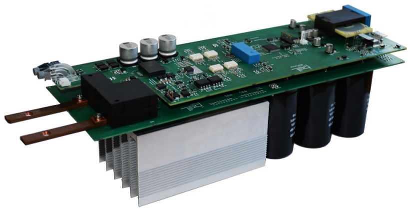
- Flexible in terms of voltage scaling
- High quality voltage waveforms



▲ Branch equivalent circuit with its voltage waveform

- Existing SM design is assumed
- **Linear** S=f(V) change **for a given current rating**



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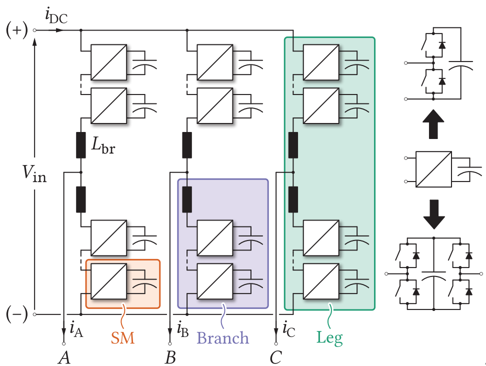
MODULAR MULTILEVEL CONVERTER POWER SCALING



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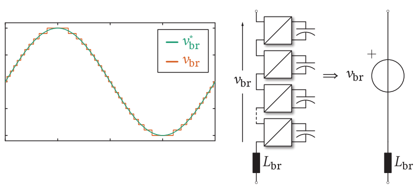
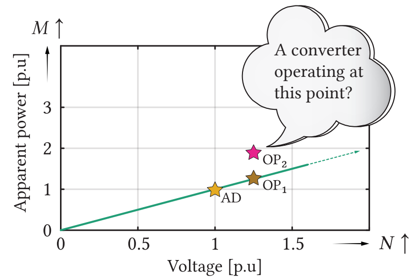


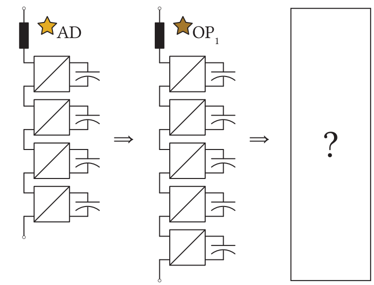
▲ Branch equivalent circuit with its voltage waveform



▲ MMC power scaling

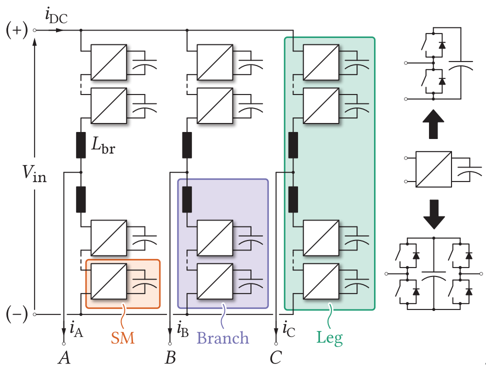
- Existing SM design is assumed
- **Linear** S=f(V) change **for a given current rating**

▲ SM designed at PEL

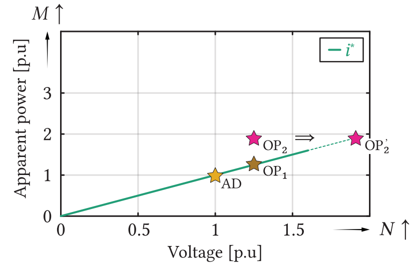


▲ MMC branch voltage scaling

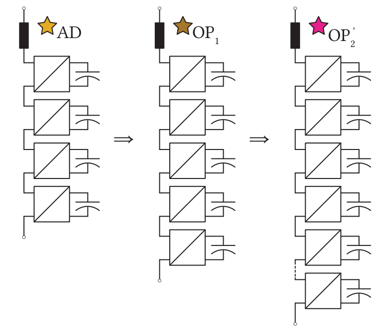
MODULAR MULTILEVEL CONVERTER POWER SCALING



▲ Modular Multilevel Converter

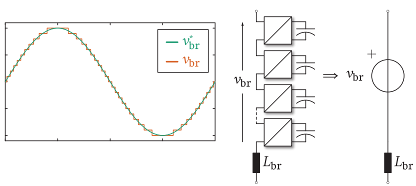


▲ MMC power scaling



▲ MMC branch voltage scaling

- Series connection of HB/FB Submodules (SMs)
- Flexible in terms of voltage scaling
- High quality voltage waveforms



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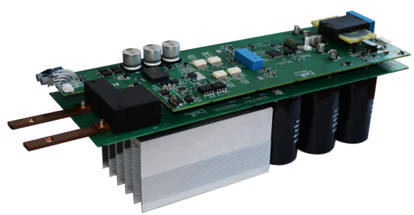
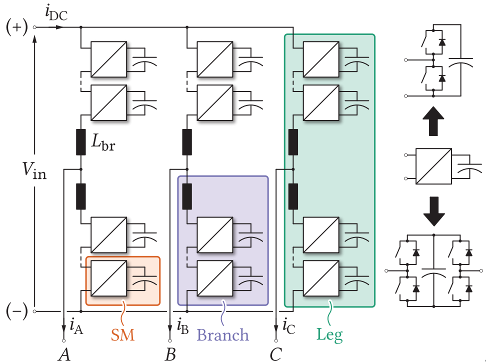


▲ SM designed at PEL

MODULAR MULTILEVEL CONVERTER POWER SCALING



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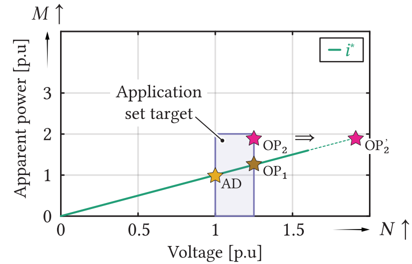
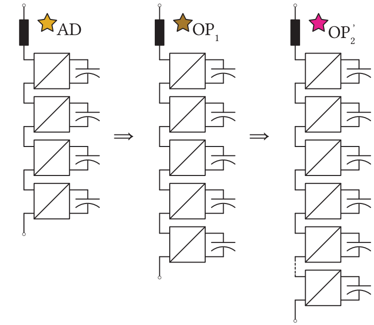


▲ MMC power scaling



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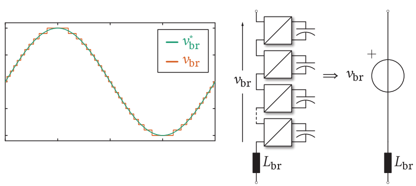

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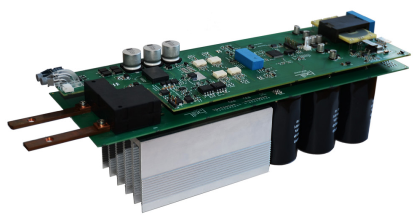
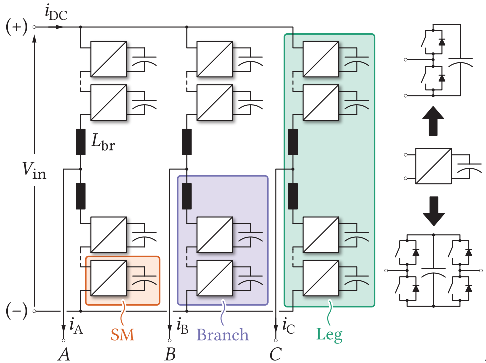
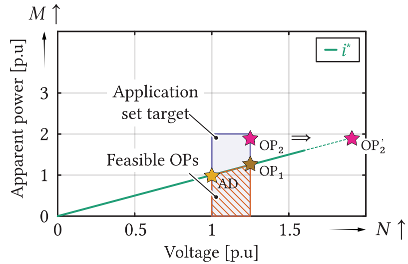


▲ SM designed at PEL

MODULAR MULTILEVEL CONVERTER POWER SCALING



▲ Modular Multilevel Converter



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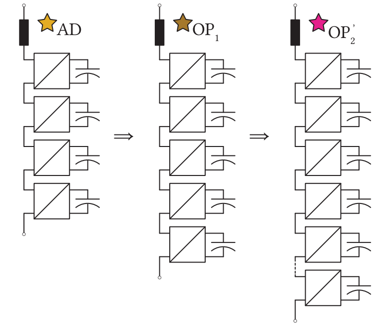

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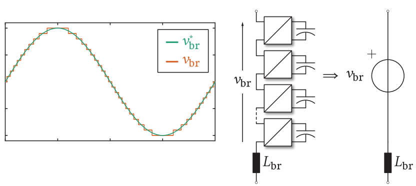

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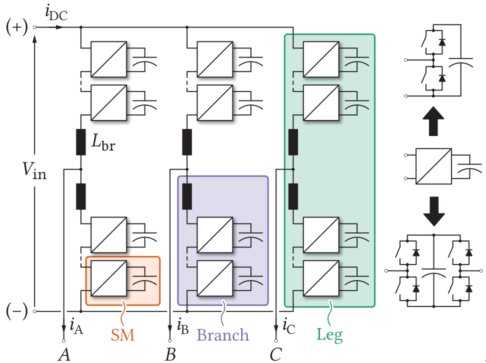
MODULAR MULTILEVEL CONVERTER POWER SCALING



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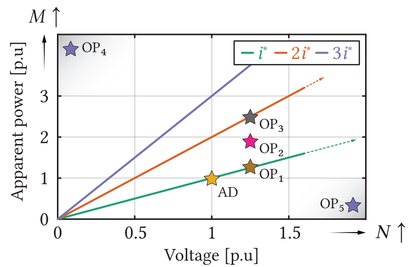

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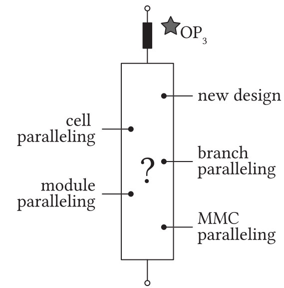

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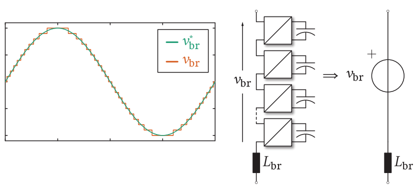
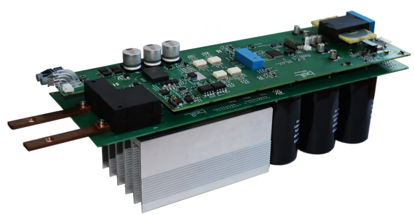


▲ Branch equivalent circuit with its voltage waveform

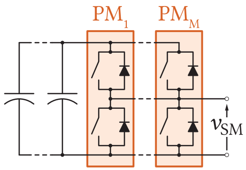
- Existing SM design is assumed
- **Linear** S=f(V) change **for a given current rating**
- Current capacity ↑ ⇒ new characteristics



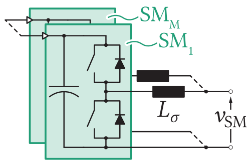
▲ SM designed at PEL

? How to increase current capacity?

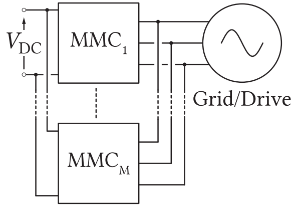
COMMON MMC CURRENT CAPACITY INCREASE METHODS



▲ Paralleling semiconductor modules

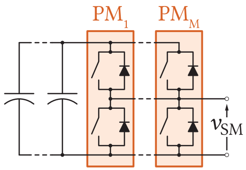


▲ Paralleling SMs



▲ Paralleling converters

COMMON MMC CURRENT CAPACITY INCREASE METHODS



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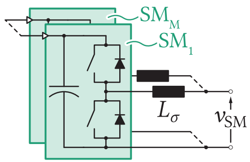

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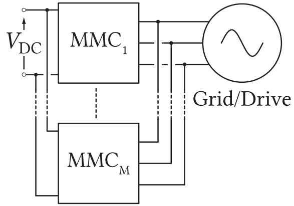

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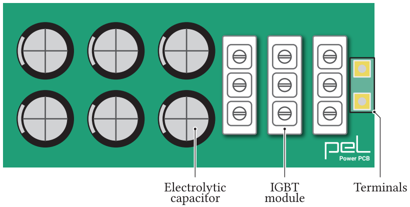
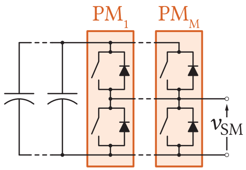


▲ Exemplary cell design; Current capacity - $3I_{\text{rated}}$

COMMON MMC CURRENT CAPACITY INCREASE METHODS



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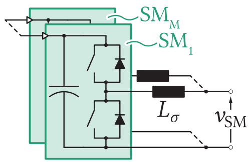

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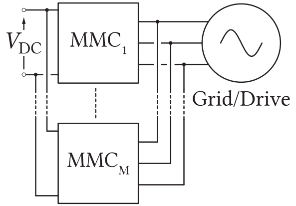
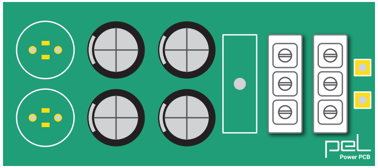
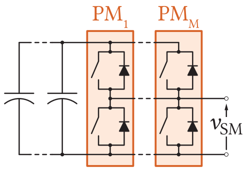


▲ Paralleling converters



▲ Exemplary cell design; Current capacity - $2I_{\text{rated}}$



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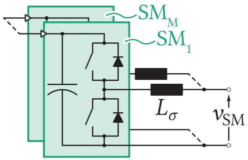

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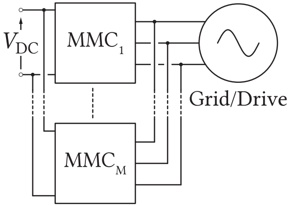

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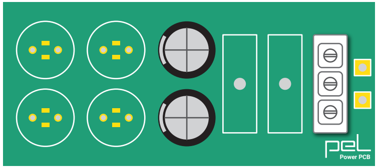
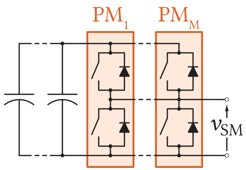


▲ Exemplary cell design; Current capacity - I_{rated}

- Special design considerations
- Cell frame size does not change
- Possible heat sink oversizing?

COMMON MMC CURRENT CAPACITY INCREASE METHODS



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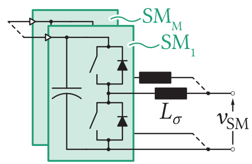

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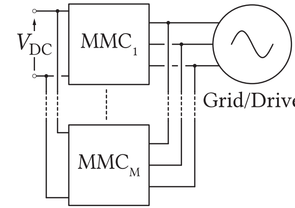

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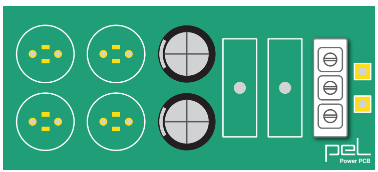

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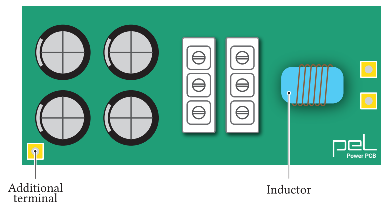
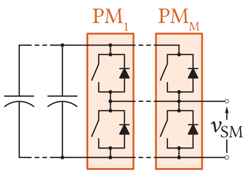


▲ Cell designed for paralleling

- Additional inductor is needed
- Additional terminal for the capacitors
- Special gate driver structure

COMMON MMC CURRENT CAPACITY INCREASE METHODS



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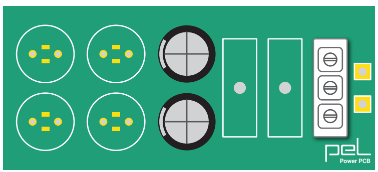

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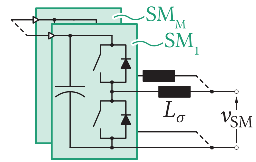

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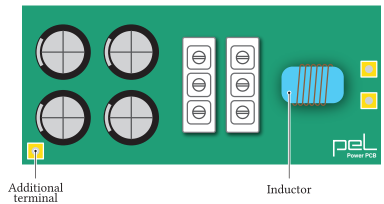

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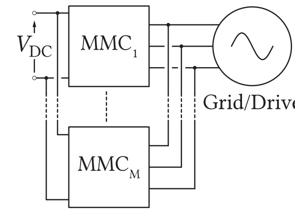
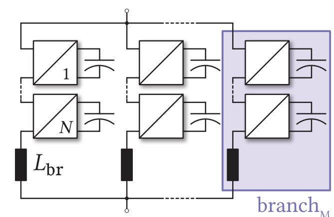


▲ Paralleling converters

- Well known principle
- Problem is shifted to the control domain

Paralleled MMC branches $\Rightarrow$ System simplification



▲ Paralleling branches

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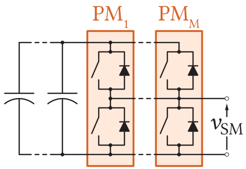

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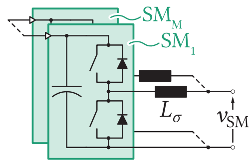

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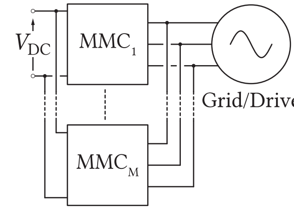

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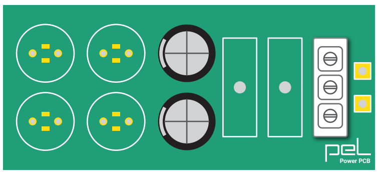

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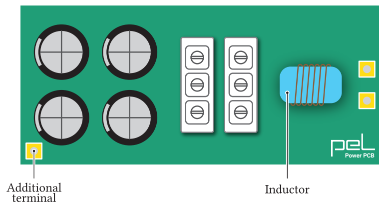

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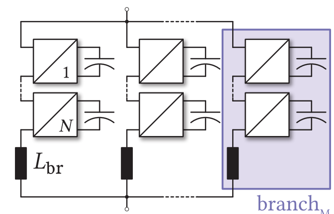


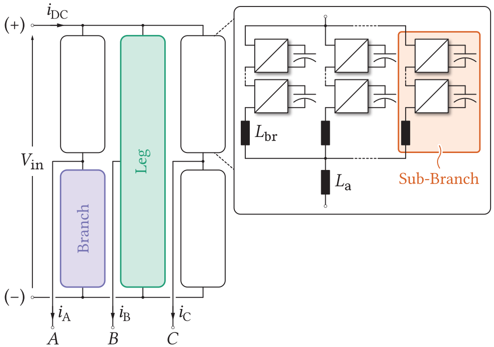
▲ Paralleling branches

⇒ If the branches are paralleled, there is no need to go through a new design process to accomplish the MMC power extension

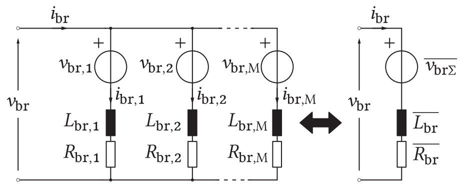
MODELING AND CONTROL

Deriving the additional control layer...

MODELING



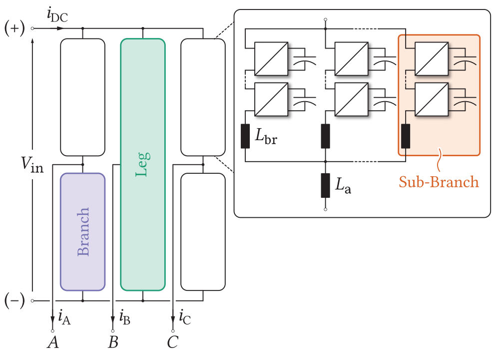
▲ MMC with paralleled (sub)branches



▲ Branch equivalent circuit

$$\overline{v_{br\Sigma}} = \frac{1}{M}\sum_{i=1}^{M} v_{br,i}$$

$$\overline{Z_{br}} = \frac{1}{M} Z_{br,i}$$



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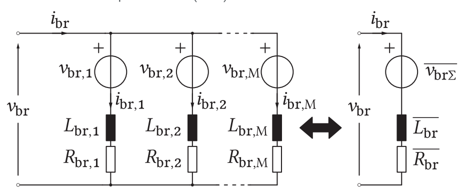

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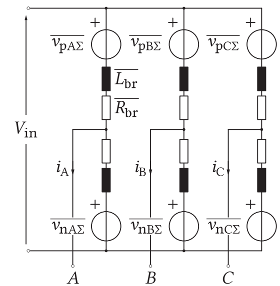
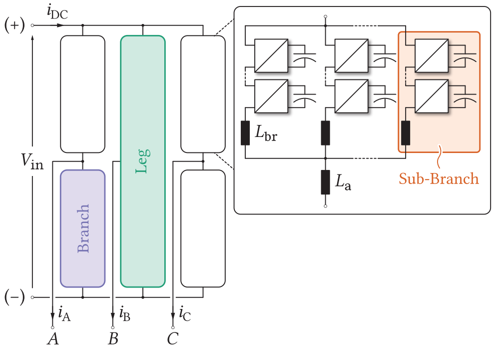


▲ Equivalent circuit of the converter operating with paralleled (sub)branches



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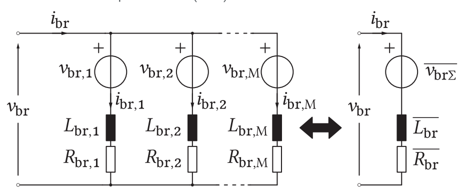

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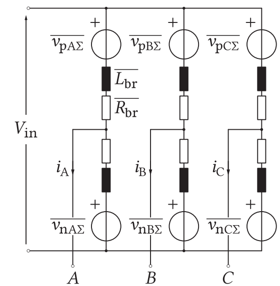
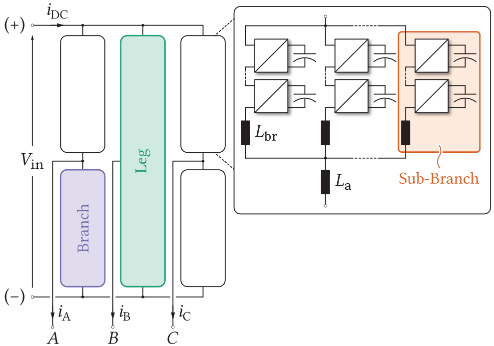
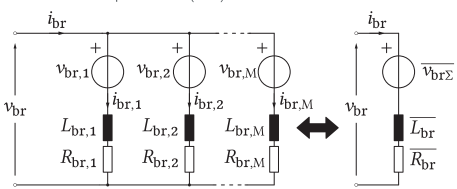


▲ Equivalent circuit of the converter operating with paralleled (sub)branches

⇒ Equivalent circuit ≡ Conventional MMC



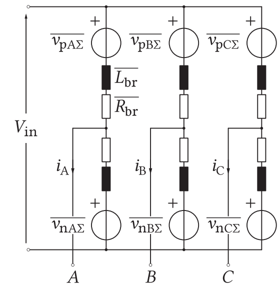
▲ MMC with paralleled (sub)branches



▲ Branch equivalent circuit

$$\overline{V_{br\Sigma}} = \frac{1}{M}\sum_{i=1}^{M} V_{br,i}$$

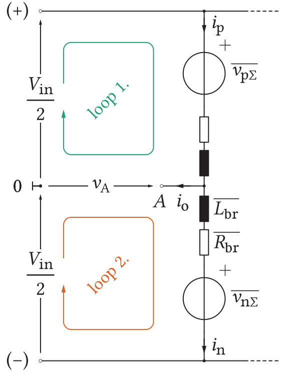
$$\overline{Z_{br}} = \frac{1}{M} Z_{br,i}$$



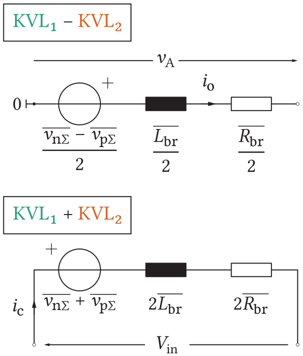
▲ Equivalent circuit of the converter operating with paralleled (sub)branches

⇒ Equivalent circuit ≡ Conventional MMC

- All state of the art control considerations still hold
- New layers of control to be added?
  - Unequal SBR parameters
  - SBR energy balance
  - SBR current balance
- Voltage quality improvement due to paralleling
  - (N+1)-level modulation
  - (2N+1)-level modulation
  - (NM+1)-level modulation
  - (2NM+1)-level modulation



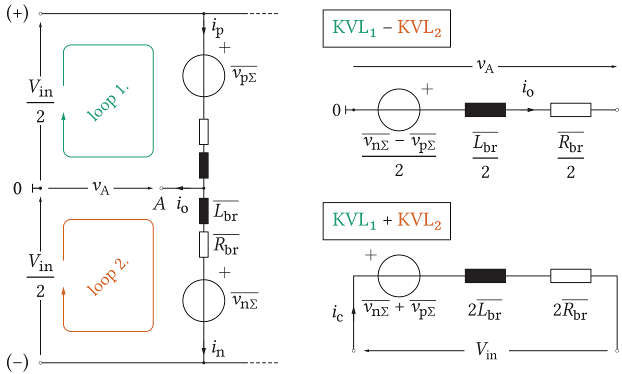
▲ Equivalent circuit of a leg



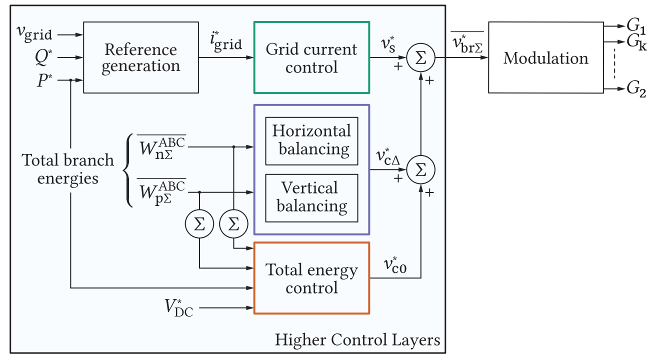
Definition of variables identical to the 3PH-MMC

- $i_c = \frac{i_p + i_n}{2}$ - Leg common-mode current
- $i_o = i_p - i_n$ - Leg output current
- $v_c = \frac{\overline{v_{n\Sigma}} + \overline{v_{p\Sigma}}}{2}$ - Leg common-mode voltage
- $v_s = \frac{\overline{v_{n\Sigma}} - \overline{v_{p\Sigma}}}{2}$ - Leg differential voltage

CONTROL - HIGHER CONTROL LAYERS



▲ Equivalent circuit of a leg



▲ Higher Control Layers

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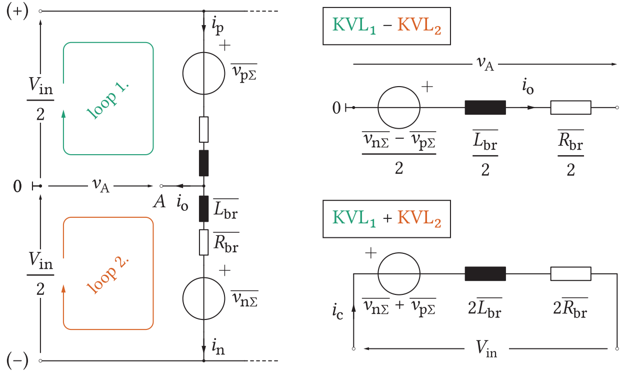
⇒ Well known 3PH-MMC control logic is retained!

Standard balancing directions

- HB ⇒ **total** energies stored within the **legs**
- VB ⇒ **total** energies stored within the **branches** belonging to the same leg

CONTROL - HIGHER CONTROL LAYERS



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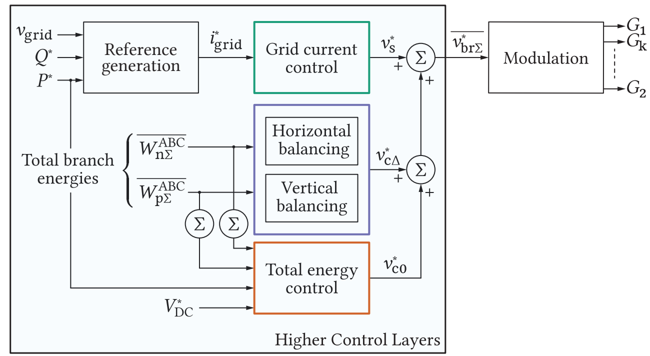

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⇒ Well known 3PH-MMC control logic is retained!

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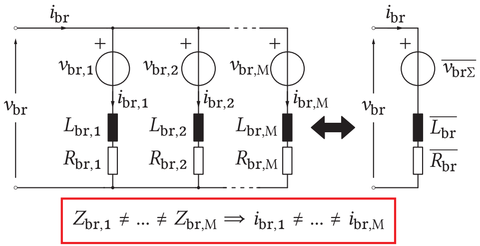
? Is this enough to keep the whole structure balanced?



▲ Equivalent circuit of the branch

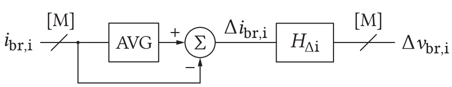
$$L_{br}\frac{d}{dt}\underbrace{\left(i_{br,i}-\frac{i_{br}}{M}\right)}_{\Delta i_{br,i}}+R_{br}\left(i_{br,i}-\frac{i_{br}}{M}\right)=\overline{v_{br\Sigma}}-v_{br,i}$$

Should $v_{br,i}$ be chosen like: $v_{br,i}=\overline{v^{*}_{br\Sigma}}+\Delta v_{br,i}$

$$L_{br}\frac{d}{dt}\Delta i_{br,i}+R_{br}\Delta i_{br,i}=-\Delta v_{br,i}$$

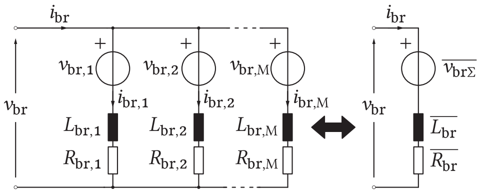
- Current split can be controlled by means of $\Delta v_{br,i}$
- Total branch voltage must not be corrupted!

$$\sum_{i=1}^{M}\Delta v_{br,i}=0$$



▲ SBR current balancing controller

CONTROL - SBR BALANCING



$$Z_{br,1} \neq \ldots \neq Z_{br,M} \Longrightarrow i_{br,1} \neq \ldots \neq i_{br,M}$$

▲ Equivalent circuit of the branch

$$L_{br}\frac{d}{dt}\underbrace{\left(i_{br,i} - \frac{i_{br}}{M}\right)}_{\Delta i_{br,i}} + R_{br}\left(i_{br,i} - \frac{i_{br}}{M}\right) = \overline{v_{br\Sigma}} - v_{br,i}$$

Should $v_{br,i}$ be chosen like: $v_{br,i} = \overline{v^*_{br\Sigma}} + \Delta v_{br,i}$

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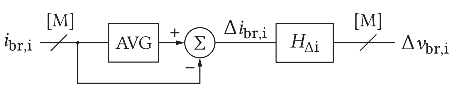
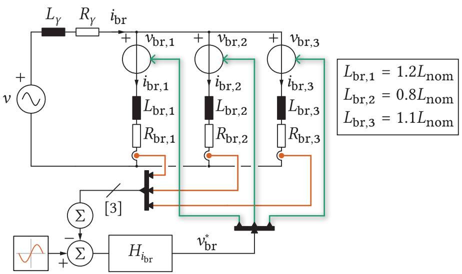
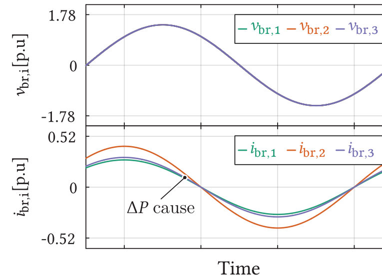


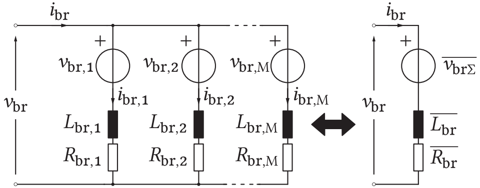
▲ SBR current balancing controller

Energy vs. current balance





CONTROL - SBR BALANCING



$Z_{br,1} \neq \ldots \neq Z_{br,M} \Longrightarrow i_{br,1} \neq \ldots \neq i_{br,M}$

▲ Equivalent circuit of the branch

$$L_{br}\frac{d}{dt}\Big(\underbrace{i_{br,i} - \frac{i_{br}}{M}}_{\Delta i_{br,i}}\Big) + R_{br}\Big(i_{br,i} - \frac{i_{br}}{M}\Big) = \overline{v_{br\Sigma}} - v_{br,i}$$

Should $v_{br,i}$ be chosen like: $v_{br,i} = \overline{v^*_{br\Sigma}} + \Delta v_{br,i}$

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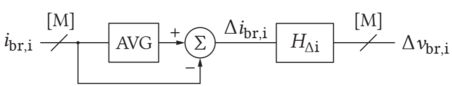
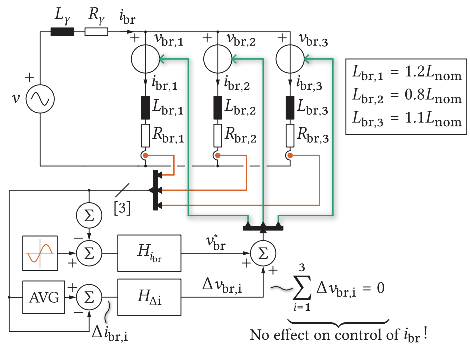
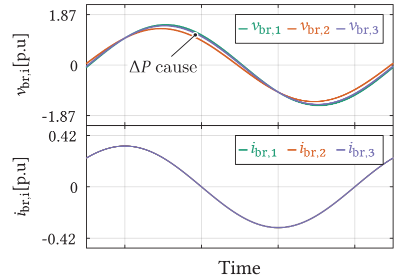


▲ SBR current balancing controller

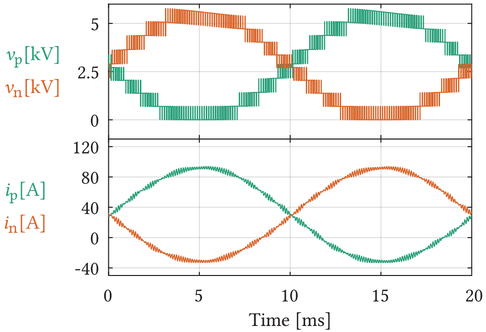
Energy vs. current balance





Current balancing is not enough!

SBR powers are different ⇒ capacitor energy (voltage) divergence



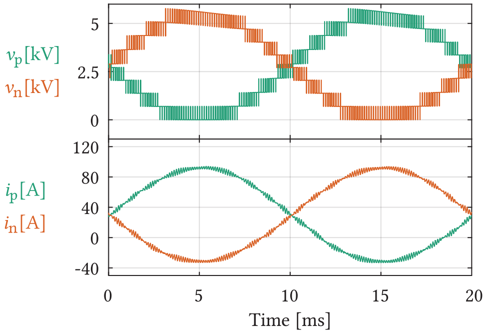
▲ Typical voltage/current waveforms of a (sub)branch

(Sub)branch power equation

$$
\begin{aligned}
P_{\text{sbr}} &= \overline{v_{sbr} i_{sbr}} \\
&= V_{\text{sbr}}^{\text{DC}} I_{\text{sbr}}^{\text{DC}} + \overline{v_{sbr}^{\sim} i_{sbr}^{\sim}}
\end{aligned}
$$

Taylor series expansion

$$
P_{\text{sbr}} = P_{\text{sbr}}^{\text{nom}} + \underbrace{\Delta P_{\text{sbr}}^{\text{DC}}}_{\approx \frac{1}{2} V_{\text{DC}}^{*} \Delta i_{\text{sbr}}^{\text{DC}}} + \underbrace{\Delta P_{\text{sbr}}^{\text{AC}}}_{\text{depends on } \Delta L_{\text{br}}}
$$



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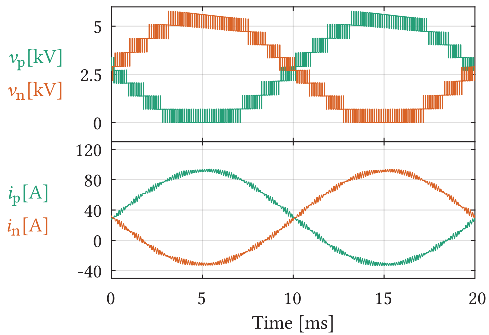
⇒ SBR energy control through SBR currents mismatches

CONTROL - SBR BALANCING



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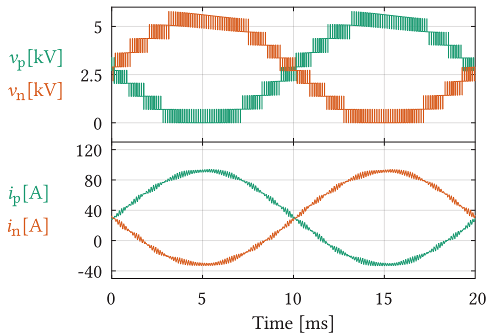
⇒ SBR energy control through SBR currents mismatches

Reminder

$$L_{\mathrm{br}} \frac{d}{dt} \Delta i_{\mathrm{br,i}} + R_{\mathrm{br}} \Delta i_{\mathrm{br,i}} = -\Delta v_{\mathrm{br,i}}$$

$$\overline{v_{\mathrm{br}\Sigma}} = \frac{1}{M} \sum_{i=1}^{M} v_{\mathrm{br,i}} = \frac{1}{M} \sum_{i=1}^{M} \left[\underbrace{\overline{v_{\mathrm{br}\Sigma}^{*}}}_{\mathrm{CMV}} + \Delta v_{\mathrm{br,i}} \right]$$

CONTROL - SBR BALANCING



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$$P_{sbr} = \overline{v_{sbr} i_{sbr}} = V_{sbr}^{DC} I_{sbr}^{DC} + \overline{v_{sbr}^{\sim} i_{sbr}^{\sim}}$$

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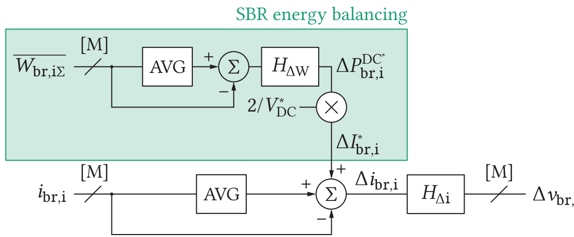
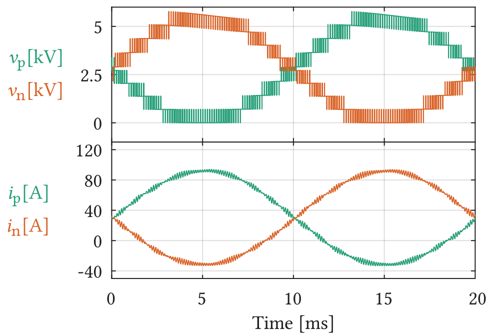
ϟ $\sum_{i=1}^{M} \Delta v_{br,i} = 0$ must be respected at all times!



▲ SBR energy controller

$$\sum_{i=1}^{M} \Delta v_{br,i} = H_{\Delta i} H_{\Delta W} \Big(M \cdot \underbrace{\frac{1}{M} \sum_{i=1}^{M} \overline{W_{br,i\Sigma}}}_{W_{avg}} - \sum_{i=1}^{M} \overline{W_{br,i\Sigma}} \Big) + H_{\Delta i} \Big(M \cdot \underbrace{\frac{1}{M} \sum_{i=1}^{M} i_{br,i}}_{i_{avg}} - \sum_{i=1}^{M} i_{br,i} \Big) = 0$$



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$$\overline{v_{br\Sigma}} = \frac{1}{M} \sum_{i=1}^{M} v_{br,i} = \frac{1}{M} \sum_{i=1}^{M} \left[\underbrace{\overline{v_{br\Sigma}^{*}}}_{\text{CMV}} + \Delta v_{br,i} \right]$$

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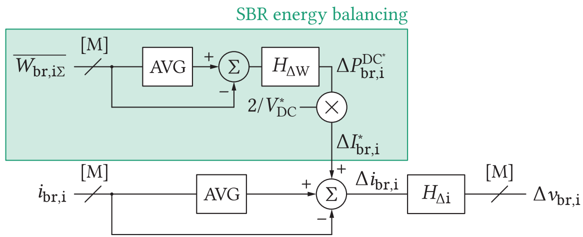

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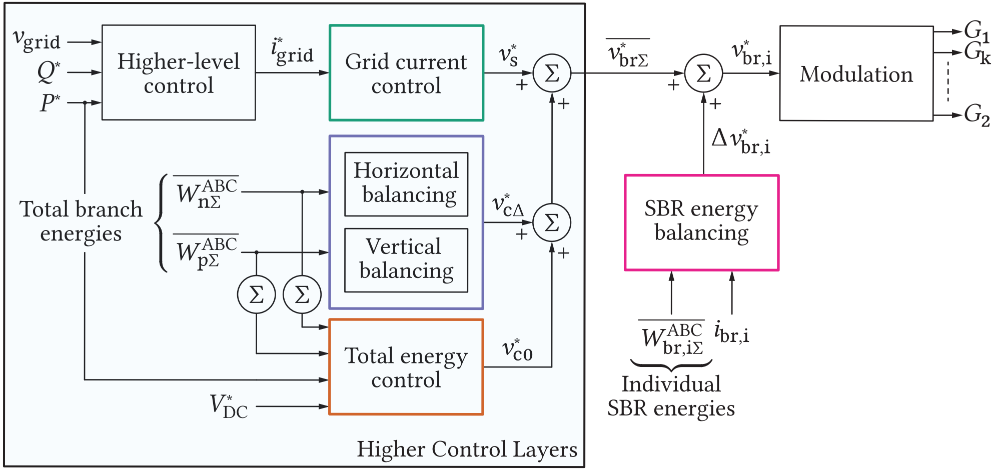
$$\sum_{i=1}^{M} \Delta v_{br,i} = H_{\Delta i} H_{\Delta W} \Big(M \cdot \underbrace{\frac{1}{M} \sum_{i=1}^{M} \overline{W_{br,i\Sigma}}}_{W_{avg}} - \sum_{i=1}^{M} \overline{W_{br,i\Sigma}} \Big) + H_{\Delta i} \Big(M \cdot \underbrace{\frac{1}{M} \sum_{i=1}^{M} i_{br,i}}_{i_{avg}} - \sum_{i=1}^{M} i_{br,i} \Big) = 0$$



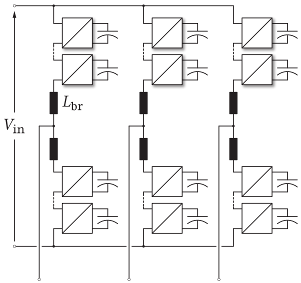
▲ Converter control layers

- Additional control layer (conventional MMC control is retained as can be seen on the left-hand side)
- Decoupling from the higher control levels ensured by means of $\sum_{i=1}^{M} \Delta v_{br,i} = 0$
- Independent on the number of paralleled SBRs (the same approach for both odd and even M)
- Power scalability depending solely upon the control system limitations

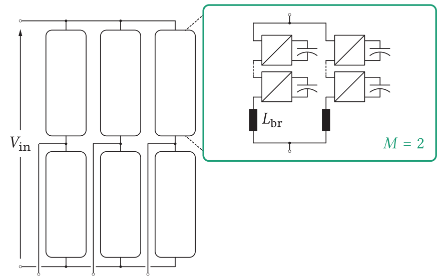
SIMULATION RESULTS

General solution for arbitrary number of Sub-Branches

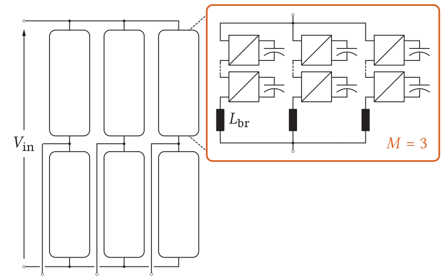
SIMULATION SCENARIO



▲ Available converter design

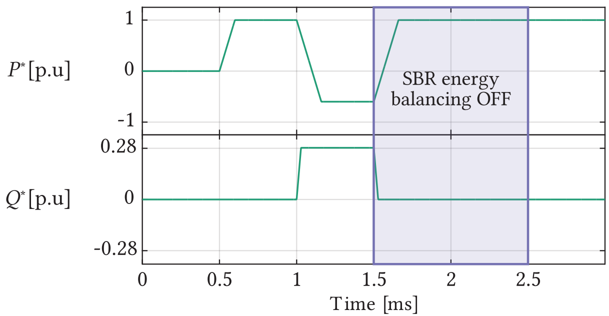


▲ Doubling the converter rated power



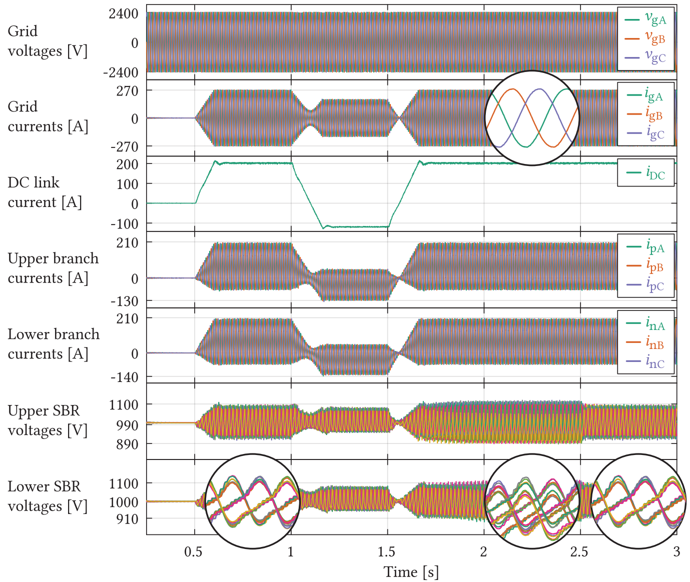
▲ Tripling the converter rated power

	Simulation 1	Simulation 2
Rated power (P)	1MW	1.5MW
Input voltage (V_{in})	5kV	5kV
No. of cells/SBR (N)	5	5
Cell rated voltage (V_{SM})	1kV	1kV
Cell capacitance (C_{SM})	0.83mF	0.83mF
Number of paralleled SBRs (M)	2	3
SBR inductance (L_{br})	5mH	7.5mH
SBR resistance (R_{br})	60mΩ	60mΩ
Switching frequency (f_c)	999Hz	999Hz

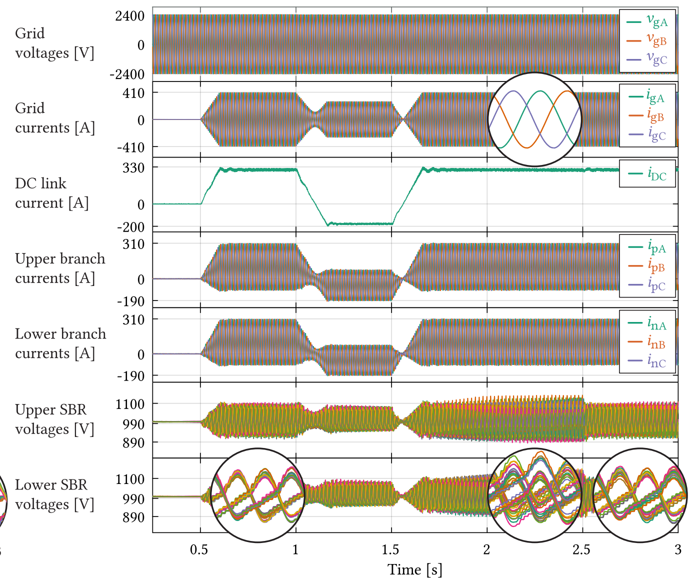


▲ Power profile used to test SBR energy balancing control

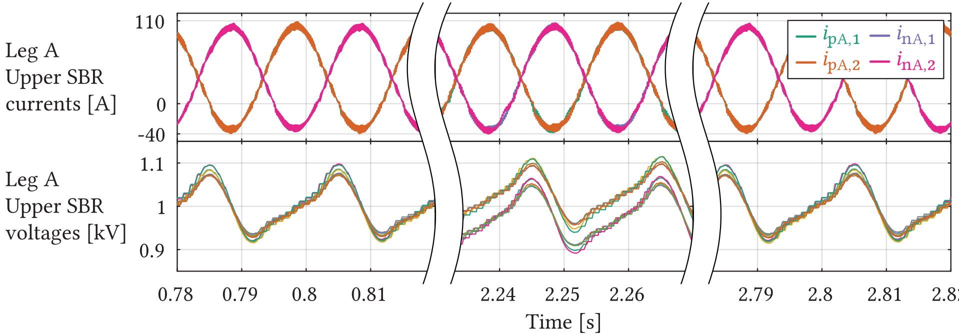
	Rated power (P)	Input voltage (V_{in})	No. of cells/SBR (N)	Cell rated voltage (V_{cell})	Cell capacitance (C_{cell})	No. of paralleled SBRs (M)	SBR inductance (L_{br})	SBR resistance (R_{br})	Sw. frequency (f_{sw})
Left	1MW	5kV	5	1kV	0.83mF	2	5mH	60mΩ	999Hz
Right	1.5MW	5kV	5	1kV	0.83mF	3	5mH	60mΩ	999Hz



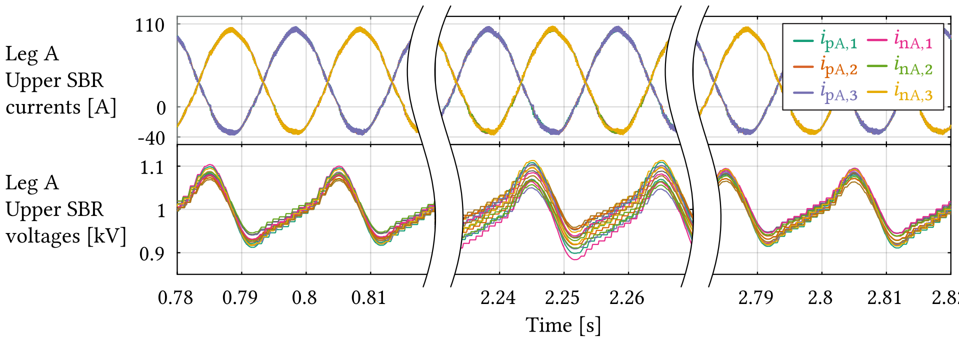
▲ Simulation results in case $M = 2$



▲ Simulation results in case $M = 3$



▲ Leg A upper and lower SBR currents (top) along with SBR voltages (bottom) in case $M = 2$



▲ Leg A upper and lower SBR currents (top) along with SBR voltages (bottom) in case $M = 3$

SIMULATION RESULTS

There are two relevant questions one might ask:

- How aggressive is the SBR energy balancing controller?
- Should current rating of the SMs be increased owing to the presence of SBR energy balancing?

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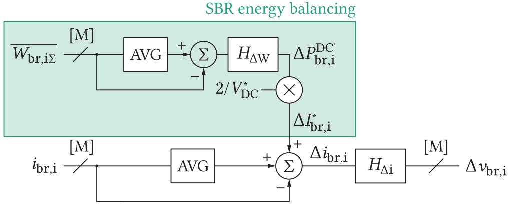
$$\Delta I^*_{\mathrm{br,i}} = \underbrace{\Delta W_{\mathrm{br,i}\Sigma}}_{\text{Energy error}} \cdot \underbrace{H_{\Delta W}}_{\text{Controller TF}} \cdot \underbrace{\frac{2}{V^*_{\mathrm{DC}}}}_{\text{several kV}}$$



SIMULATION RESULTS

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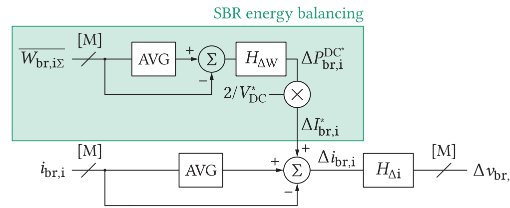
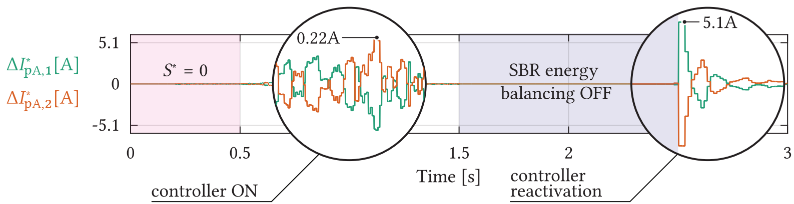
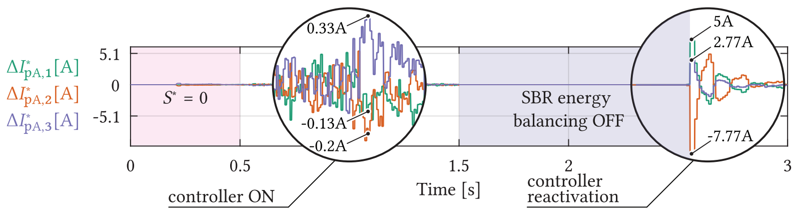




▲ References provided by the SBR energy balancing controller ($M = 2$)



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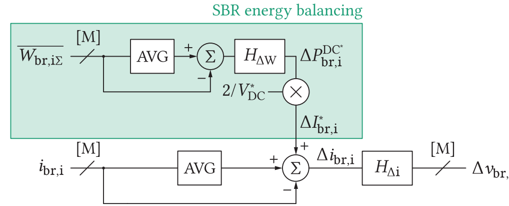
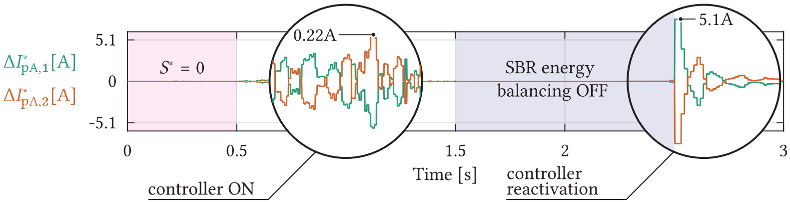


- $\Delta I^*_{br,i} < 10\% \; \hat{i}_{br}$ **(Modest response!)**



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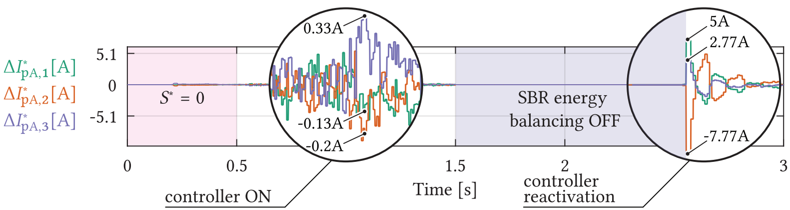

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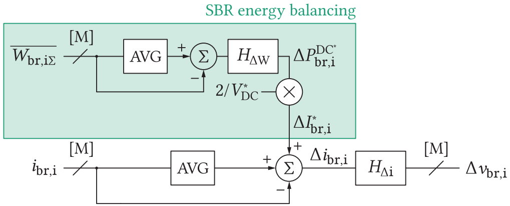

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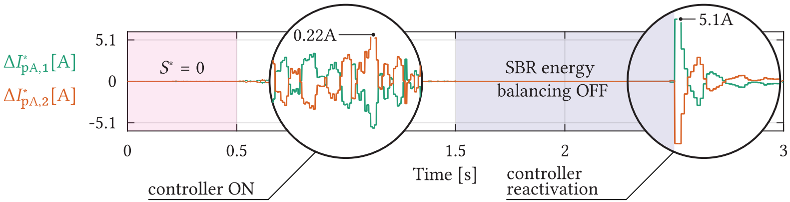

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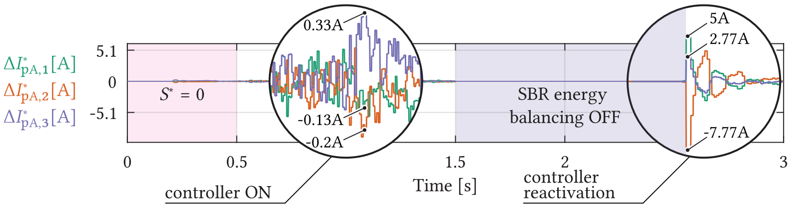

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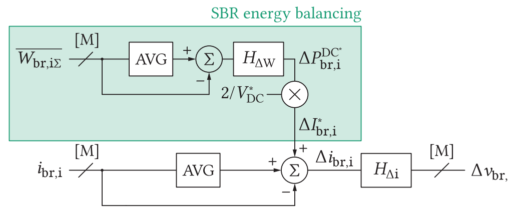

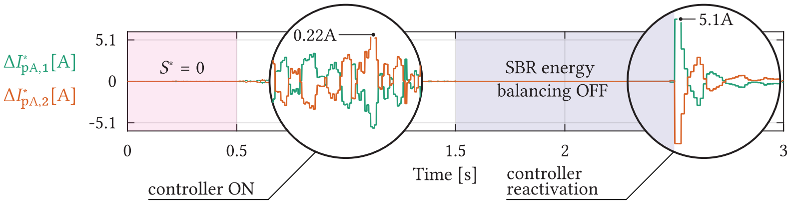

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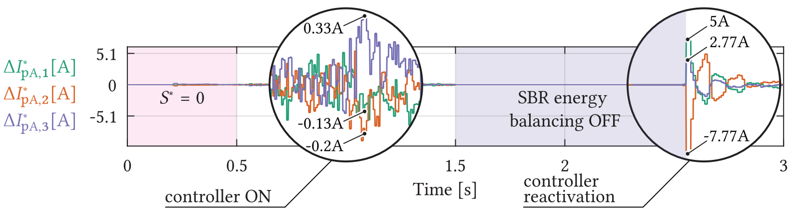

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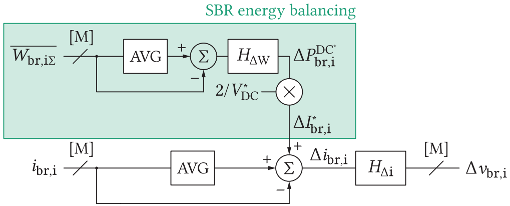

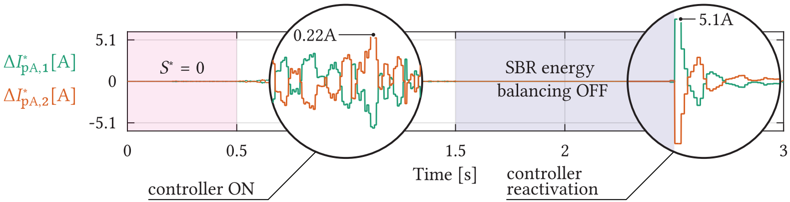

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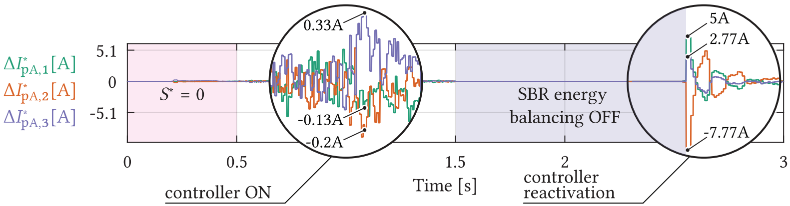

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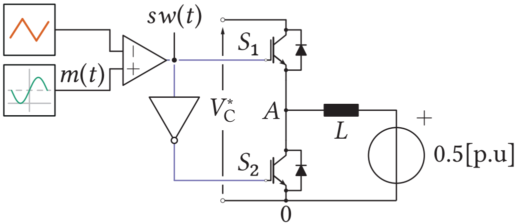
⇒ No need for SM current rating upgrade!

MODULATION CONSIDERATIONS

...impact on the voltage quality

PRELIMINARY CONSIDERATIONS

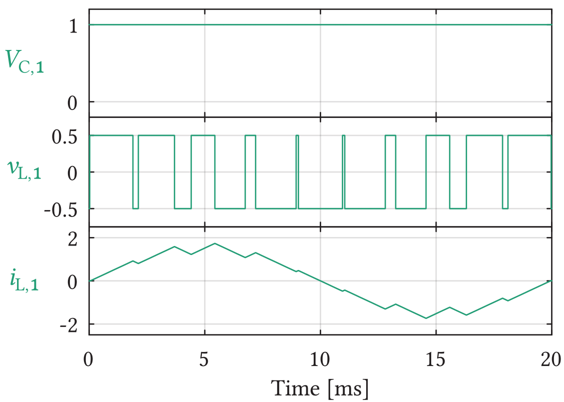


$$m_1(t) = \frac{1}{2} + \frac{\hat{m}}{2}\cos(\omega t)$$

$$v_{A0} = sw(t) \cdot V_{C,1}$$

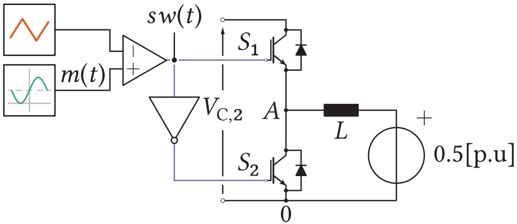
$$= \big[m_1(t) + \underbrace{\mathrm{st}(\theta_1) + \mathrm{st}(\theta_2)}_{\text{higher order harmonics}}\big] V_{C,1}$$

$$= \frac{V_C^*}{2} + \hat{m}\frac{V_C^*}{2}\cos(\omega t) + H_1(\omega t)$$

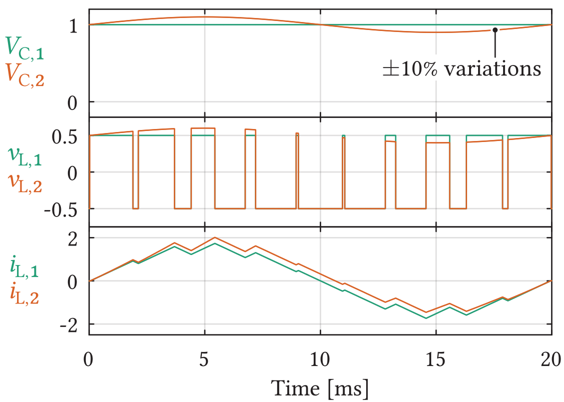


▲ PSC modulation example with one HB module

PRELIMINARY CONSIDERATIONS



$$m_2(t) = \frac{1}{2} + \frac{\hat{m}}{2}\cos(\omega t)$$



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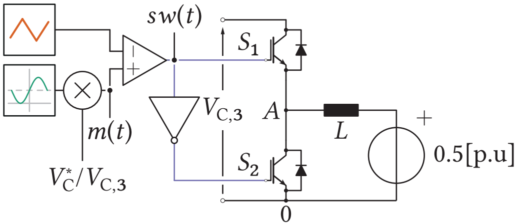
$$v_{A0} = sw(t)\cdot V_{C,2}$$

$$= \left[m_2(t) + \underbrace{st(\theta_1) + st(\theta_2)}_{\text{higher order harmonics}}\right]V_{C,2}$$

$$= \underbrace{\frac{V_C^* + \Delta v_C}{2}}_{\text{DC + osc.}} + \underbrace{(V_C^* + \Delta v_C)\frac{\hat{m}}{2}\cos(\omega t)}_{\text{DC + osc.}} + H_2(\omega t)$$



$$m_3(t) = \left\{\frac{1}{2} + \frac{\hat{m}}{2}\cos(\omega t)\right\}\frac{V_C^*}{V_{C,3}}$$

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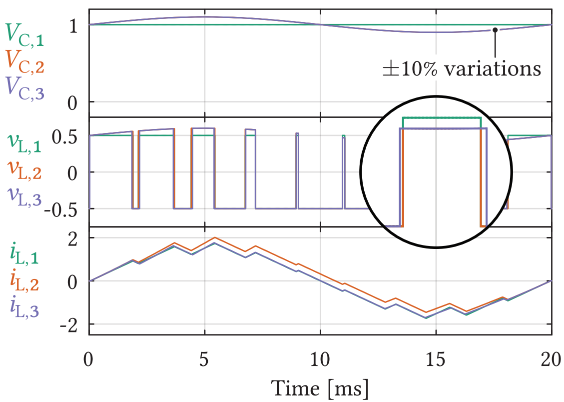

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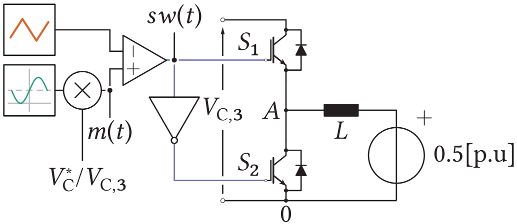

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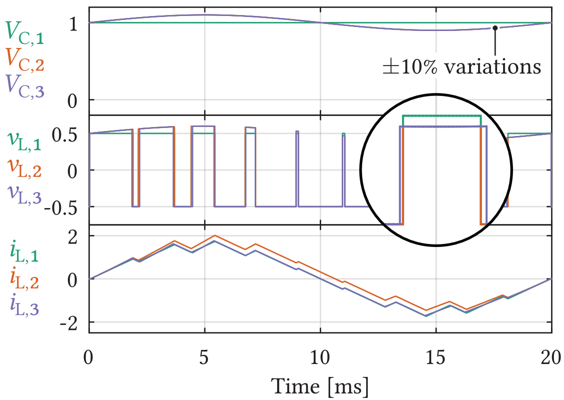

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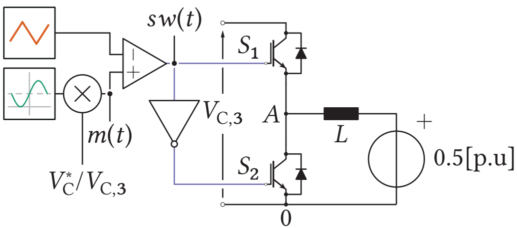
⇒ Correction of $m(t)$ ensures DC link voltage ripple effect mitigation!



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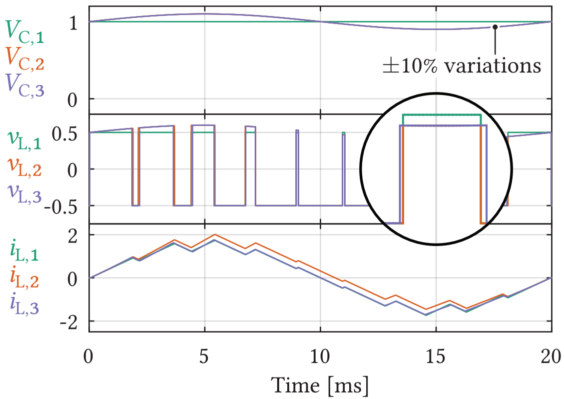

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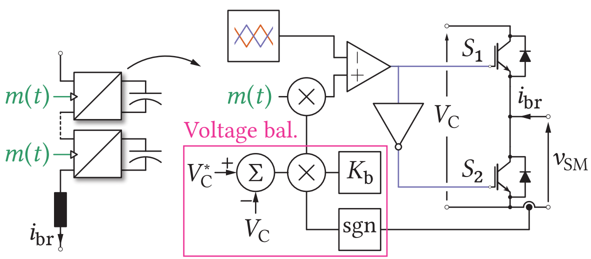
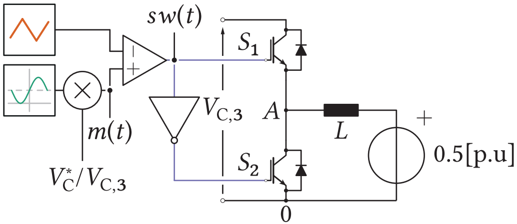
Closed loop control of the MMC utilizes similar procedure, where

$$m_{\{n,p\}} = \frac{v_C^* \pm v_S^*}{v_{\{n,p\}\Sigma}}$$

However, not all of the SMs are the same ⇒ Additional $m(t)$ compensation is needed!



▲ Additional compensation of modulation index



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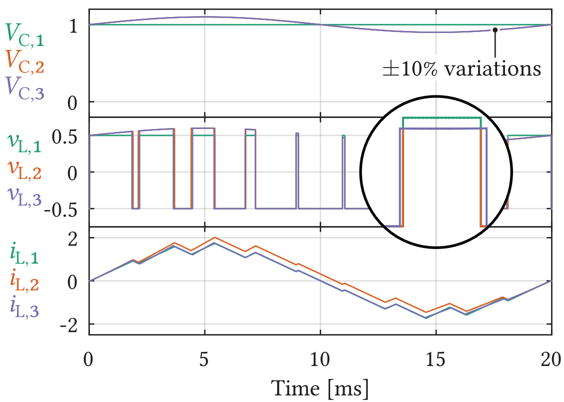

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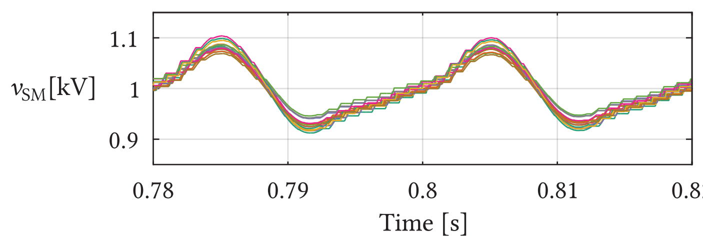


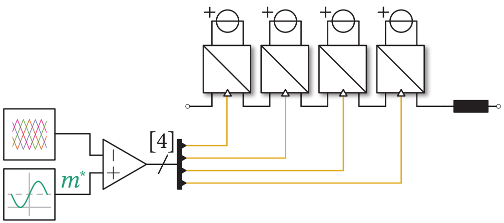
▲ MMC SM voltages in case PSC modulation is used

PSC MODULATION APPLIED TO A SINGLE BRANCH

For the purpose of qualitative analysis, three assumptions are made:

- Closed-loop control of the internal quantities
- Voltage across all the SMs is approximately the same (PSC modulation)
- Active balancing contribution to modulation index corrections is negligible

⇒ **every SM capacitor is perceived as a stiff voltage source**



▲ A branch with N = 4 SMs (an exemplary case)

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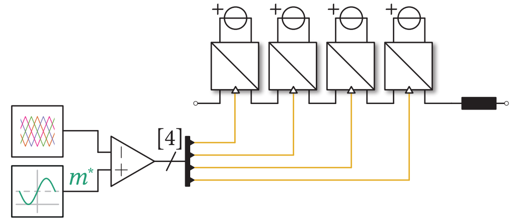
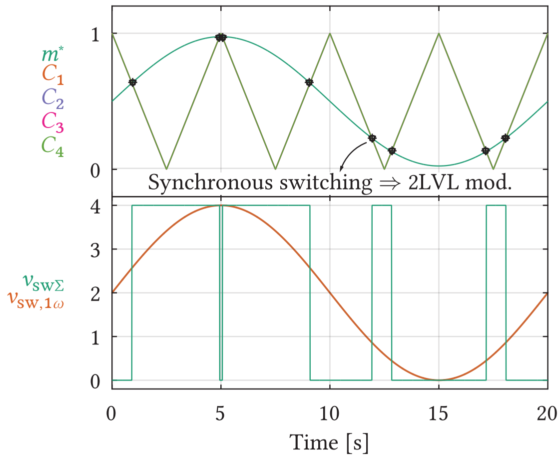


▲ A branch with $N = 4$ SMs (an exemplary case)



▲ Obtained voltage waveform in case $m(t) = \frac{1}{2} + \frac{0.95}{2}\cos(2\pi 50 t)$ and $\Theta_c = 0$

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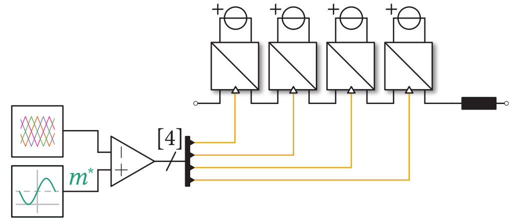

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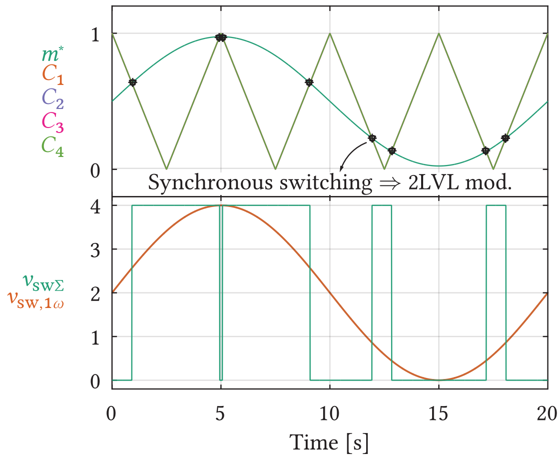

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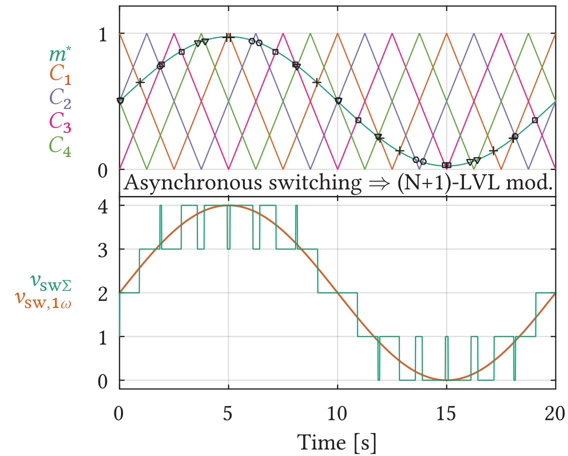
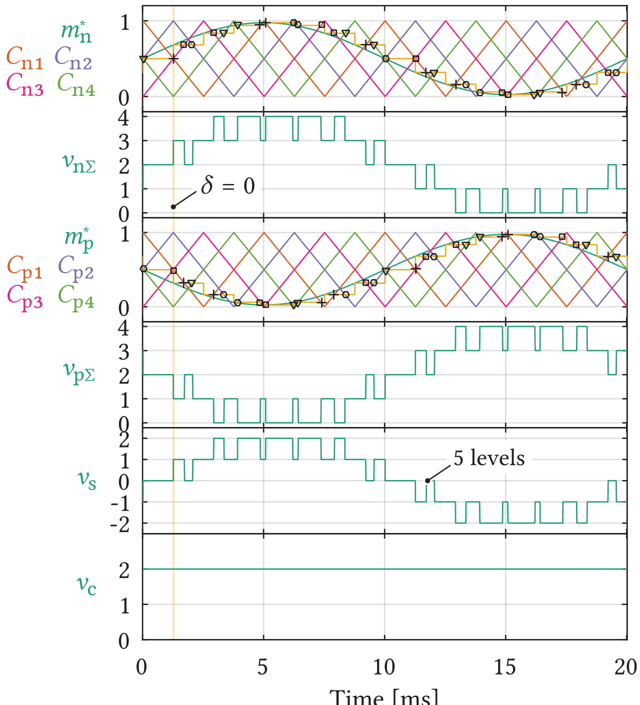


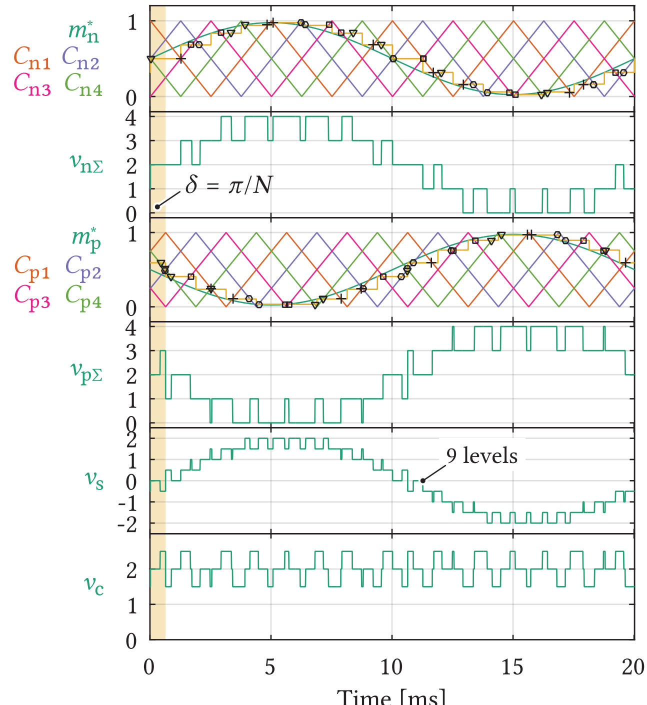
▲ Obtained voltage waveform in case $m(t) = \frac{1}{2} + \frac{0.95}{2}\cos(2\pi 50t)$ and $\Theta_c = \frac{2\pi}{4}$

PSC MODULATION APPLIED TO A REGULAR MMC LEG

Synchronous switching of branches ⟹ $(N+1)$-level modulation



Asynchronous switching of branches ⟹ $(2N+1)$-level modulation



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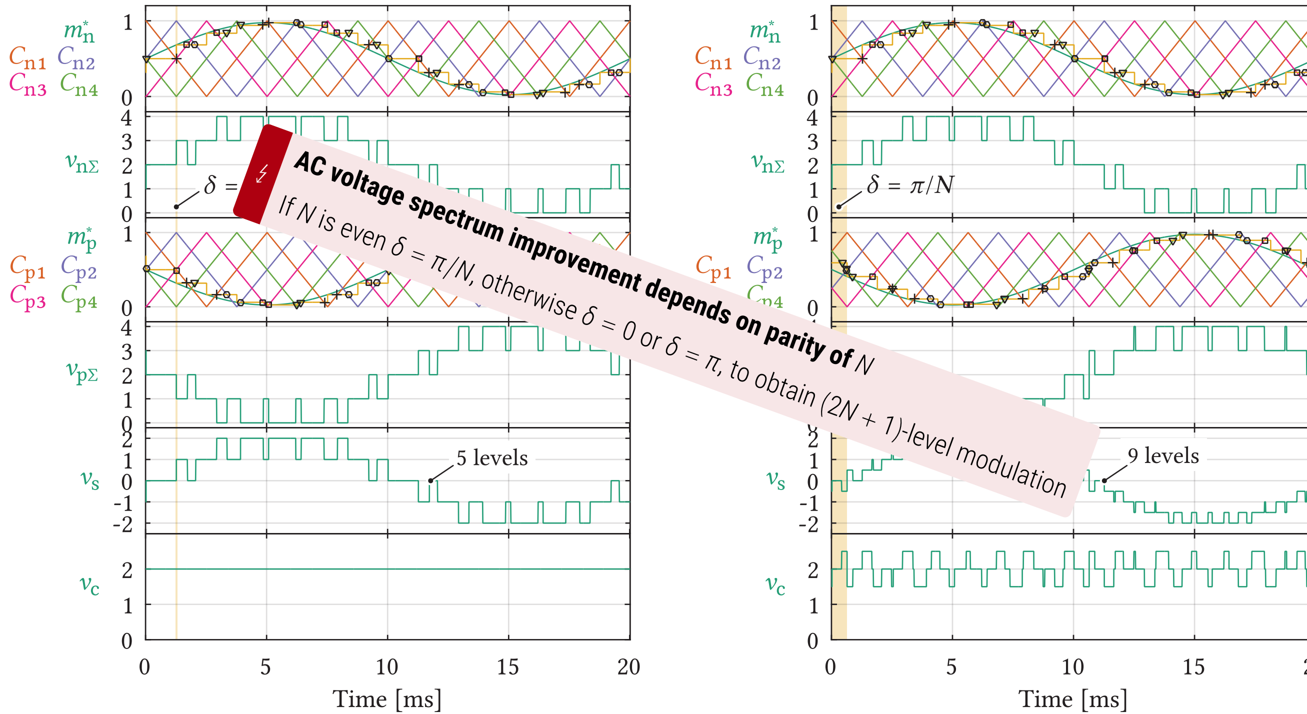
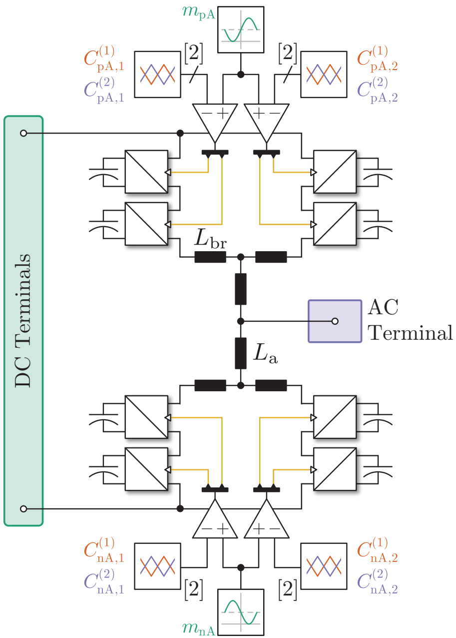


AC voltage spectrum improvement depends on parity of N

If N is even $\delta = \pi/N$, otherwise $\delta = 0$ or $\delta = \pi$, to obtain $(2N+1)$-level modulation

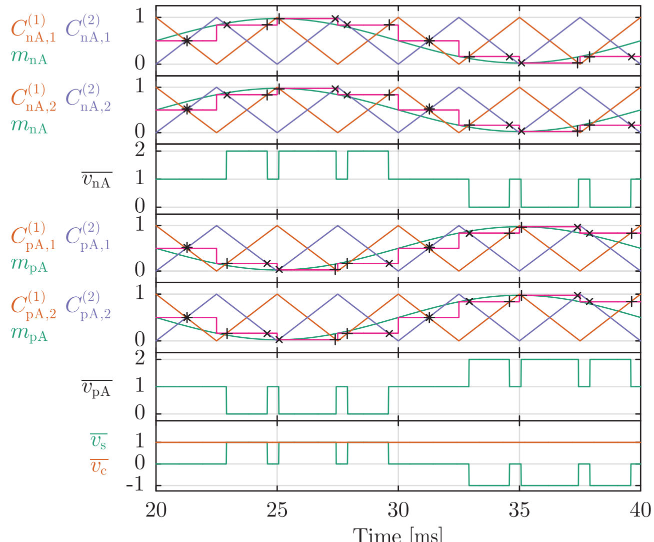
PSC MODULATION APPLIED TO A MMC LEG WITH TWO PARALLEL SBRS



▲ MMC leg utilizing two parallel SBRs (an exemplary case)

There are two relevant phase-shifts:

- δ - phase shift between two carrier sets within two SBRs belonging to adjacent branches
- β - phase shift between two carrier sets within two SBRs belonging to the same branch



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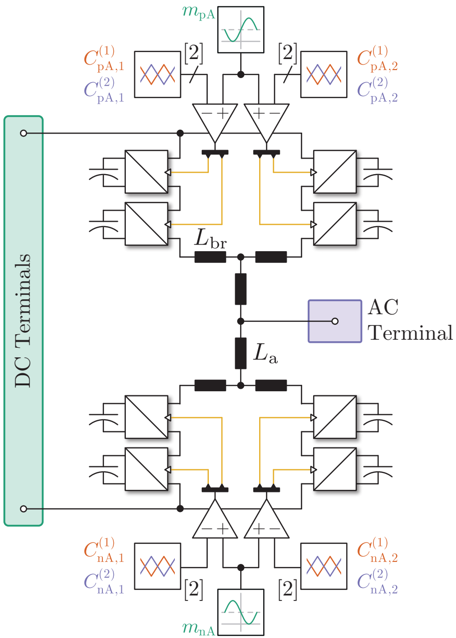

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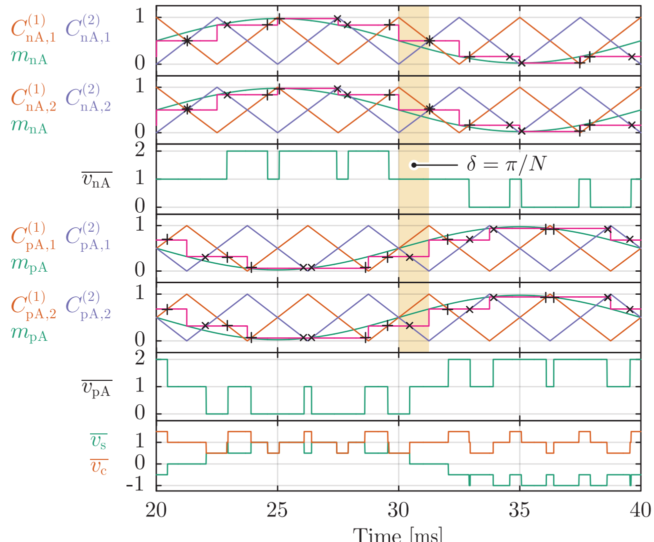

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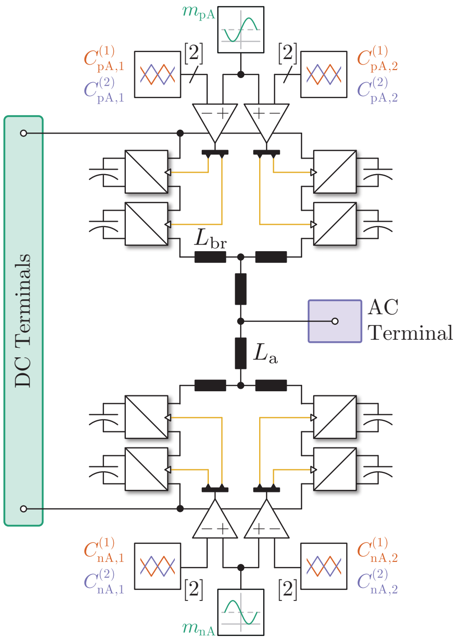

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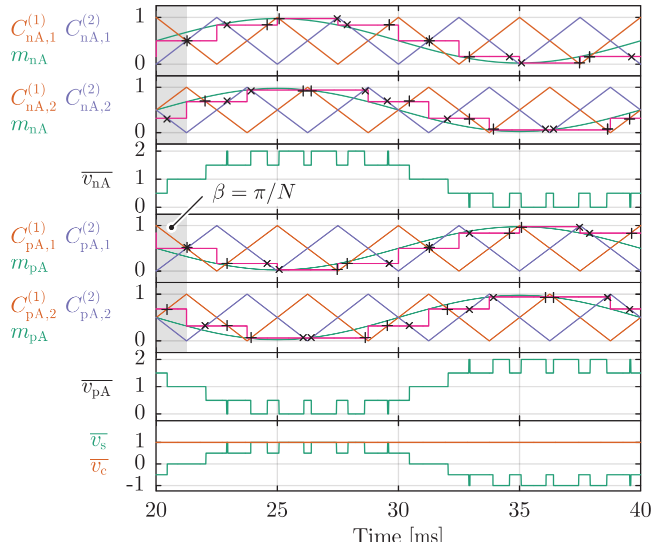

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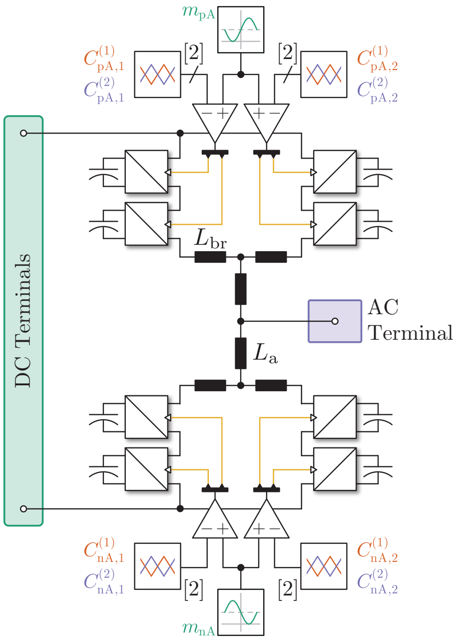

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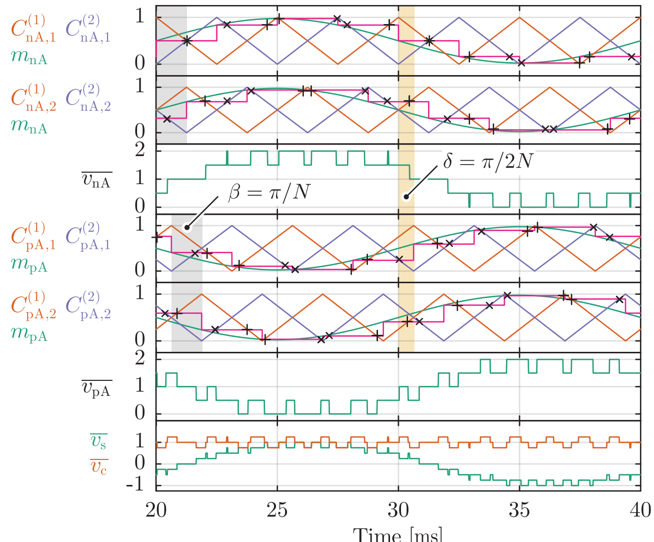
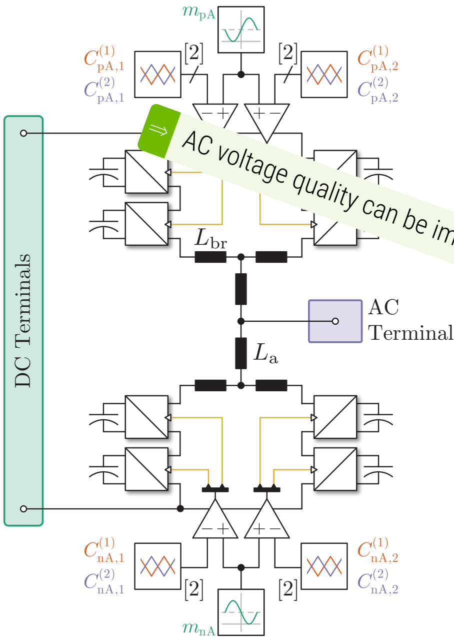


▲ $(2MN + 1)$-level modulation

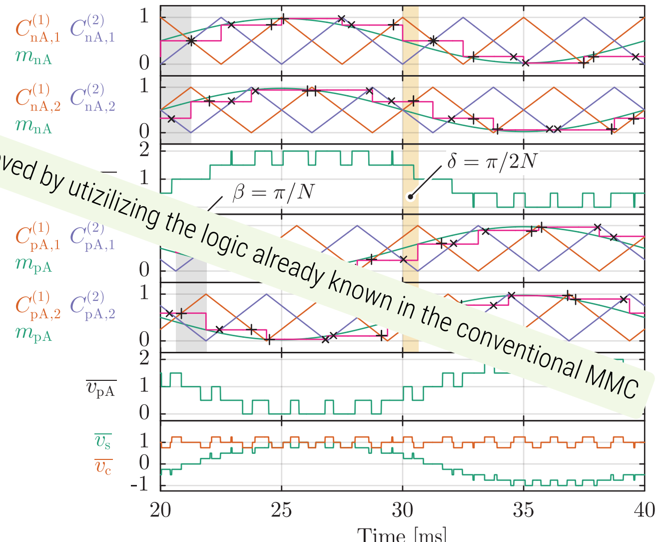
PSC MODULATION APPLIED TO A MMC LEG WITH TWO PARALLEL SBRS



▲ MMC leg utilizing two parallel SBRs (an exemplary case)

There are two relevant phase-shifts:

- δ - phase shift between two carrier sets within two SBRs belonging to adjacent branches
- β - phase shift between two carrier sets within two SBRs belonging to the same branch

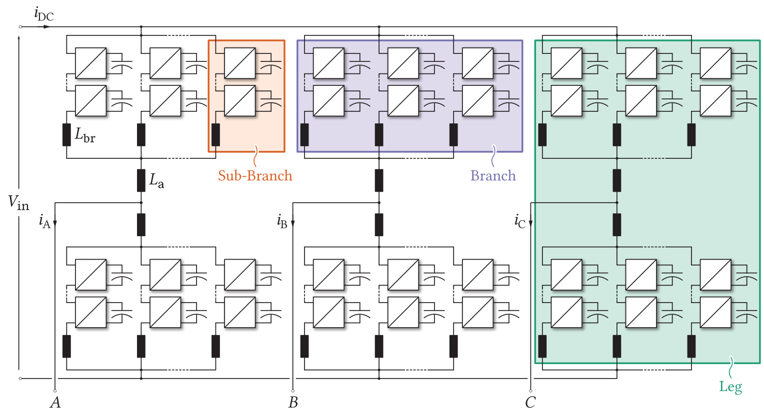


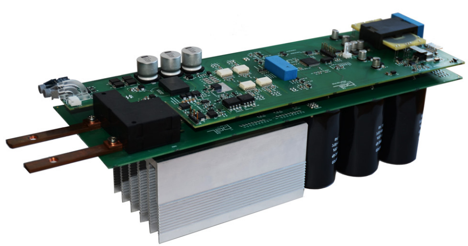
▲ $(2MN + 1)$-level modulation

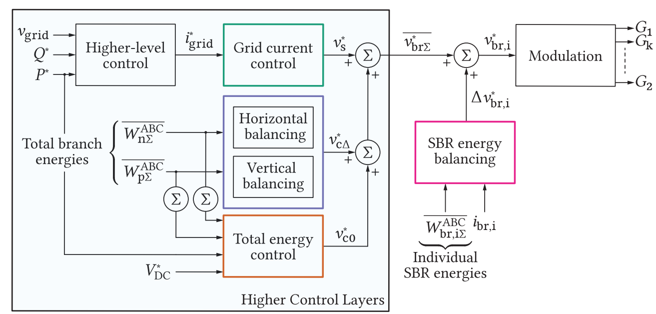
⇒ AC voltage quality can be improved by utizilizing the logic already known in the conventional MMC

CONCLUSION

- **MMC power extension** as a main motivation
- **Simple and cheap** (no need for major redesign of the converter parts)
- The challenge is shifted to the **control domain**
- State of the art control methods + **Additional loops**
- Possible AC **voltage quality improvement**







DC-DC CONVERTERS

Building blocks of Solid State Transformers

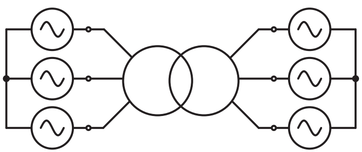
SOLID-STATE TRANSFORMER (SST)

Concept and motivation?

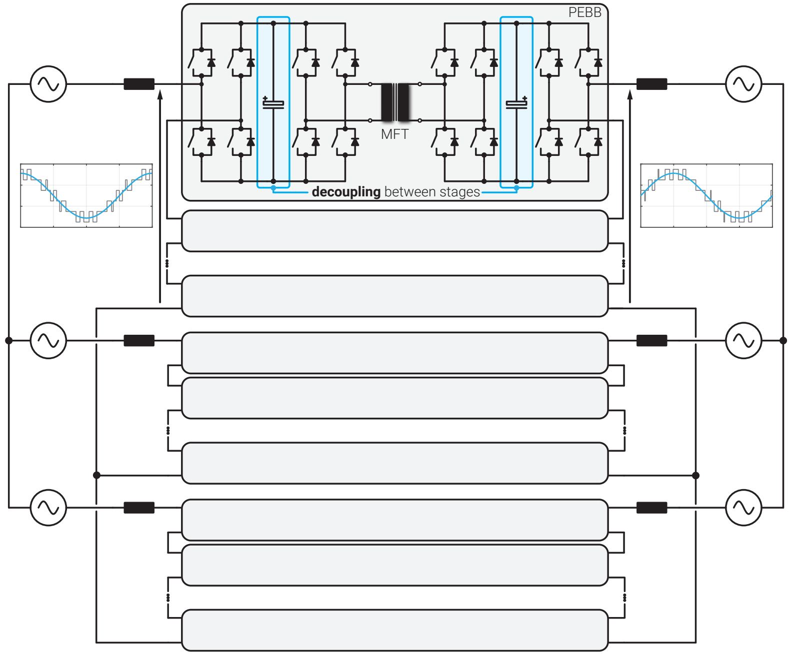
- SST = Switching stages + Isolation
- Firstly envisioned within AC grids
- Power Electronic Building Blocks (PEBBs)
- Conventional transformer vs SST?
- Operating frequency increase **(MFT)**

	Grid Tx	SST
Controlability	No	Yes
Efficiency	$\eta \geq 99\%$	P_γ
Q compensation	No	Yes
Fault tolerance	No	Yes
Size	Bulky	Compact

Advantages at the expense of reduced efficiency!



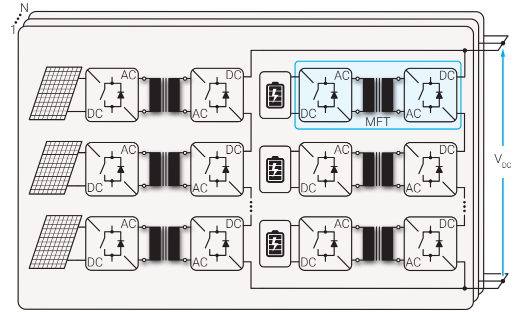
▲ Conventional AC grid transformer



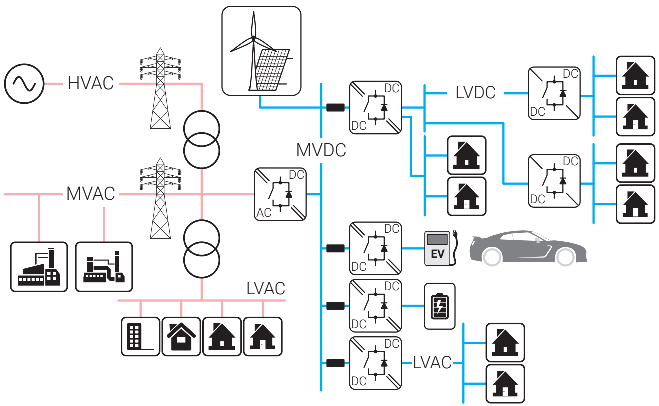
▲ Solid-State Transformer employed with the aim of interfacing two AC systems [28], [29]

DC-DC SST

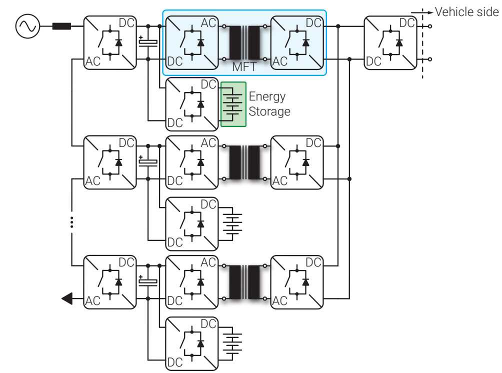
- Inherent part of the AC-AC SST
- Expansion of the existing power system
- Enabling technology for MVDC
- Penetration of renewable energy sources
- Fast / Ultra Fast EV charging
- **Medium Frequency** conversion



▲ Employment of a DC-DC SST within RES-based systems



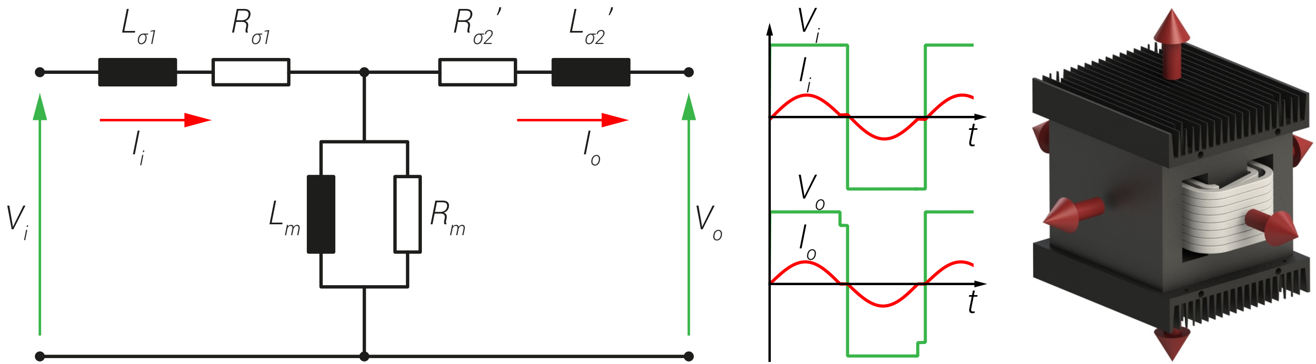
▲ Concept of a modern power system



▲ Fast EV charging concept

MFT CHALLENGES

- **Skin and proximity effect losses:** impact on efficiency and heating
- **Cooling:** increase of power density $\Rightarrow$ decrease in size $\Rightarrow$ less cooling surface $\Rightarrow$ higher R_{th} $\Rightarrow$ higher temperature gradients
- **Non-sinusoidal excitation:** impact on core and winding losses and insulation
- **Insulation:** coordination and testing taking into account high $\frac{dV}{dt}$ characteristic for power electronic converters
- **Accurate electric parameter control:** especially in case of resonant converter applications

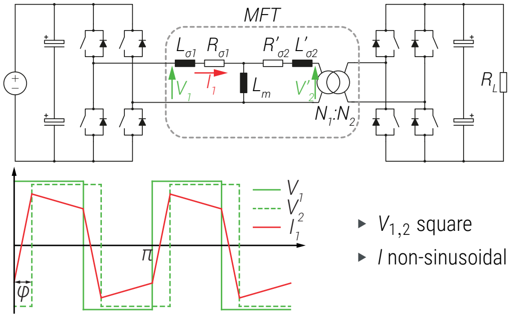


▲ Medium Frequency Transformer challenges

⇒ MFT design is generally challenging and requires multiphysics considerations and multiobjective optimization

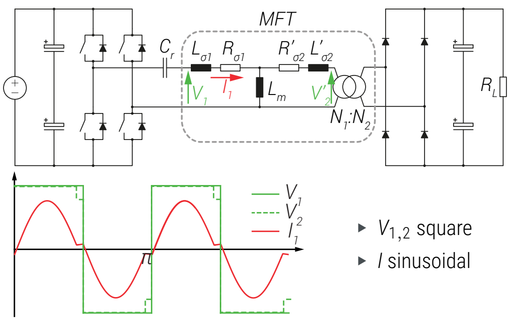
MFT NONSINUSOIDAL POWER ELECTRONIC WAVEFORMS

DAB Converter:



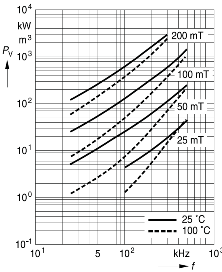
- $V_{1,2}$ square
- I non-sinusoidal

Series Resonant Converter:



- $V_{1,2}$ square
- I sinusoidal

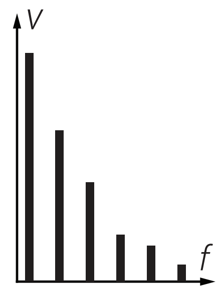
Core Losses:



▲ Specific AC core losses

- Data-sheet - sinusoidal excitation
- Steinmetz - sinusoidal excitation losses
- Core is excited with square pulses!
- Losses must be correctly evaluated
- Generalization of Steinmetz model

Winding Losses:

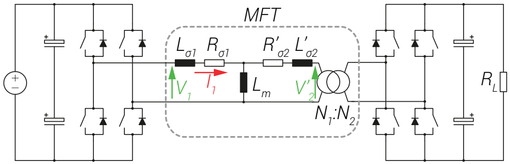


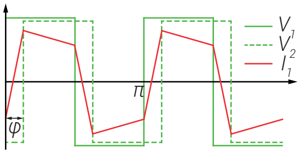
▲ Harmonics impacting winding losses

- Current waveform impacts the winding losses
- Copper is a linear material
- Losses can be evaluated in harmonic basis
- Current harmonic content must be evaluated
- Losses are the sum of the individual harmonic losses

MFT ACCURATE PARAMETERS CONTROL

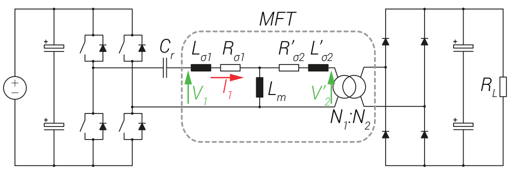
DAB Converter:

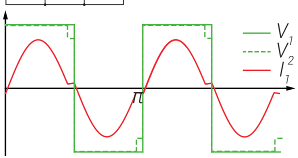




- $V_{1,2}$ square
- I non-sinusoidal

Series Resonant Converter:





- $V_{1,2}$ square
- I sinusoidal

DAB

- Leakage Inductance
- Controllability of the power flow
- Higher than $L_{\sigma.min}$:

$$L_{\sigma.min} = \frac{V_{DC1} V_{DC2} \varphi_{min} (\pi - \varphi_{min})}{2 P_{out} \pi^2 f_s n}$$

- Magnetizing Inductance is normally high

SRC

- Leakage inductance is part of resonant circuit
- Must match the reference:

$$L_{\sigma.ref} = \frac{1}{\omega_0^2 C_r}$$

- Magnetizing inductance is normally high
- Reduced in case of LLC
- Limits the magnetization current to the reference $I_{m.ref}$
- Limits the switch-off current and losses

$$L_m = \frac{n V_{DC2}}{4 f_s I_{m.ref}}$$

- $I_{m.ref}$ has to be sufficiently high to maintain ZVS

MFT VARIETY OF DESIGNS...

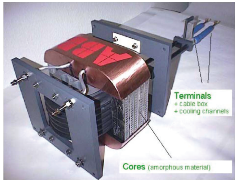


ABB: 350kW, 10kHz

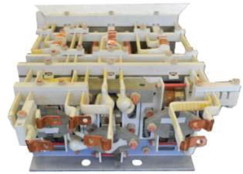
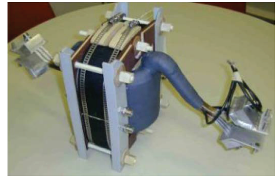
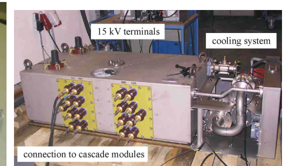
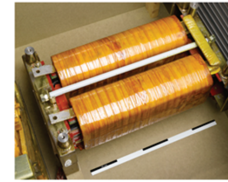


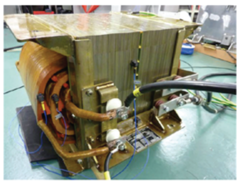
ABB: 3x150kW, 1.8kHz

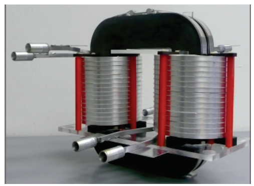

BOMBARDIER: 350kW, 8kHz



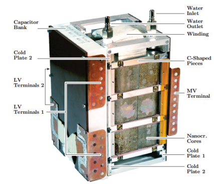
ALSTOM: 1500kW, 5kHz


IKERLAN: 400kW, 5kHz

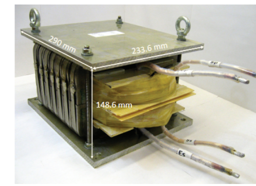

IKERLAN: 400kW, 1kHz


FAU-EN: 450kW, 5.6kHz


CHALMERS: 50kW, 5kHz

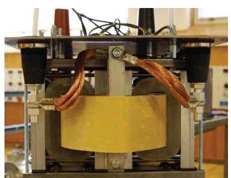


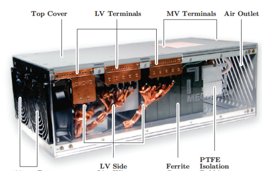
ETHZ: 166kW, 20kHz



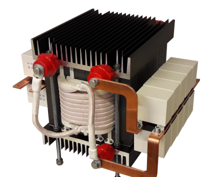
EPFL: 300kW, 2kHz


STS: 450kW, 8kHz


KTH: 170kW, 4kHz



ETHZ: 166kW, 20kHz


EPFL: 100kW, 10kHz

?

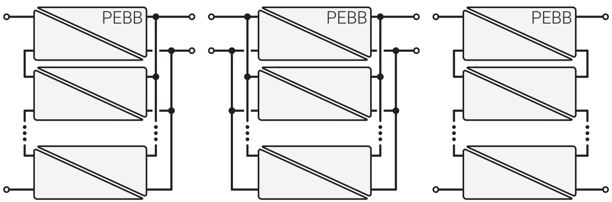
ACME: ???kW, ???kHz

HP DC-DC CONVERTERS

Going into Medium Voltage..

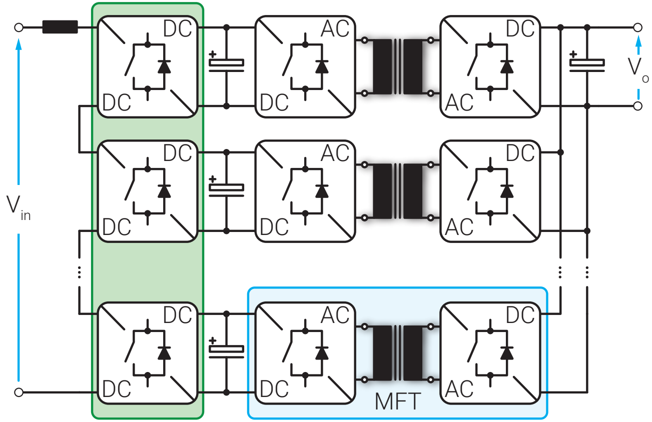
Fractional power processing

- Multiple MFTs
- Equal power distribution among PEBBs
- MFT isolation?
- Various PEBB configurations



(a) ISOP (b) IPOP (c) ISOS

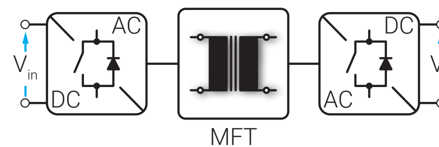
▲ Different structures employed depending upon the voltage level



▲ ISOP Structure

Bulk power processing

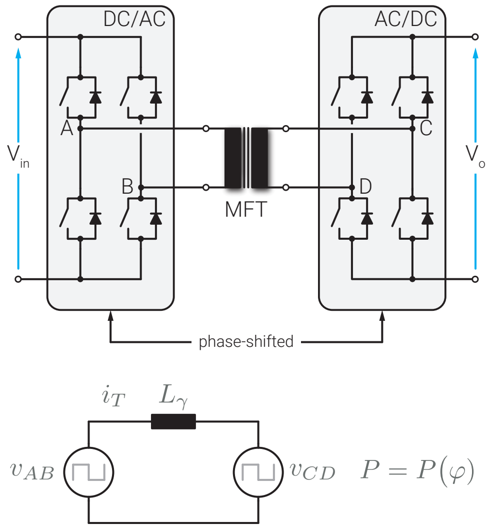
- Single MFT
- Isolation solved only once
- Various configurations/operating principles



▲ Bulk power processing concept

COMMON PEBB CONFIGURATIONS

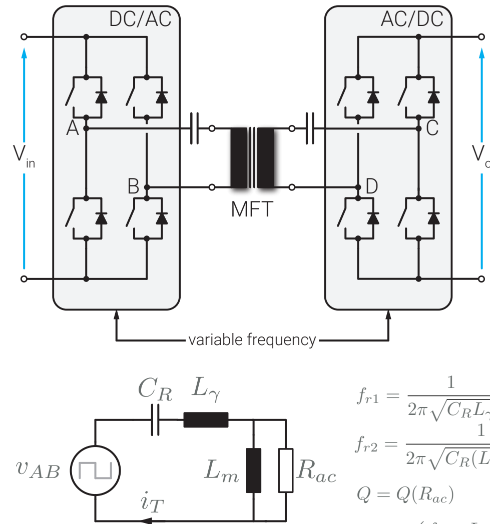
Dual-Active Bridge



$$P = P(\varphi)$$

▲ Dual Active Bridge [30]

Resonant Converters



$$f_{r1} = \frac{1}{2\pi\sqrt{C_R L_\gamma}}$$

$$f_{r2} = \frac{1}{2\pi\sqrt{C_R(L_\gamma + L_m)}}$$

$$Q = Q(R_{ac})$$

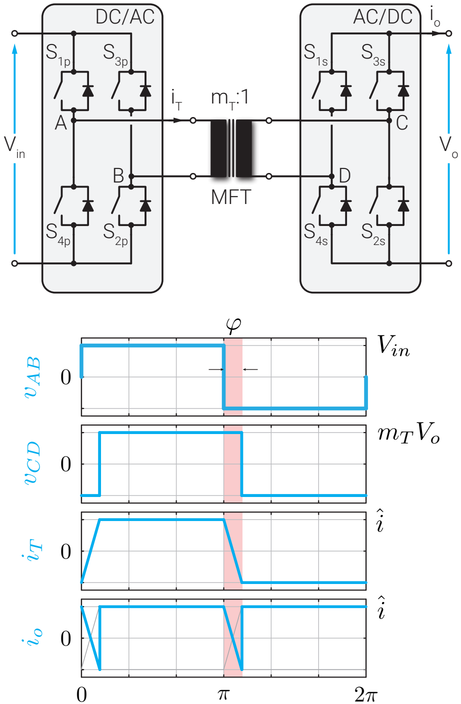
$$G = G\left(\frac{f_{sw}}{f_{r1}}, \frac{L_m}{L_\gamma}, Q\right)$$

▲ LCL Resonant Converter

1-PHASE DAB

Basic operating principles

SINGLE-PHASE (1PH) DUAL ACTIVE BRIDGE (DAB)



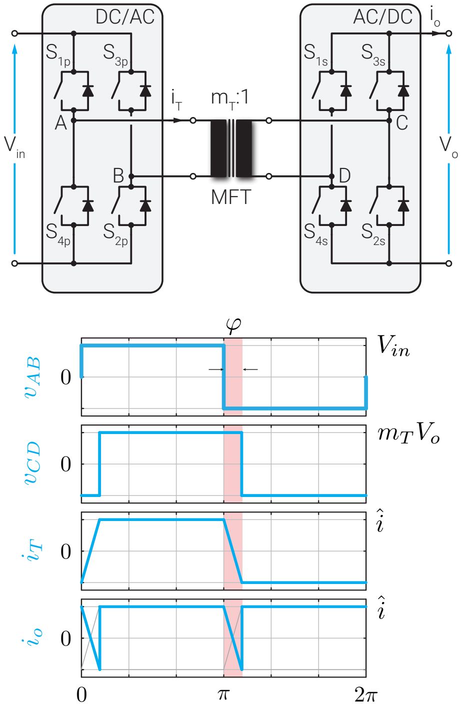
▲ 1PH-DAB with its relevant waveforms

Power equation

$$P = \frac{1}{T}\int_0^T v_{AB} i_T dt$$

$$= m_T \frac{V_{in} V_o}{\omega L_\Sigma} \varphi \left(1 - \frac{|\varphi|}{\pi}\right)$$

SINGLE-PHASE (1PH) DUAL ACTIVE BRIDGE (DAB)



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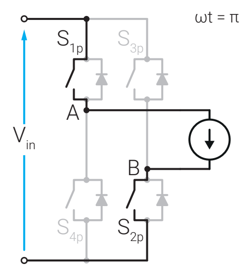
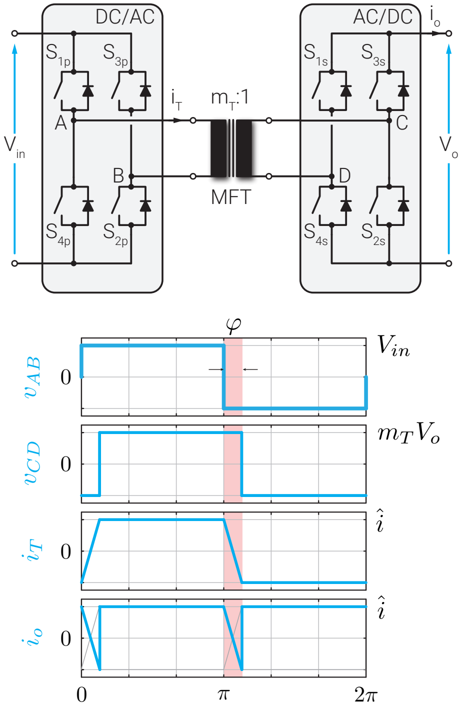
Switching cycle



SINGLE-PHASE (1PH) DUAL ACTIVE BRIDGE (DAB)



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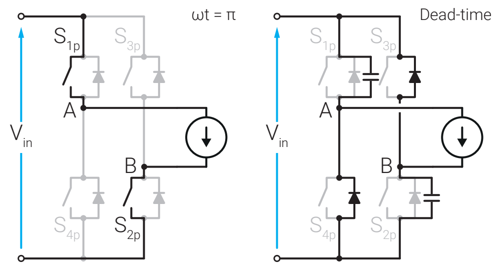
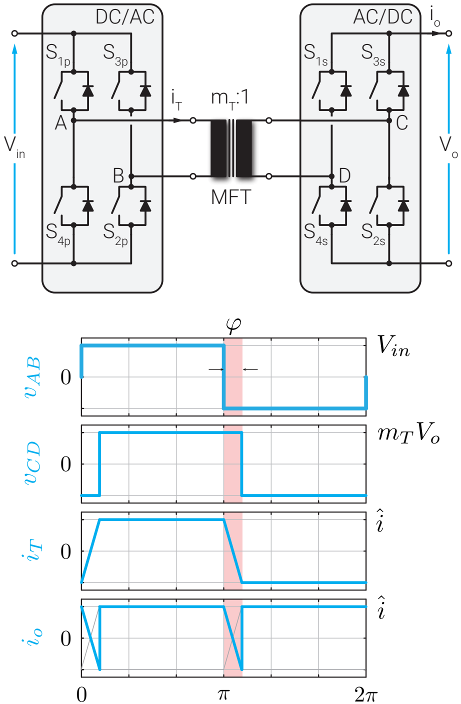
Switching cycle



SINGLE-PHASE (1PH) DUAL ACTIVE BRIDGE (DAB)



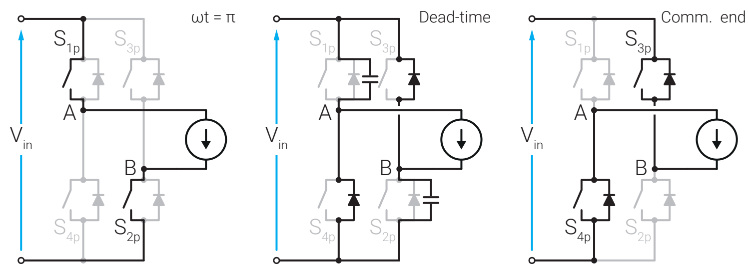
▲ 1PH-DAB with its relevant waveforms

Power equation

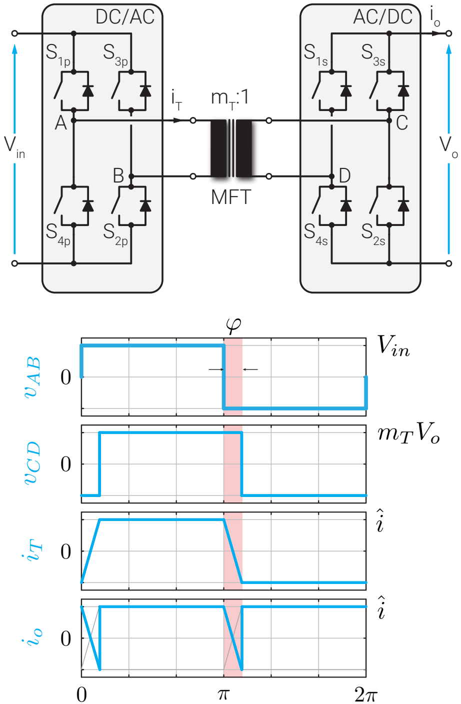
$$P = \frac{1}{T}\int_0^T v_{AB} i_T dt$$

$$= m_T \frac{V_{in} V_o}{\omega L_\Sigma} \varphi \left(1 - \frac{|\varphi|}{\pi}\right)$$

Switching cycle



SINGLE-PHASE (1PH) DUAL ACTIVE BRIDGE (DAB)



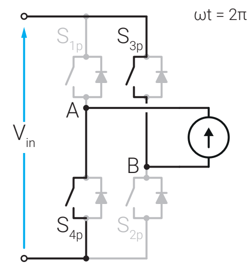
▲ 1PH-DAB with its relevant waveforms

Power equation

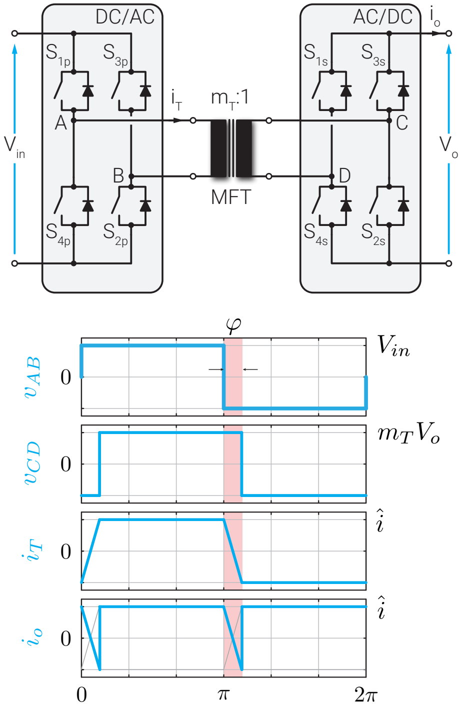
$$P = \frac{1}{T}\int_0^T v_{AB} i_T dt$$

$$= m_T \frac{V_{in}V_o}{\omega L_\Sigma}\varphi\left(1 - \frac{|\varphi|}{\pi}\right)$$

Switching cycle



SINGLE-PHASE (1PH) DUAL ACTIVE BRIDGE (DAB)



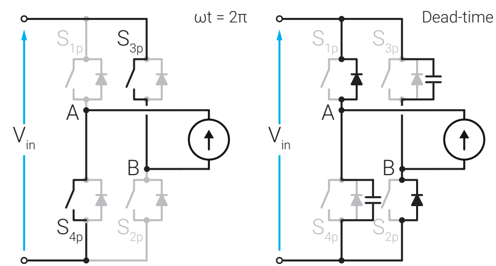
▲ 1PH-DAB with its relevant waveforms

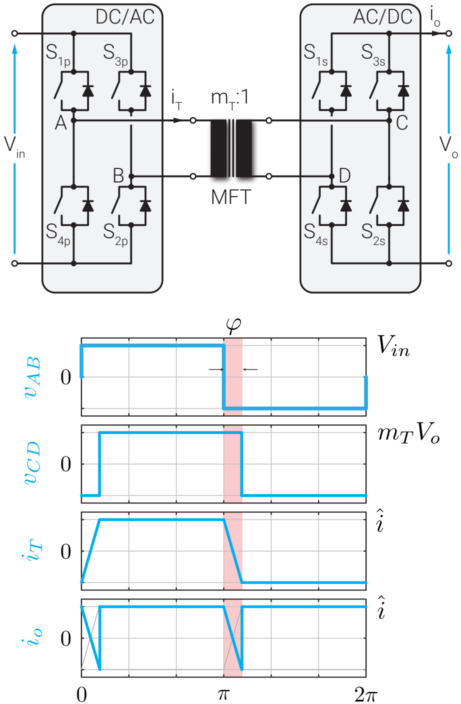
Power equation

$$P = \frac{1}{T}\int_0^T v_{AB} i_T dt$$

$$= m_T \frac{V_{in} V_o}{\omega L_\Sigma} \varphi \left(1 - \frac{|\varphi|}{\pi}\right)$$

Switching cycle





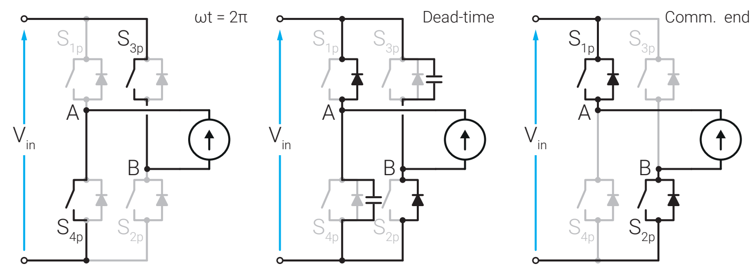
▲ 1PH-DAB with its relevant waveforms

Power equation

$$P = \frac{1}{T}\int_0^T v_{AB} i_T dt$$

$$= m_T \frac{V_{in} V_o}{\omega L_\Sigma} \varphi \left(1 - \frac{|\varphi|}{\pi}\right)$$

Switching cycle

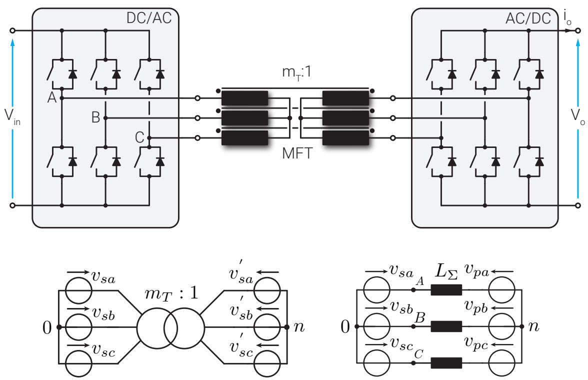


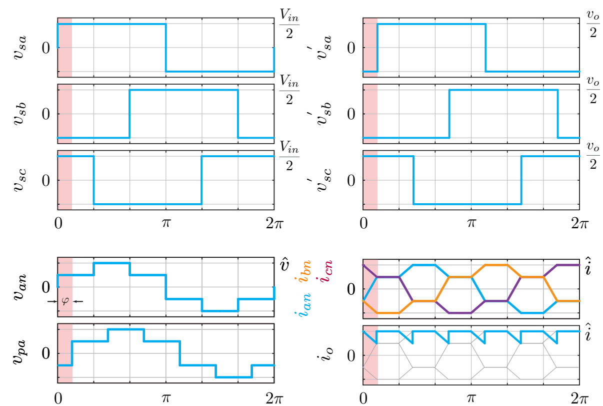
Main featuress

- Phase-Modulated converter
- Simple power flow control
- Soft-switching capability

3-PHASE DAB

Somewhat more complicated...





$$v_{an} = \frac{2v_{sa} - v_{sb} - v_{sc}}{3} \qquad v_{pa} = m_T \frac{2v'_{sa} - v'_{sb} - v'_{sc}}{3}$$

▲ 3PH-DAB with its relevant waveforms

Power Equation

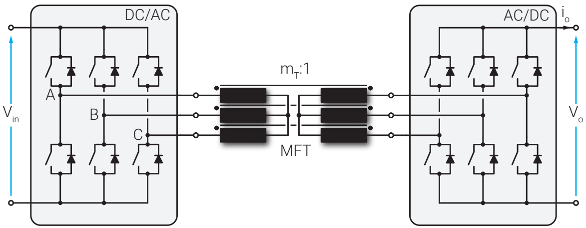
$$P = \frac{3}{T}\int_0^T v_{an} i_{an} dt$$

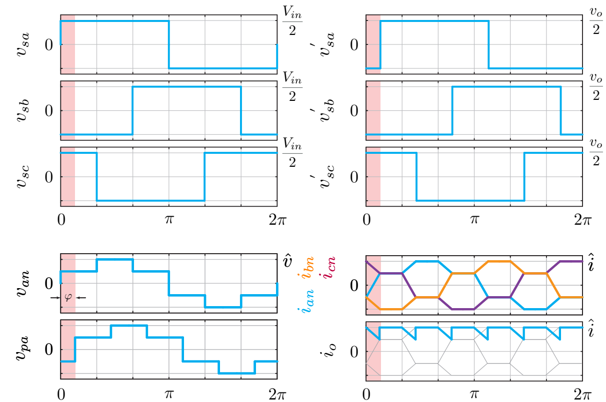
$$= m_T \frac{4}{3}\frac{V_{in}V_o}{\omega L_\Sigma}\varphi\left(\frac{1}{2} - \frac{3|\varphi|}{8\pi}\right)$$

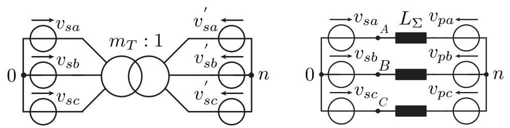
1-PH vs 3-PH DAB

	Control Simplicity	Tx utilization	Soft Switching	In/Out current ripple
1-PH DAB	☺	☹	☺	☹
3-PH DAB	☺	☺	☺	☺

THREE-PHASE (3PH) DAB







$$v_{an} = \frac{2v_{sa} - v_{sb} - v_{sc}}{3} \qquad v_{pa} = m_T \frac{2v'_{sa} - v'_{sb} - v'_{sc}}{3}$$

▲ 3PH-DAB with its relevant waveforms

Power Equation

$$P = \frac{3}{T}\int_0^T v_{an} i_{an} dt$$

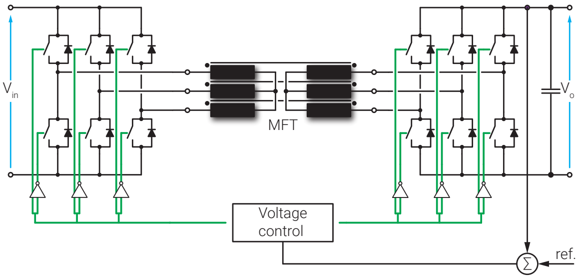
$$= m_T \frac{4}{3} \frac{V_{in} V_o}{\omega L_\Sigma} \varphi \left(\frac{1}{2} - \frac{3|\varphi|}{8\pi} \right)$$

1-PH vs 3-PH DAB

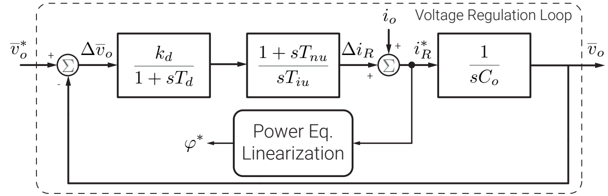
	Control Simplicity	Tx utilization	Soft Switching	In/Out current ripple
1-PH DAB	☺	☹	☺	☹
3-PH DAB	☺	☺	☺	☺

⇒ 3PH-DAB is considered favorable!

3PH-DAB CONTROL



▲ Observed DAB-based system



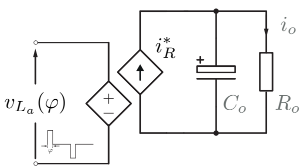
▲ Output voltage control loop

Assuming $P_{in} = P_{out}$:

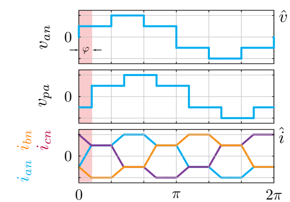
$$\cancel{V_o} i_o = \frac{4 m_T V_{in} \cancel{V_o}}{3\omega L} \varphi \left(\frac{1}{2} - \frac{3|\varphi|}{8\pi} \right)$$

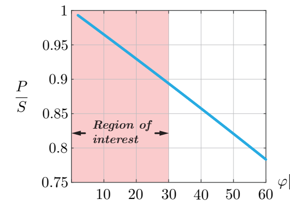
$$\Rightarrow i_o = \frac{4 m_T V_{in}}{3\omega L} \varphi \left(\frac{1}{2} - \frac{3|\varphi|}{8\pi} \right)$$

⇒ Controlled current source behavior!

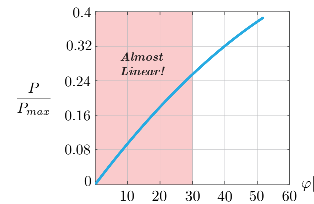


▲ DAB equivalent circuit seen from the controlled side



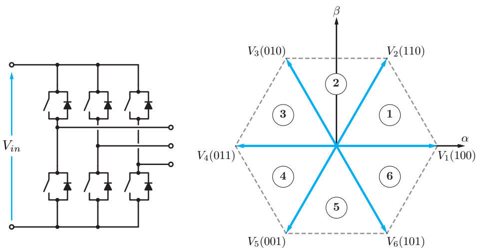


$$\frac{P}{S} = \frac{4\pi - 3\varphi}{2\pi\sqrt{\frac{4\pi - \varphi}{\pi}}}$$

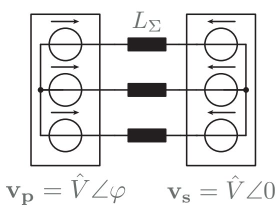


ABRUPT PHASE ANGLE CHANGES? (I)

- Six step modulation
- Limited number of voltage states



▲ Either side of the 3PH-DAB



▲ DAB equivalent circuit

? Current shape in the $\alpha\beta$ plane?

For $\omega t \in [(k-1)\frac{\pi}{3}, k\frac{\pi}{3}]$

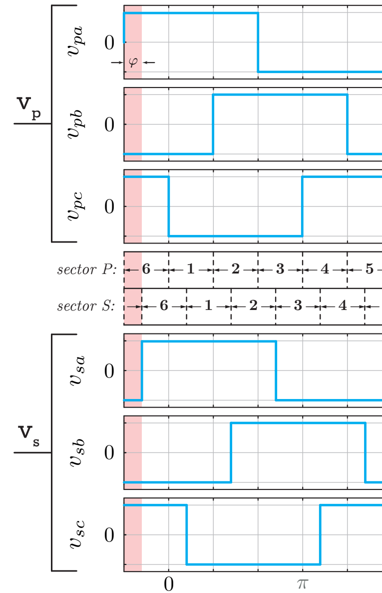
$$\mathbf{V_p} = \mathbf{V_k}$$

$$\mathbf{V_s} = \begin{cases} \mathbf{V_{k-1}}, & \omega t \in [(k-1)\frac{\pi}{3}, (k-1)\frac{\pi}{3}+\varphi] \\ \mathbf{V_k}, & \omega t \in [(k-1)\frac{\pi}{3}+\varphi, k\frac{\pi}{3}] \end{cases}$$

$$L\frac{d\mathbf{i}}{dt} = \mathbf{V_p} - \mathbf{V_s}$$

$$= \begin{cases} \hat{V}e^{j(k+1)\frac{\pi}{3}}, & \omega t \in [(k-1)\frac{\pi}{3}, (k-1)\frac{\pi}{3}+\varphi] \\ 0, & \omega t \in [(k-1)\frac{\pi}{3}+\varphi, k\frac{\pi}{3}] \end{cases}$$

$$\mathbf{i} = \begin{cases} \mathbf{i_{0,k}} + \frac{\hat{V}}{L_\Sigma} t e^{j(k+1)\frac{\pi}{3}}, & \omega t \in [(k-1)\frac{\pi}{3}, (k-1)\frac{\pi}{3}+\varphi] \\ \mathbf{i_{0,k}} + \frac{\hat{V}}{\omega L_\Sigma}\varphi\, e^{j(k+1)\frac{\pi}{3}}, & \omega t \in [(k-1)\frac{\pi}{3}+\varphi, k\frac{\pi}{3}] \end{cases}$$



▲ DAB switching signals

ABRUPT PHASE ANGLE CHANGES? (I)

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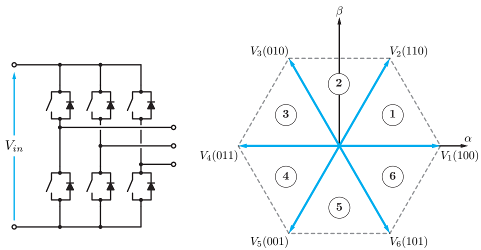

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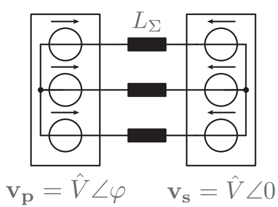

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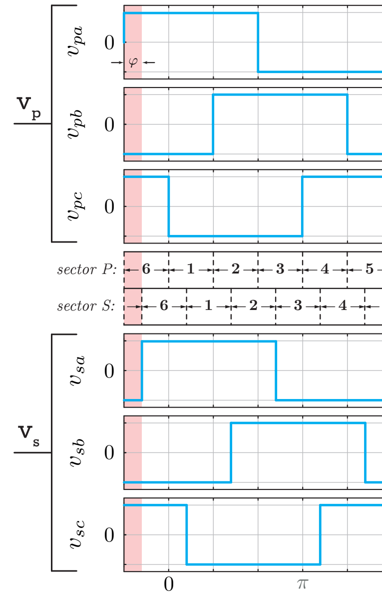
$$\mathbf{i} = \begin{cases} \mathbf{i_{0,k}} + \frac{\hat{V}}{L_\Sigma} t e^{j(k+1)\frac{\pi}{3}}, & \omega t \in [(k-1)\frac{\pi}{3}, (k-1)\frac{\pi}{3}+\varphi] \\ \mathbf{i_{0,k}} + \frac{\hat{V}}{\omega L_\Sigma}\varphi\, e^{j(k+1)\frac{\pi}{3}}, & \omega t \in [(k-1)\frac{\pi}{3}+\varphi, k\frac{\pi}{3}] \end{cases}$$

- Amplitude of the change proportional to φ
- Phase change in 60° steps

⇒ Current slides along a hexagon!



▲ DAB switching signals

ABRUPT PHASE ANGLE CHANGES? (II)

Recap

- Limited number of voltage states V_p and V_s
- Current vector stepwise phase changes (60°)
- Current vector magnitude directly proportional to phase angle
- Current vector slides along the hexagon [31], [32]

Recap

- Limited number of voltage states V_p and V_s
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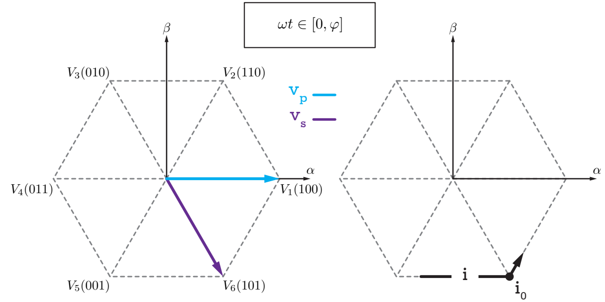
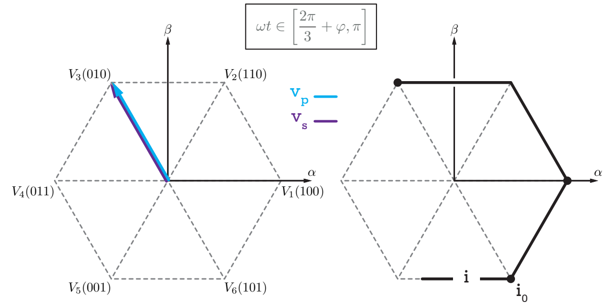




ABRUPT PHASE ANGLE CHANGES? (II)

Recap

- Limited number of voltage states V_p and V_s
- Current vector stepwise phase changes (60°)
- Current vector magnitude directly proportional to phase angle
- Current vector slides along the hexagon [31], [32]

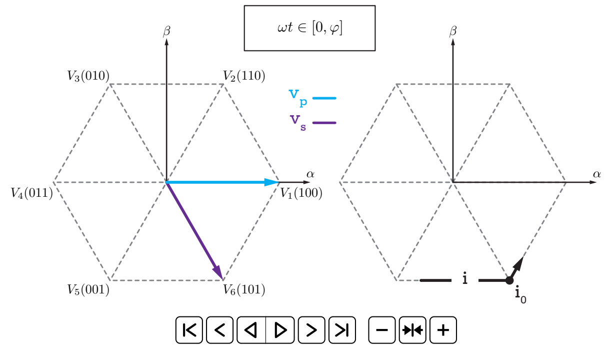
> ? What if the phase angle gets abruptly changed?

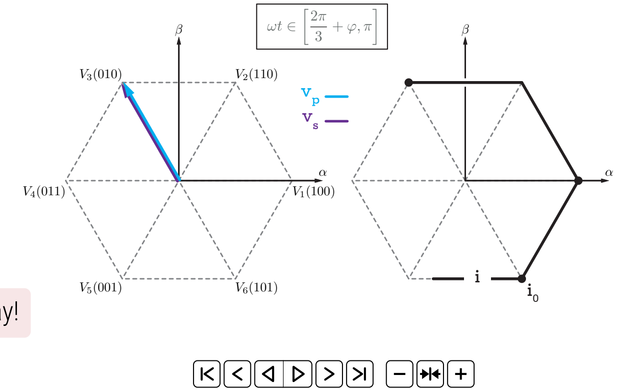
- New current vector trajectory
- Hexagon decentralization $\Rightarrow$ Transformer currents asymmetry!

Inverse $\alpha\beta0$ transformation:

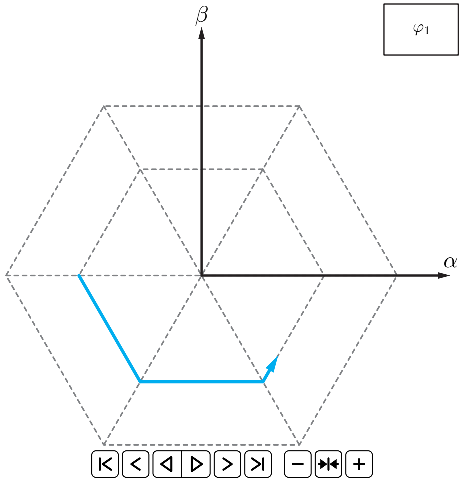
$$\begin{bmatrix} i_a^{off} \\ i_b^{off} \\ i_b^{off} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & 1 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & 1 \end{bmatrix} \cdot \begin{bmatrix} i_{\alpha,hex}^{off} \\ i_{\beta,hex}^{off} \\ 0 \end{bmatrix}$$

> ⚡ Time constant L_Σ / R_Σ determines asymmetric components decay!

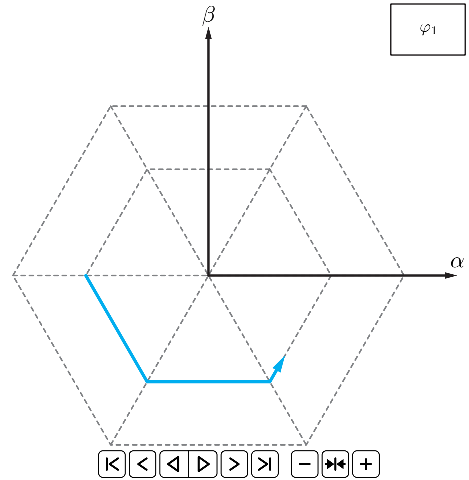




ABRUPT PHASE ANGLE CHANGES? (III)



▲ Safe way of achieving phase angle change (I)



▲ Safe way of achieving phase angle change (II)

Applied phase angle sequence:

$$\underbrace{\varphi_1}_{\textit{Angle change!}} \Rightarrow \underbrace{\underbrace{\frac{\varphi_1+\varphi_2}{2}}_{\frac{T}{6}} \Rightarrow \underbrace{\frac{\varphi_1+\varphi_2}{2}}_{\frac{T}{6}} \Rightarrow \underbrace{\frac{\varphi_1+\varphi_2}{2}}_{\frac{T}{6}}}_{\textit{Transition time} = \frac{T}{2}} \Rightarrow \underbrace{\varphi_2}_{\textit{Transition end}}$$

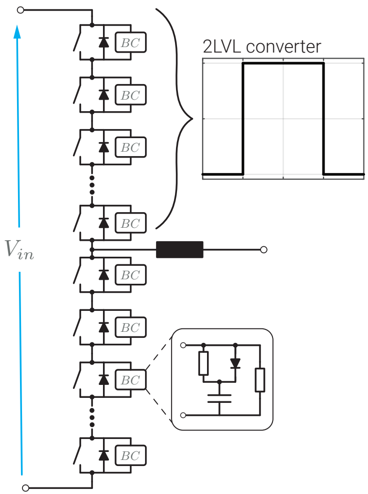
Applied phase angle sequence:

$$\underbrace{\varphi_1}_{\textit{Angle change!}} \Rightarrow \underbrace{\underbrace{\varphi_2}_{\frac{T}{6}} \Rightarrow \underbrace{\varphi_1}_{\frac{T}{6}}}_{\textit{Transition time} = \frac{T}{3}} \Rightarrow \underbrace{\varphi_2}_{\textit{Transition end}}$$

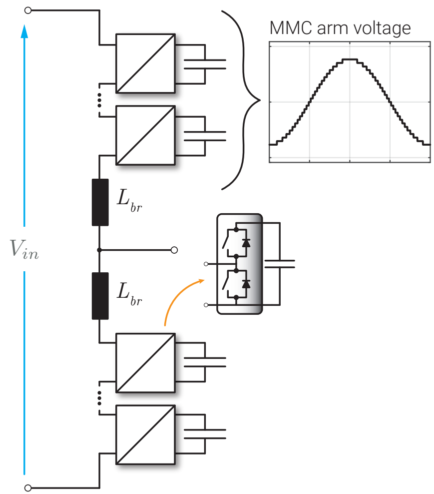
MEDIUM VOLTAGE DC-DC

Extending previously presented concepts...

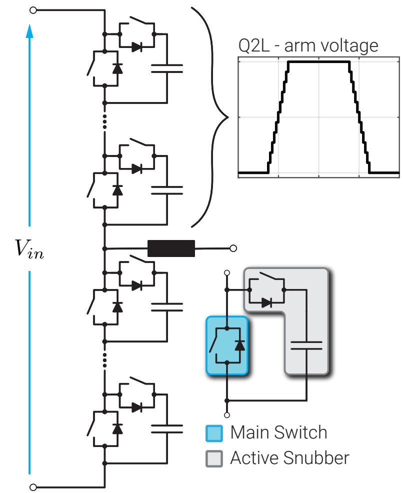
HOW TO HANDLE HIGH/MEDIUM VOLTAGES?



▲ Series connection of switches [33]



▲ Modular Multilevel Converter (MMC)



▲ Quasi Two-Level (Q2L) Converter [34], [35]

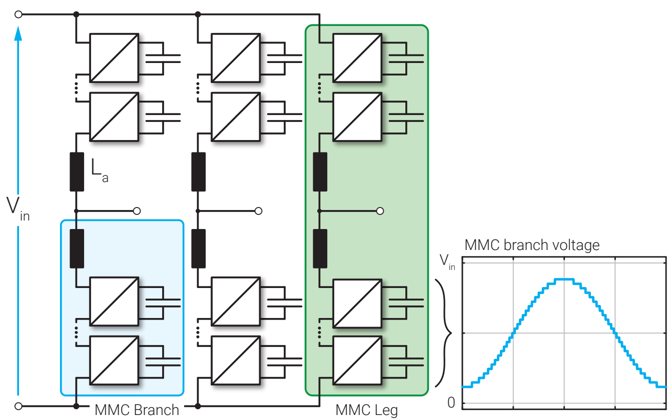
- Series connection of switches with snubbers
- Two voltage levels ($n_{LVL} = 2$)
- Two-Level voltage waveforms

- Series connection of Submodules (SM)
- n_{LVL} depending upon number of SMs
- Arbitrary voltage waveform generation

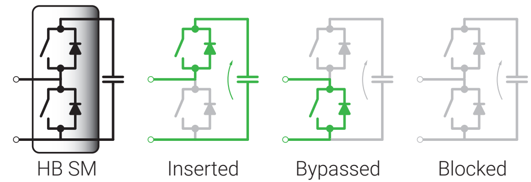
- Series connection of MMC-alike SMs
- n_{LVL} depending upon number of SMs
- Quasi Two-Level (trapezoidal) voltage waveform

MODULAR MULTILEVEL CONVERTER (MMC)

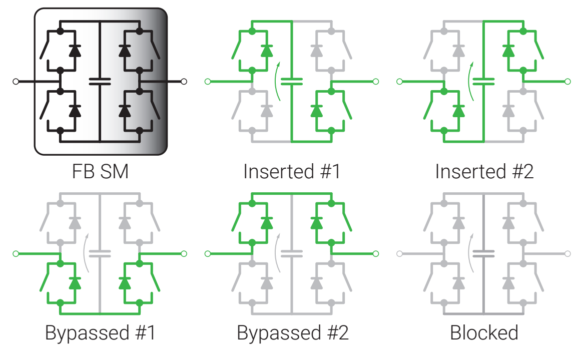
- Variety of conversion possibilities
- Variety of modulations
- Different types of submodules (SMs)
  - Half-Bridge (HB)
  - Full-Bridge (FB)
  - Others...
- Arbitrary voltage waveform generation



▲ Modular Multilevel Converter (MMC)



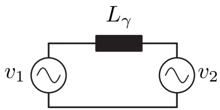
▲ Half-Bridge submodule and its allowed states



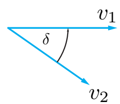
▲ Full-Bridge submodule and its allowed states

MMC-BASED DUAL ACTIVE BRIDGE (DAB)

- Basic operation principles are retained
- Easy to comprehend (AC equivalent)

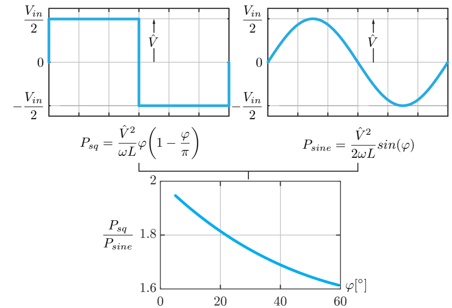


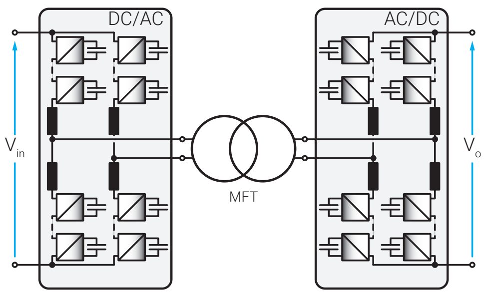
$$P = \frac{V_1 V_2}{\omega L_\gamma} sin(\delta)$$



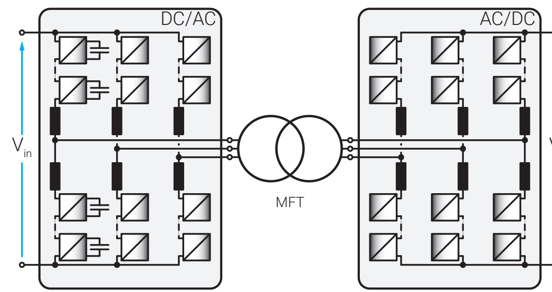
Challenges?

- Modulation choice (sine, square, etc ... ?)
- System design (N vs V_{grid})
- Energy balancing
- Q2L mode & capacitors sizing
- Engagement within bipolar grids





▲ MMC-based 1PH-DAB [36]



▲ MMC-based 3PH-DAB

MMC-BASED DUAL ACTIVE BRIDGE (DAB)

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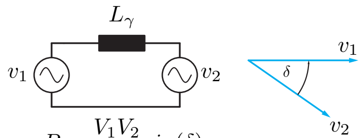

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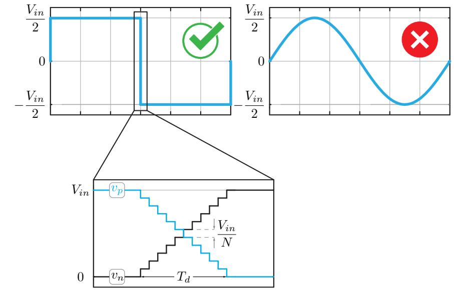

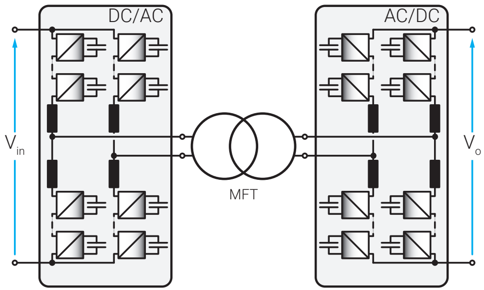

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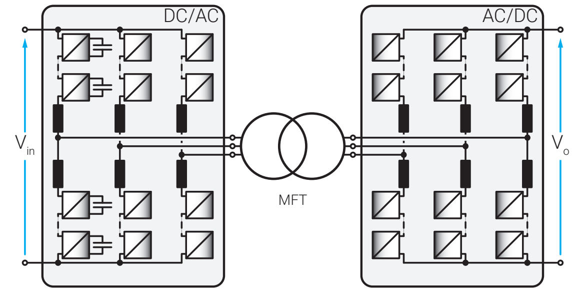
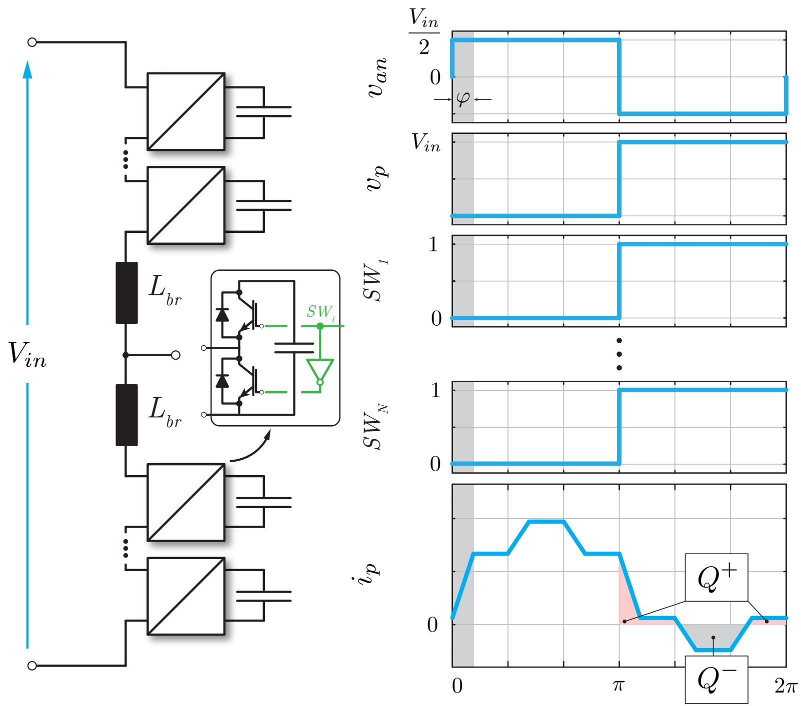


▲ MMC-based 3PH-DAB

MMC ENERGY BALANCING AND QUASI SQUARE WAVE OPERATION (I)

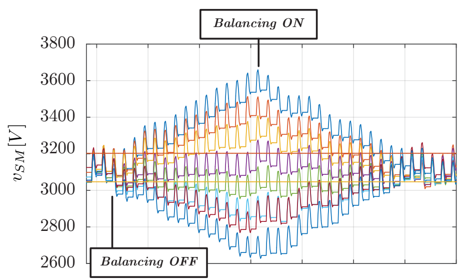


▲ MMC operating as a two level converter and its relevant waveforms

Ideally, $Q^+ = Q^-$ ⇒ **Natural balancing**

However, reality is different...

- Branch resistances affect the MMC current
- Not all the switches are gated at the same time



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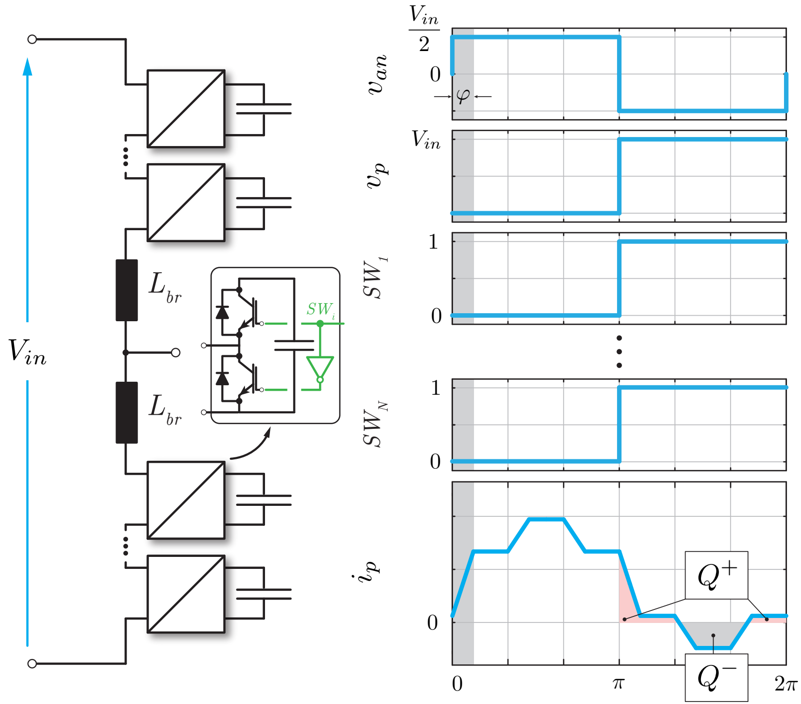

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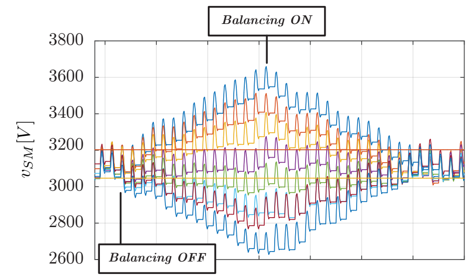
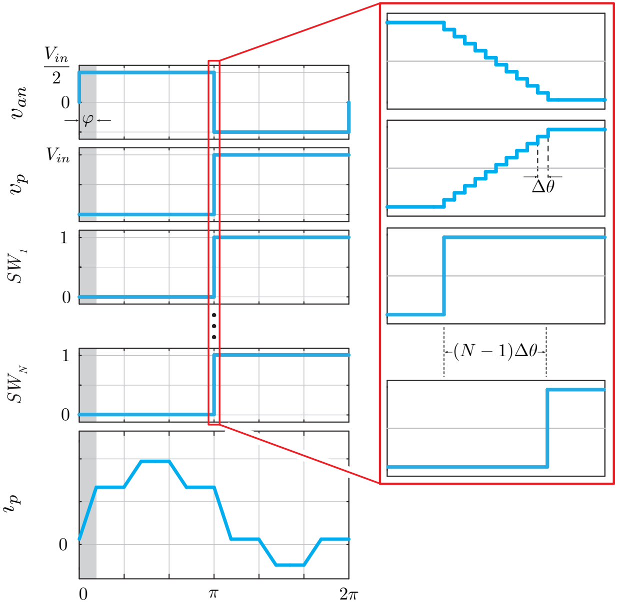


Balancing algorithm must be employed!

MMC ENERGY BALANCING AND QUASI SQUARE WAVE OPERATION (II)



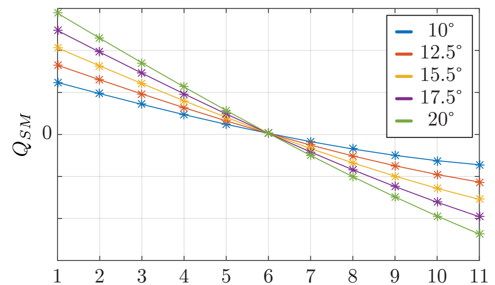
▲ MMC operating with quasi square voltages and its relevant waveforms

Quasi Square Wave operation

- Intentional displacement among gating signals
- Control of MFT voltage slopes (dV/dt)
- Control of SMs' voltages!

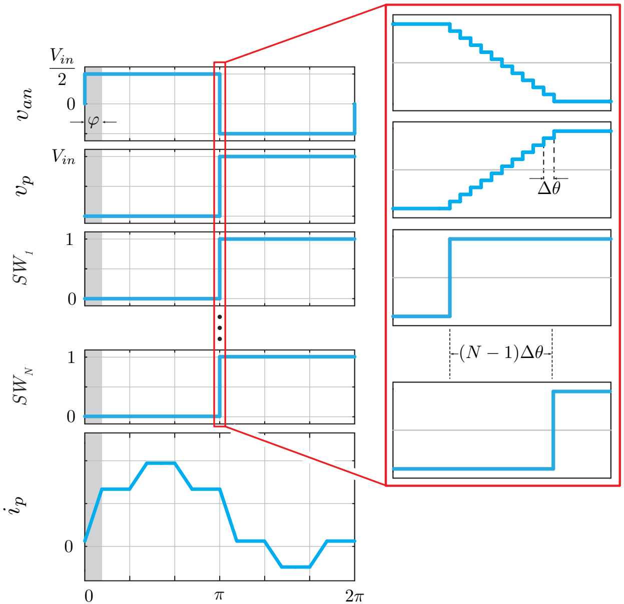
$$G = \frac{V_o m_T}{V_{in}}$$

For G = 1, SMs charge distribution can be derived.



▲ Charge received by a SM depending upon the gate signal [37]

MMC ENERGY BALANCING AND QUASI SQUARE WAVE OPERATION (II)



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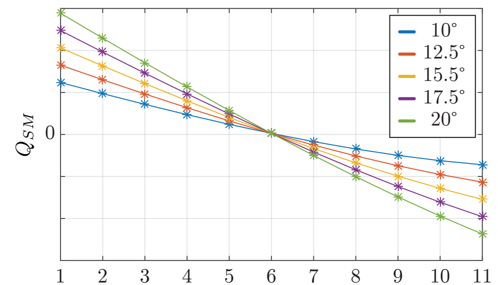

▲ Charge received by a SM depending upon the gate signal [37]

⇒ Different charge distribution enables balancing!

MMC-BASED DAB SORTING FOR N = 3 (EXAMPLE)

- $V_{SM}(k)$ - SMs voltages measured in the observed switching period
- $V_{SM}(k-1)$ - SMs voltages measured in the previous switching period
- $Gate(k-1)$ - Gate signals assigned in the previous switching period
- ΔV_{SM} - SM voltage change with respect to the previous switching period

	SM_1	SM_2	SM_3
V_{SM} (k)	1200	1050	1150
V_{SM} (k-1)	1100	1150	1200
Gate (k-1)	Signal 2	Signal 3	Signal 1
ΔV_{SM}	100	-100	-50

MMC-BASED DAB SORTING FOR N = 3 (EXAMPLE)

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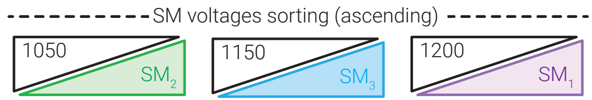
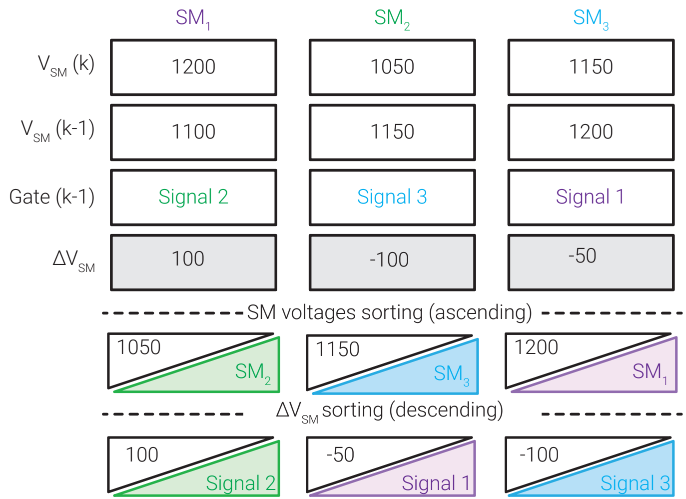
Gate (k-1)	Signal 2	Signal 3	Signal 1
ΔV_{SM}	100	-100	-50



MMC-BASED DAB SORTING FOR N = 3 (EXAMPLE)

- $V_{SM}(k)$ - SMs voltages measured in the observed switching period
- $V_{SM}(k-1)$ - SMs voltages measured in the previous switching period
- $Gate(k-1)$ - Gate signals assigned in the previous switching period
- ΔV_{SM} - SM voltage change with respect to the previous switching period



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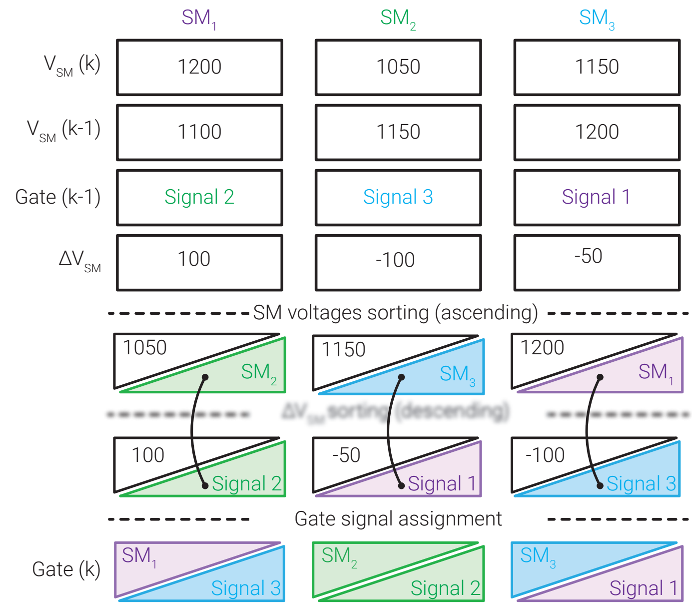
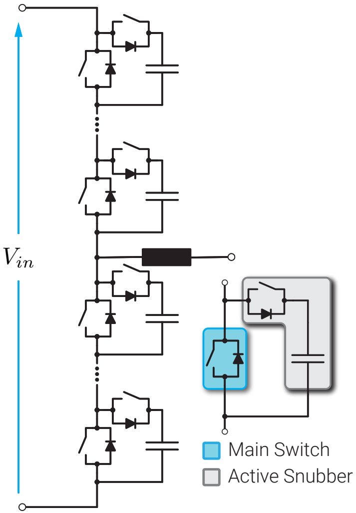
- $Gate(k)$ - Gate signal assigned to a SM in the observed switching period

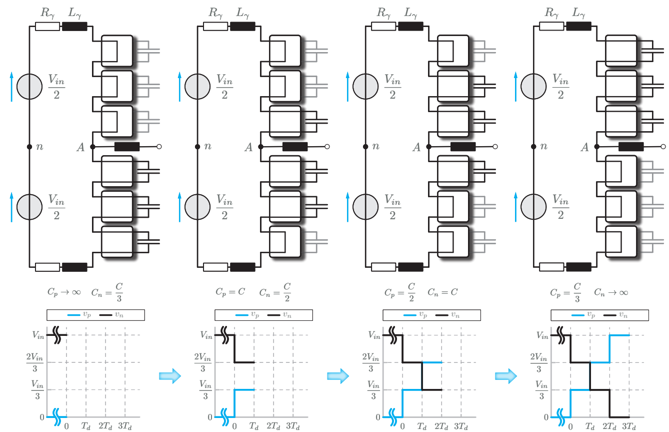


QUASI TWO-LEVEL (Q2L) CONVERTER

- MMC-alike structure
- Branch inductors removed!
- SM = Main Switch + Active Snubber
- Sequential insertion/bypassing of SMs



▲ Quasi Two-Level Converter



▲ Example of the Q2L Converter transition (N=3)

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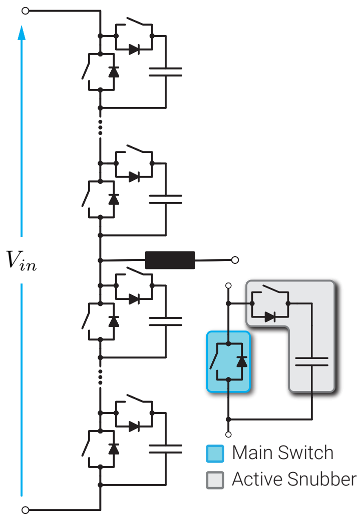

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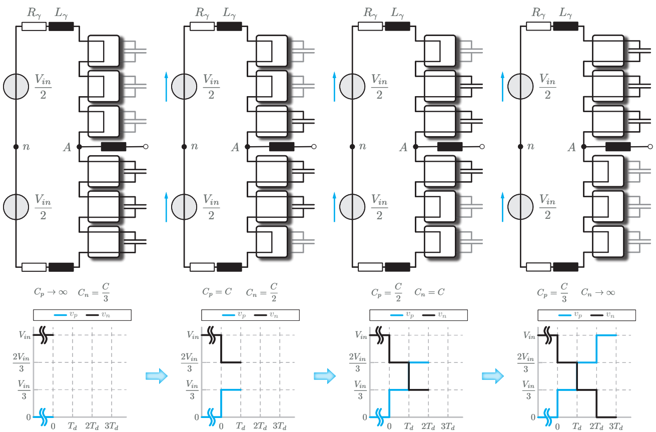

▲ Example of the Q2L Converter transition (N=3)

> Every dwell interval introduces new resonant parameters to the circuit!

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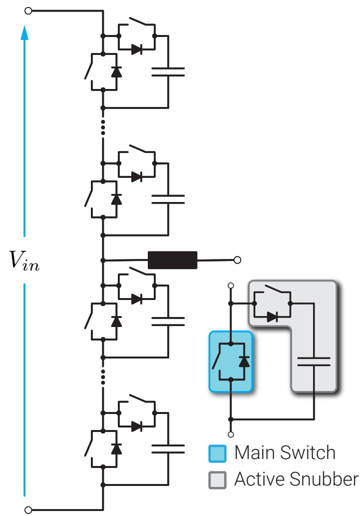

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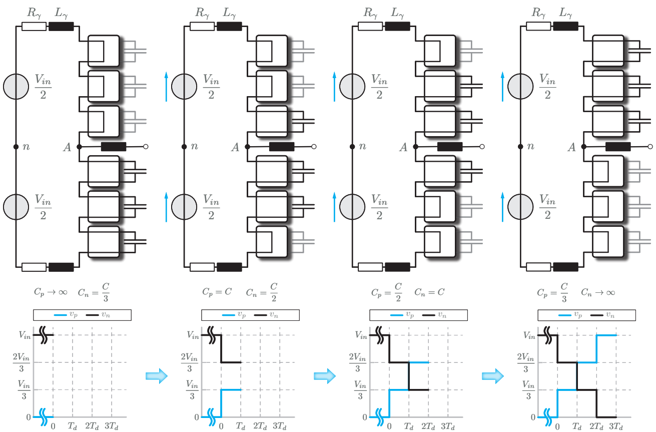

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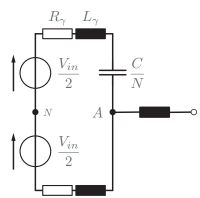

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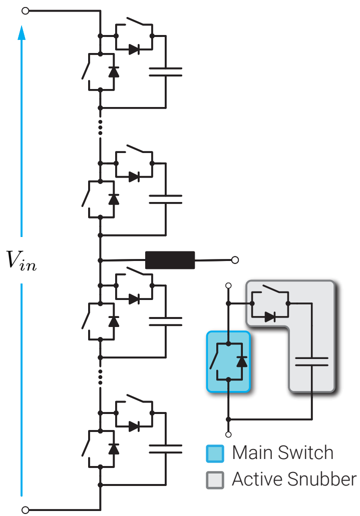

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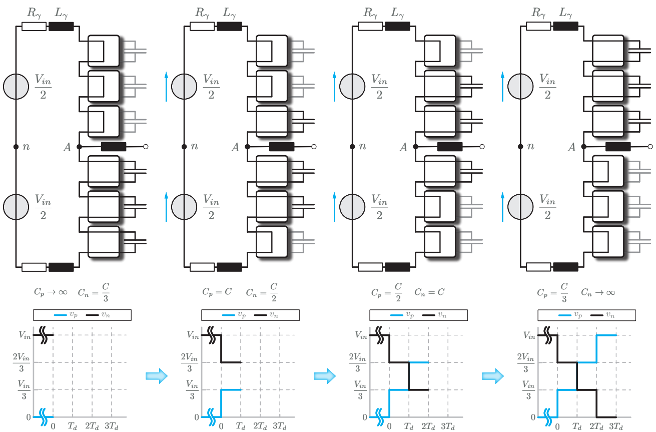

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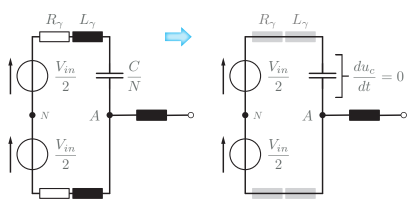

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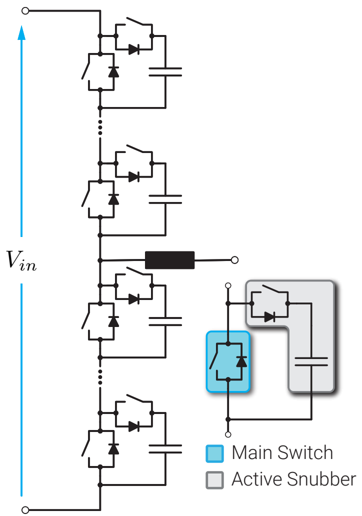
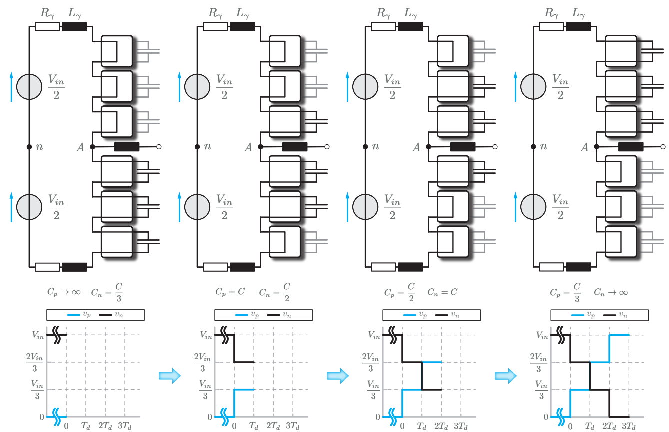
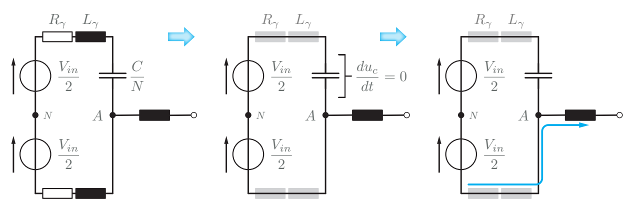


Quasi Two-Level Converter

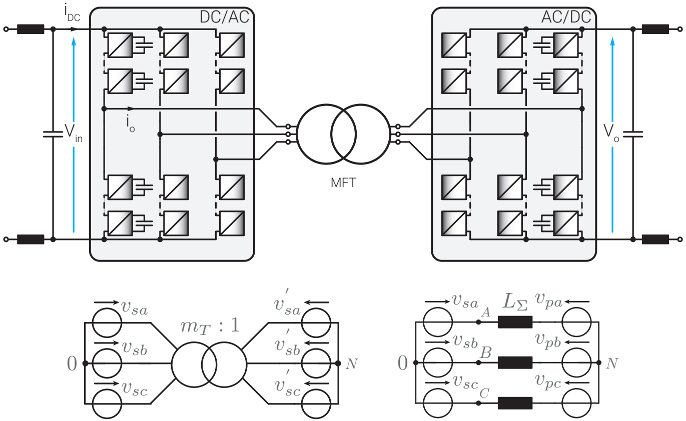


Example of the Q2L Converter transition (N=3)

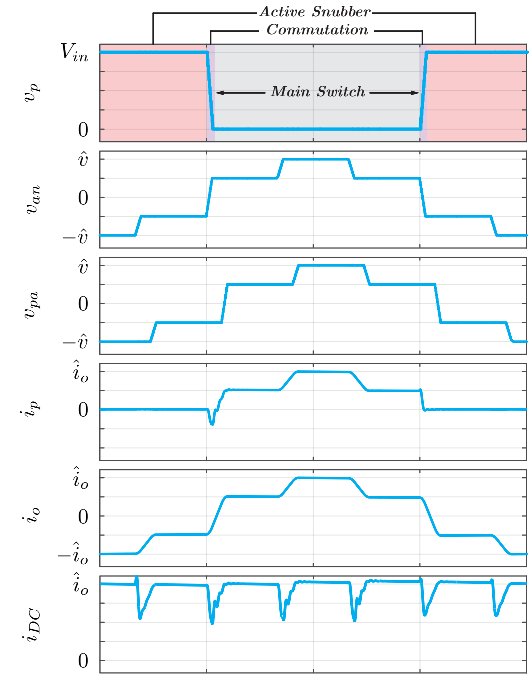


⇒ Output current drifts to a single branch. Common mode current does not exist!

Q2L CONVERTER - PROS AND CONS

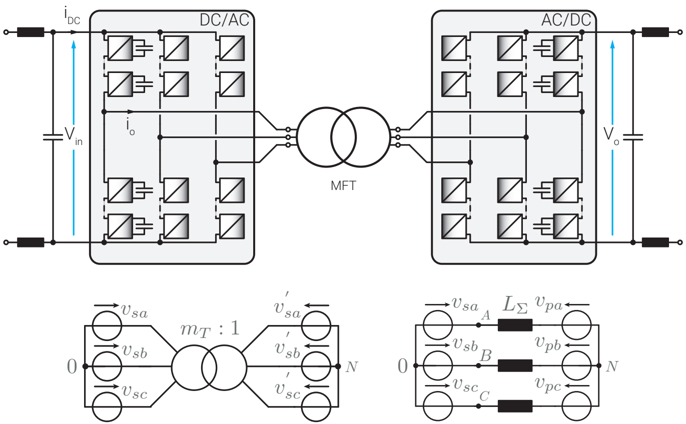


▲ Observed Q2L configuration



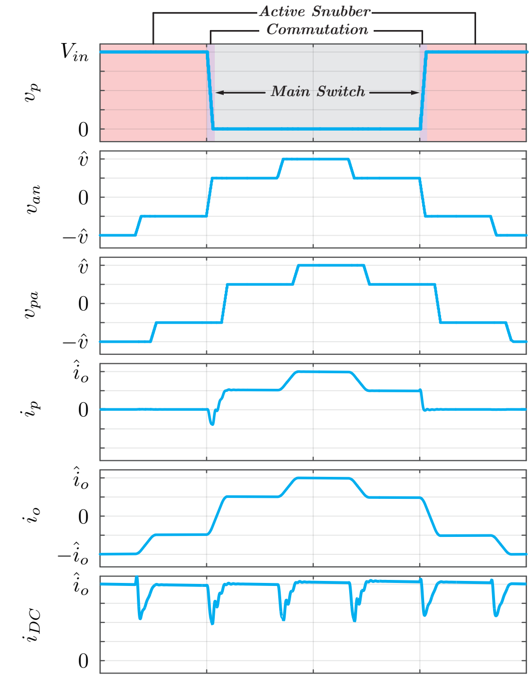
▲ Relevant waveforms of the Q2L converter operating as the 3PH-DAB

Q2L CONVERTER - PROS AND CONS



▲ Observed Q2L configuration

⇒ SM capacitor = "short-interval" energy buffer



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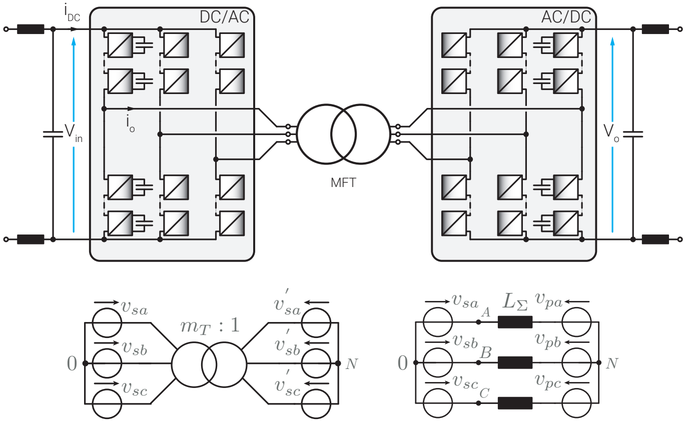
Q2L CONVERTER - PROS AND CONS



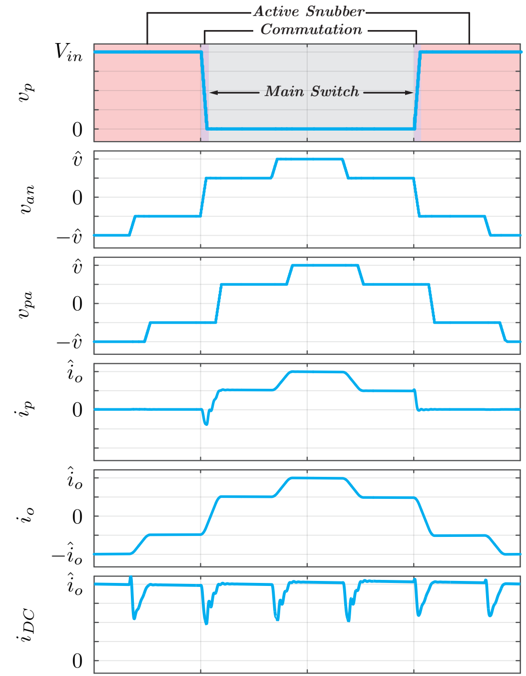
▲ Observed Q2L configuration

Pros

- Significant reduction in submodule capacitance
- Converter size reduction (no branch inductors, small SM capacitance)
- Active snubber switch can be sized for half the rated current

Cons

- Need for HV/MV input/output capacitor
- Complicated analysis of transition process/SM capacitance sizing
- SM capacitance sizing influenced by the branch stray inductance



▲ Relevant waveforms of the Q2L converter operating as the 3PH-DAB

MV MMC CONVERTER PLATFORM

University lab prototype

ONGOING MMC – RELATED ACTIVITIES

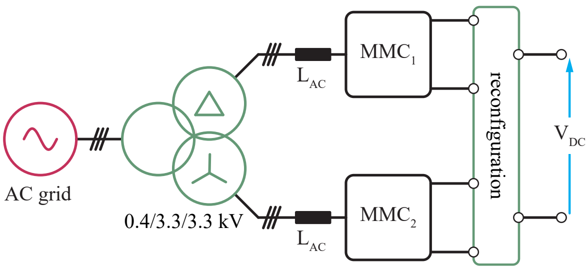
Pump Hydro Storage Research Platform

- MMC based AC/AC converter
- Interface between SG and local AC grid

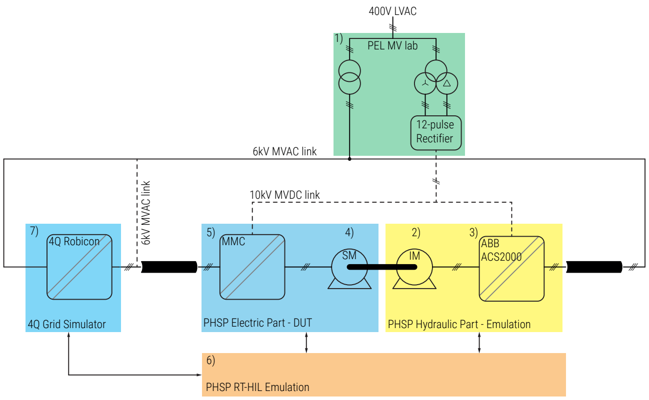
▲ MMC-Based AC/AC Converter for Pump Hydro Applications

Flexible DC Source (FlexDCS)

- MMC Based DC Source rated at 0.5 MVA
- Reconfiguration unit allows series/parallel operation
- Four quadrant operation
- Flexible voltage source in a range ±10 kV DC
- Flexible current source in a range ±100 A DC



▲ Flexible DC Source Topology

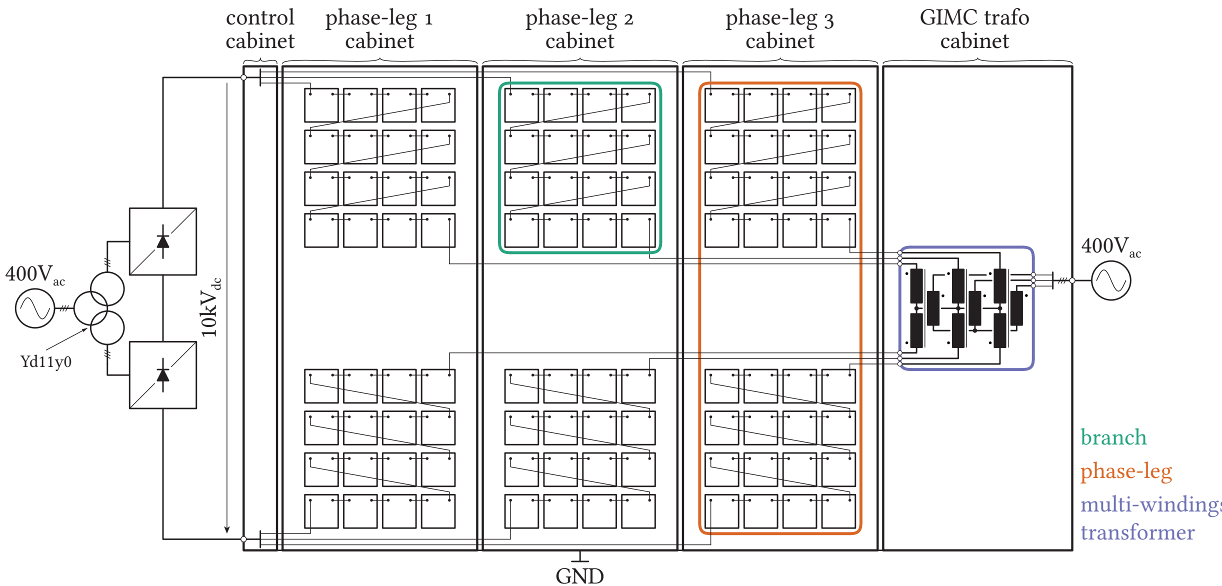


▲ Pumped Hydro Storage Plants - Research Platform

GIMC – CONVERTER LAYOUT

MMC demonstrator ratings are:

- 500 kVA
- 10 kV_{dc} ↔ 400 V_{ac} or 6.6 kV_{ac}
- 16 low voltage cells per branch ⇒ 32 cells per phase (cabinet) ⇒ 96 cells in total
- Industrial central controller and communication (ABB AC PEC 800)

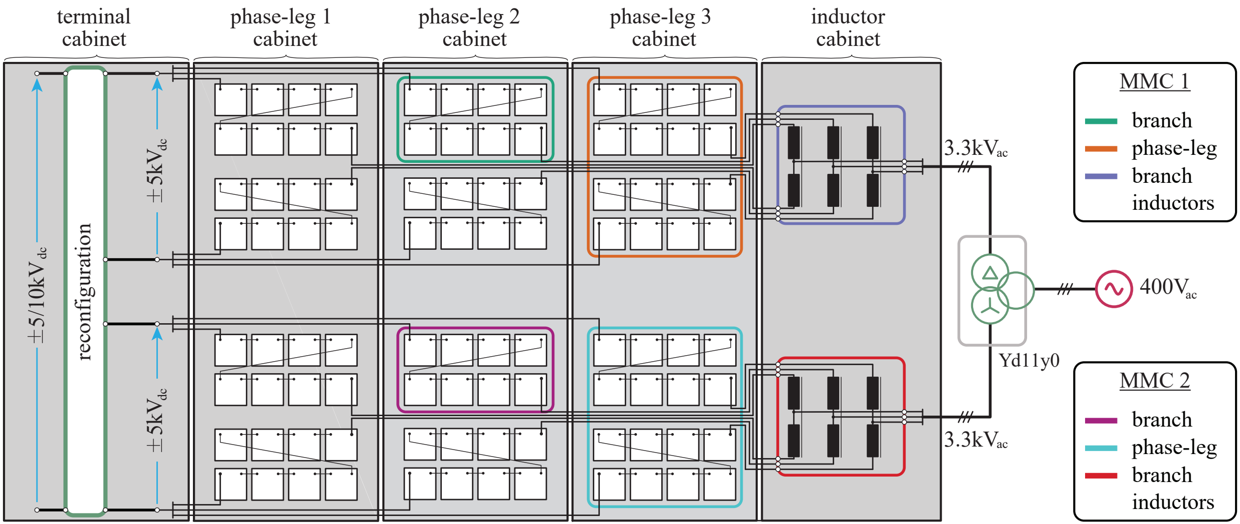


▲ DC/3-AC MMC Converter Layout

MMC – CONVERTER LAYOUT

MMC demonstrator ratings are:

- 500 kVA
- $\pm$ 10 kV$_{dc}$ $\leftrightarrow$ 2 x 3.3 kV$_{ac}$
- 8 low voltage cells per branch $\Rightarrow$ 16 cells per MMC phase $\Rightarrow$ 96 cells in total
- Industrial central controller and communication (ABB AC PEC 800)



▲ Flexible DC Source Converter Layout

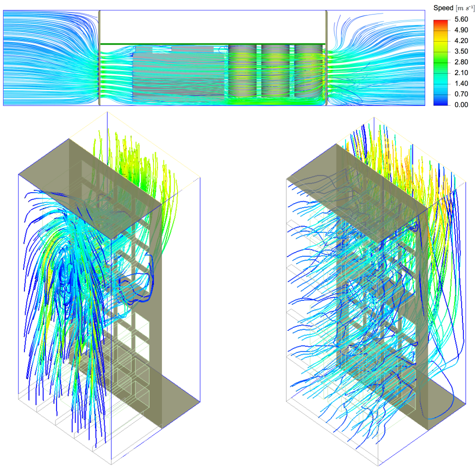
MMC – SUBMODULE OPTIMIZATION

Submodule

- 1.2 kV / 50 A full-bridge IGBT module
- $C_{cell} = 2.25\,\text{mF}$

Thermal design

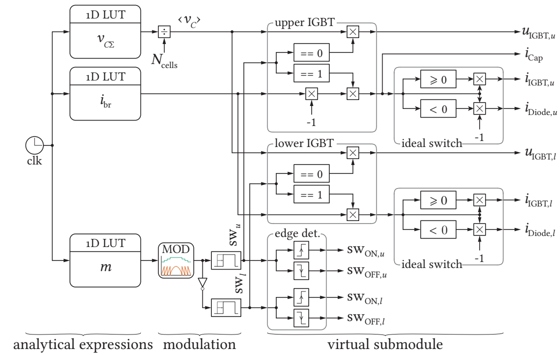
- Cell level: detailed FEM
- Cabinet level: simplified FEM

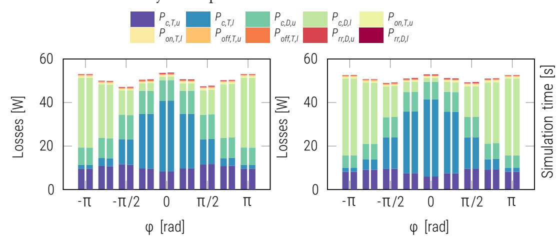


▲ CFD simulations of submodule and cabinet

Semiconductor losses

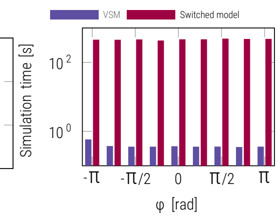
- Virtual Submodule concept has been utilized [8]
- Closed-loop waveforms are approached by analytical waveforms





▲ PS-PWM, DC circ

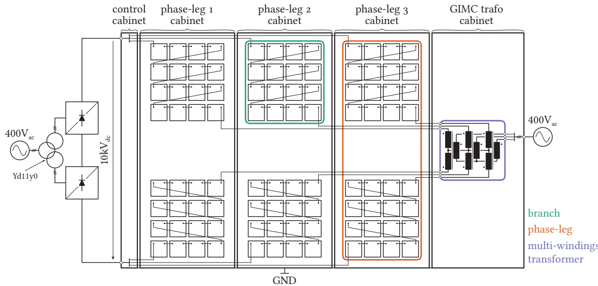
▲ PS-PWM, DC+2nd circ



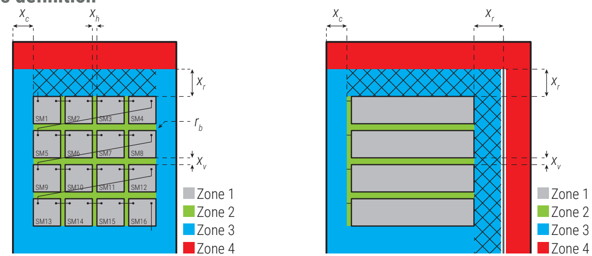
▲ Time benchmark

INSULATION COORDINATION OF A MV CONVERTER PROTOTYPE (I)

System partitioning



Zones definition



Zone 1 (ins. coord. inside a SM's enclosure) system voltage: 1 kV$_{ac}$

Zone 2 (ins. coord. branch)

- Horizontal system voltage: 1 kV$_{ac}$
- Vertical system voltage: 3.6 kV$_{ac}$

Zone 3 (ins. coord. branch - cabinet (at GND)) system voltage: 6.6 kV$_{ac}$

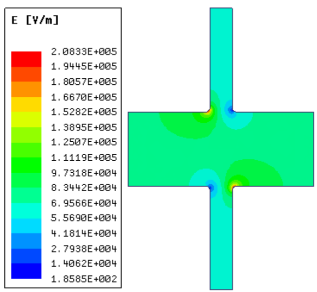
Zone 4 (ins. coord. for LV circuits) system voltage: 0.4 kV$_{ac}$

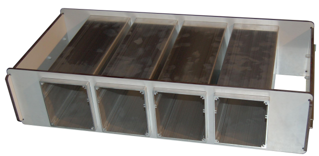
Standards

- UL840 for cell PCB (< 1 kV)
- IEC61800-5-1 (AC motor drives)
  - Pollution degree 2: "Normally, only non-conductive pollution occurs. Occasionally, however, a temporary conductivity caused by condensation is to be expected, when the PDS is out of operation."
  - Overvoltage category II: "Equipment not permanently connected to the fixed installation. Examples are appliances, portable tools and other plug-connected equipment."

Zone 2

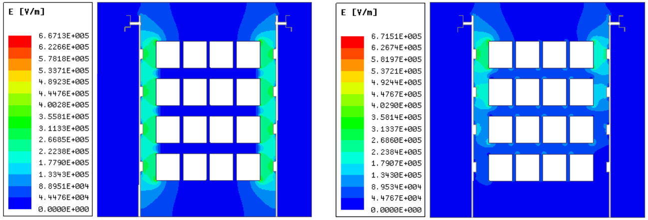
- Box at dc- cell's potential (floating)
- Box corner radius: 3 mm
- MKHP (high CTI material) drawer holding 4 cells



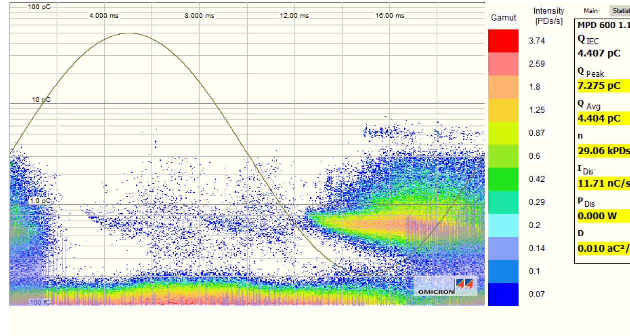


INSULATION COORDINATION OF A MV CONVERTER PROTOTYPE (II)

Zone 3 (2 out of 2^{16} combinations)



Ac dielectric withstand test



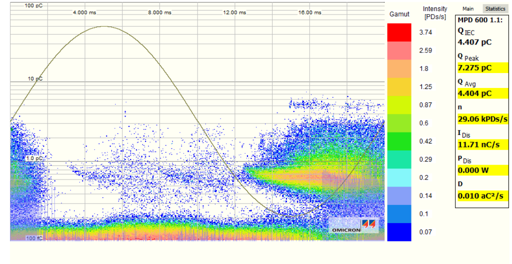
Design recap

Variable	Minimal value [mm]	Actual design value [mm]
r_b		3
$d_{L,h}$	6.8	15
$d_{C,h}$	3.2	15
$d_{L,v}$	30	50
$d_{C,v}$	12.5	275
$d_{L,c}$	60	81.5
$d_{C,c}$	60	93
$d_{L,r}$	102	120

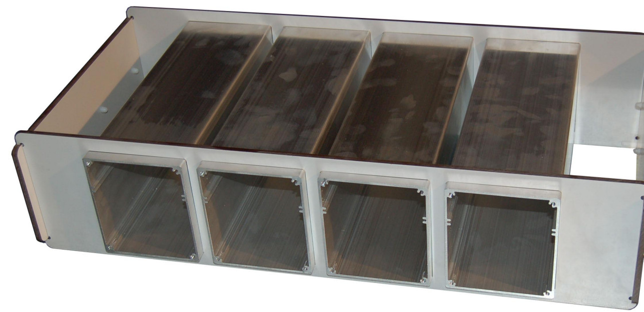
MMC – CONVERTER DESIGN

- ✓ MV MMC converter laboratory prototype layout compliant with:
  - UL840 (for cell)
  - IEC 61800-5-1
- ✓ Complete AC dielectric withstand tests on real prototype [9]

▲ Cabinet of one phase-leg (32 cells) in Faraday cage during insulation coordination testing



▲ AC dielectric withstand test result

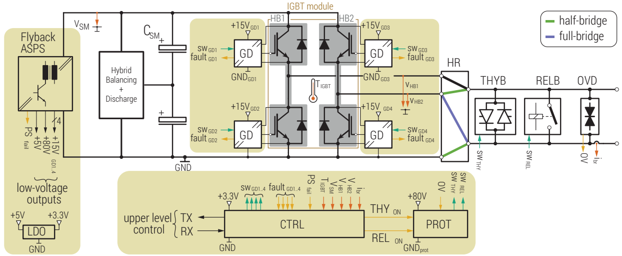


▲ Drawer holding 4 cell (MKHP material)

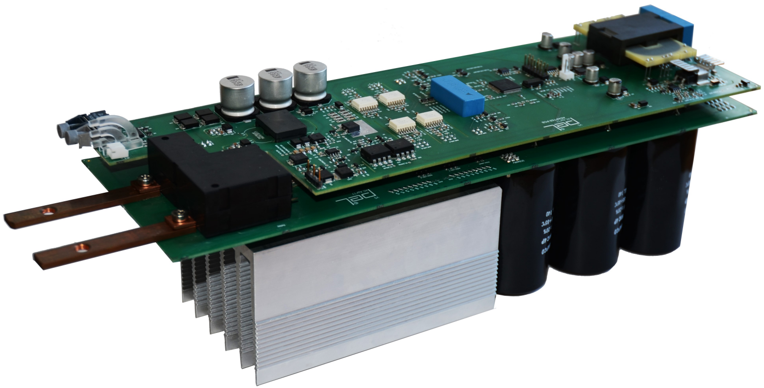
MMC SUBMODULE – STRUCTURE

Key Features

- Low voltage power components
- Full-bridge submodule structure
- Submodule rated voltage - 625 V
- Submodule insulation coordination - 900 V
- Two interconnected PCBs: **Power PCB** and **Control PCB**



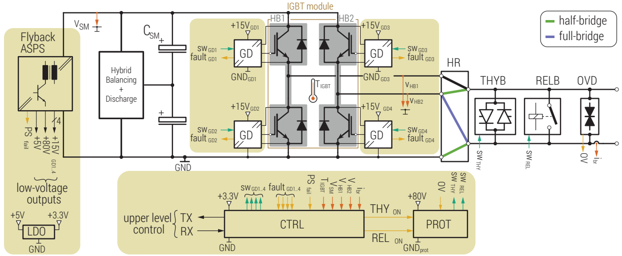
▲ MMC Submodule Structure: Yellow parts - Control PCB



▲ Developed MMC submodule

MMC SUBMODULE – POWER PCB

- Power processing part
- Semikron full-bridge IGBT module 1.2 kV/50 A
- Bank of electrolytic capacitors C_{sm} = 2.25 mF
- Protection devices: Bypass thyristor, relay and OVD
- Current and voltage measurements
- Hybrid balancing circuitry
- Hardware reconfiguration (HR)



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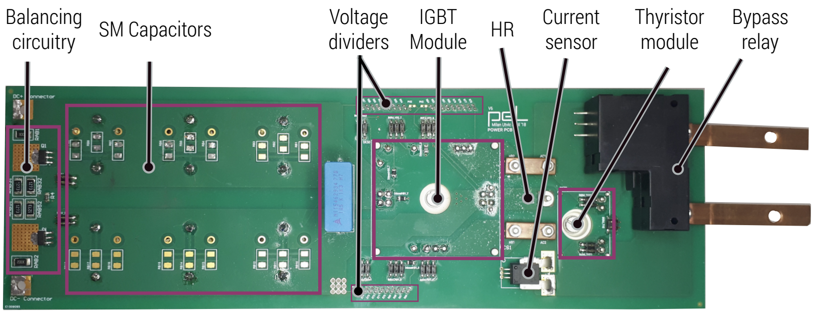
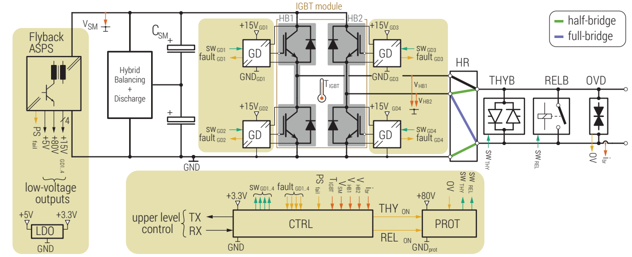


▲ Top overview of the Power PCB

MMC SUBMODULE – CONTROL PCB

- Flyback based auxiliary power supply
  - +5V Output, used as a control feedback
  - +80V Protection supply
  - +15V Gate drivers supplies
  - +15V Self-supply output
- DSP based main SM Controller
  - Communication with upper level control
  - Voltage and current measurements
  - Monitoring the SM condition
  - Decentralized modulation
- Gate drivers
- Protection logic
  - Protection activation from upper level control
  - Protection activation from DSP
  - Protection activation by overvoltage detection
- Fiber-optical communication link



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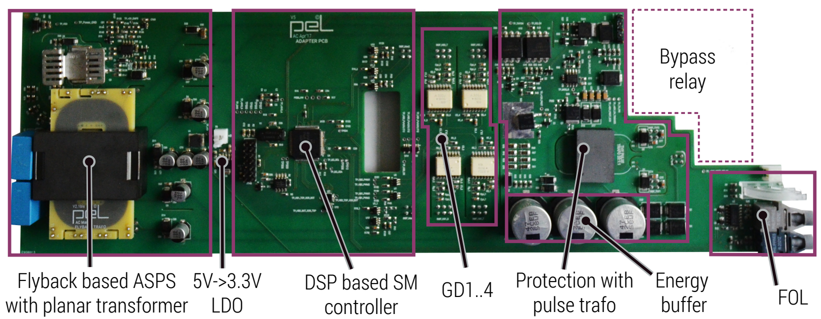


▲ MMC Top overview of the Control PCB

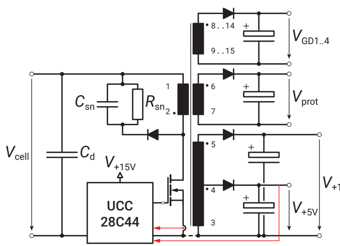
AUXILIARY SUBMODULE POWER SUPPLY (I)

Possible concepts

- Externally supplied
  - Single wire loop
  - Siebel
  - Inductive power transfer
- Internally supplied
  - Tapped inductor Buck
  - Flyback

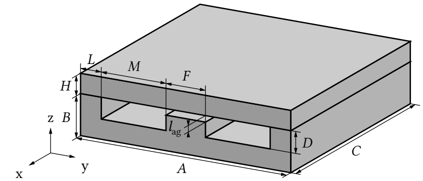
Choice

- Flyback with 6 isolated secondaries
  - 1× 5 V, 4 W for the controller supply (V_{+5V}). This output is tightly regulated in closed-loop.
  - 4× 15 V, 1.5 W for the IGBT gate drivers ($V_{GD1..4}$)
  - 1× 80 V, 15 W for 15 s operation when activated for the protection circuit (V_{prot})



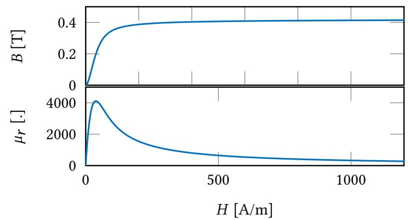
Planar trafo design

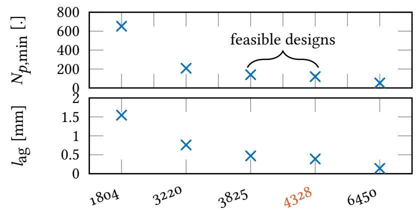
- PCB windings (isolation requirements!)
- Planar ferrite cores with custom gapping (COSMO ferrites)



Matlab design tool

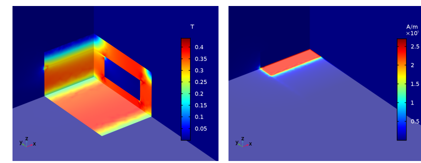
- Account for flux fringing [38]
- BH curve for CF297
- Jiles-Atherton parametrization

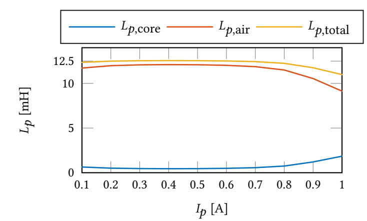




FEM

- Validate Matlab design
- 3D model for accurate leakage flux

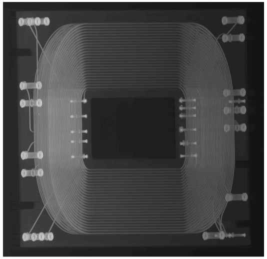


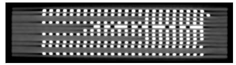


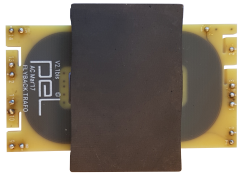
AUXILIARY SUBMODULE POWER SUPPLY (II)

Transformer assembly

- 14 copper layers PCB
- Custom gapped ferrite E+I core

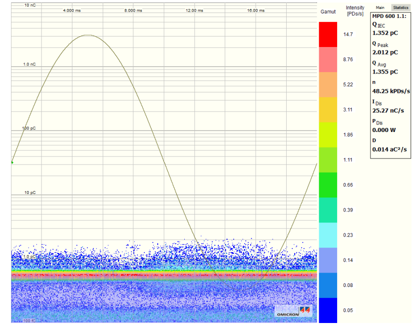




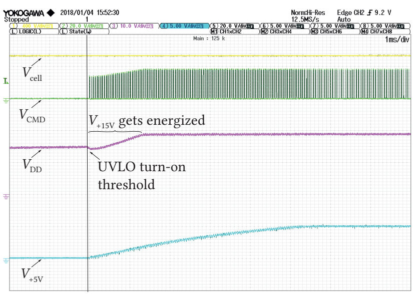


AC dielectric withstand test

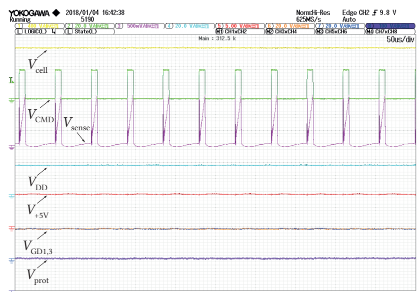
- Way below threshold level of 10pC



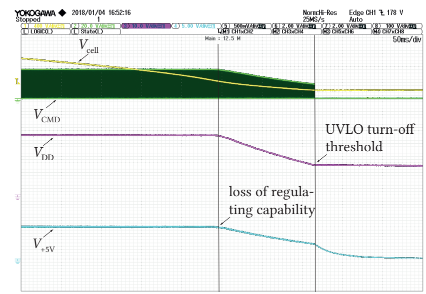
Tests



▲ Start-up

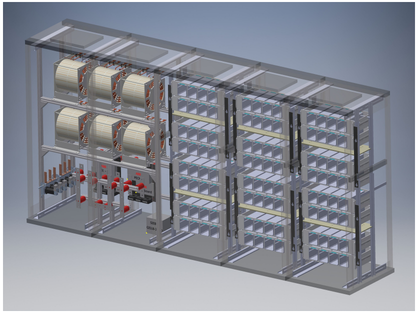


▲ Steady-state operation

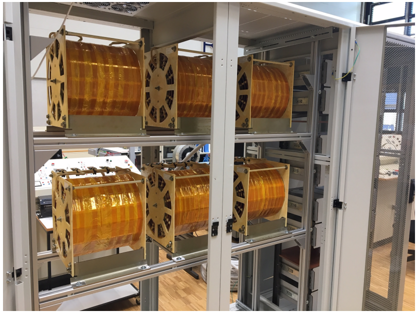


▲ Shut-down (slow dv/dt from Delta power-supply used to emulate the cell)

MMC MECHANICS

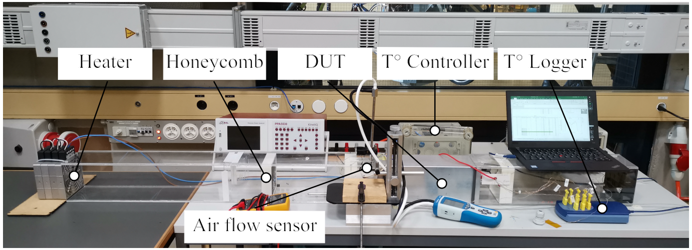


▲ MMC CAD development



▲ MMC coupled air-core branch inductors

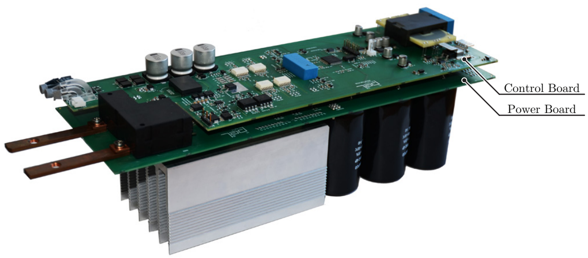
▲ MMC - Actual mechanical assembly



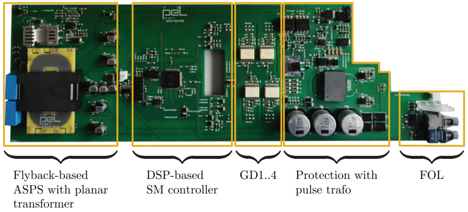
▲ MMC Submodule thermal heat-run test setup

MMC CONTROL TESTING PLATFORM BASED ON THE PLECS RT-BOX HIL

- **Digital twin** of the system being under construction
- Virtual power processing
- Safe control testing prior to commissioning
- Flexibility
- Certain adjustments need to be made
  - Adjustment of the original MMC submodule?
  - RT-Box/MMC submodule interface boards
- Two connected MMCs as the end goal (**13 RT-Boxes + 96 cells**)



▲ MMC Submodule



▲ MMC Submodule Control board

MMC CONTROL TESTING PLATFORM BASED ON THE PLECS RT-BOX HIL

- **Digital twin** of the system being under construction
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- Safe control testing prior to commissioning
- Flexibility
- Certain adjustments need to be made
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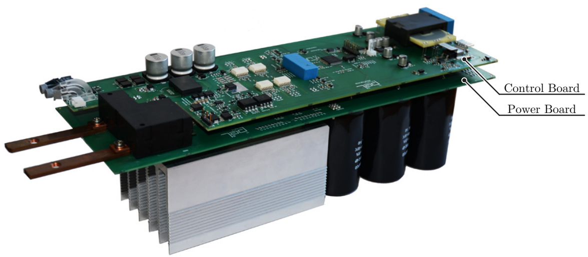
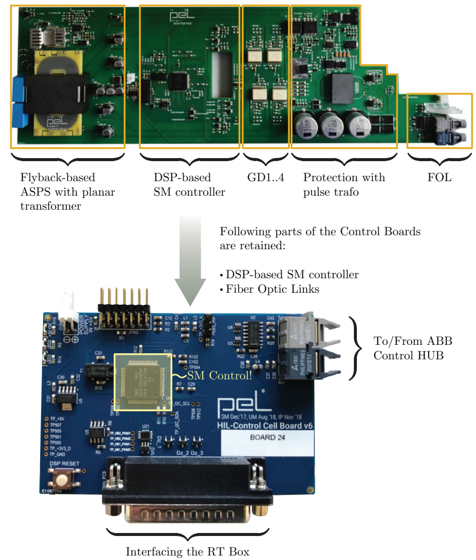
- Two connected MMCs as the end goal (**13 RT-Boxes + 96 cells**)



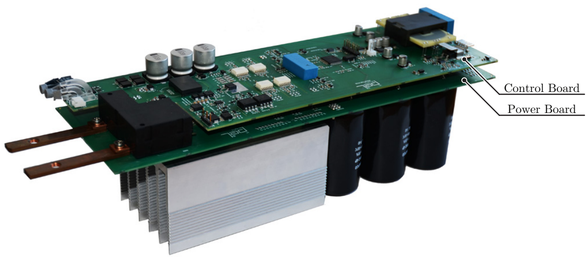
▲ MMC Submodule



▲ Control board trimming $\Rightarrow$ Adjusted Control card

MMC CONTROL TESTING PLATFORM BASED ON THE PLECS RT-BOX HIL

- **Digital twin** of the system being under construction
- Virtual power processing
- Safe control testing prior to commissioning
- Flexibility
- Certain adjustments need to be made
  - Adjustment of the original MMC submodule?
  - RT-Box/MMC submodule interface boards
- Two connected MMCs as the end goal (**13 RT-Boxes + 96 cells**)

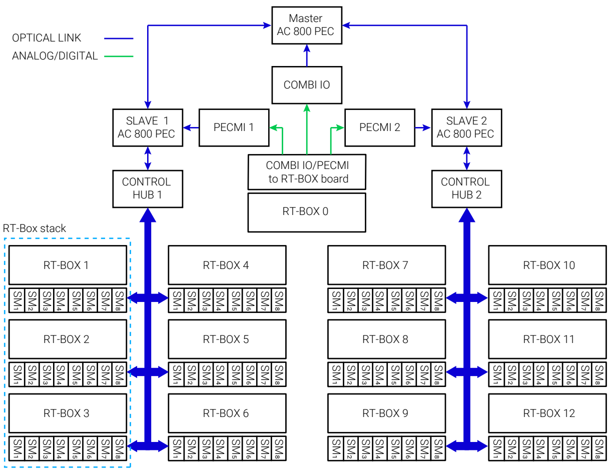


▲ MMC Submodule

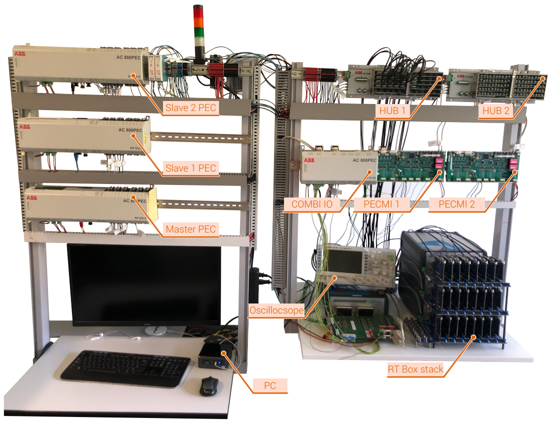
▲ Stack of PLECS RT-Boxes hosting the adjusted Control cards

MMC RT-HIL SYSTEM)

- **Digital twin** of real MMC
- Two connected MMCs (48 Submodules per MMC)
- 6 RT-Boxes per MMC (8 Submodules per RT-Box)
- 1 RT-Box for DC an AC side terminals (application)
- Safe control SW testing prior to commissioning
- Flexibility in SW testing
- Ability to work in parallel with HW development



▲ MMC RT-HIL complete scheme



▲ MMC RT-HIL system including ABB AC 800PEC industrial controllers

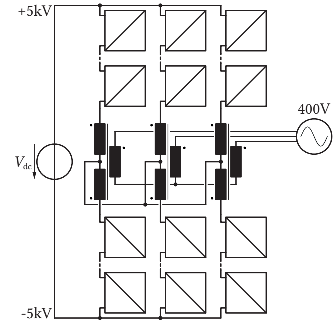
SUMMARY

SUMMARY

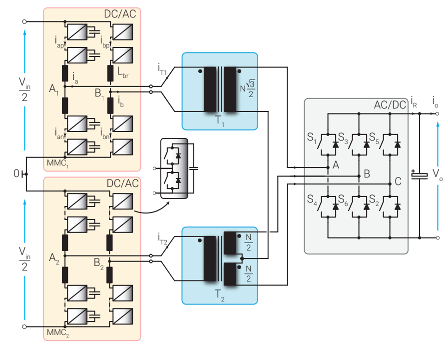
Modular Multilevel Converter

- Modular design easily scalable for higher voltages
- Flexible and adaptable for different conversion needs
- Efficient
- HVDC (early adopter)
- STATCOM, FACTS, RAIL INTERTIES, MV DRIVES
- Can serve MV and HV applications!
- Unlimited research opportunities...

▲ HVDC Light valve hall from ABB.



▲ Galvanically Isolated Modular Converter



▲ High Power DC-DC Converter Employing Scott Transformer Connection

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