MODULAR MULTILEVEL CONVERTERS
OPERATING PRINCIPLES AND APPLICATIONS

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Power Electronics Laboratory (PEL)
Switzerland
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: Liverpool John Moores University, Liverpool, United Kingdom
- 2003 – 2006: University of Novi Sad, Novi Sad, Serbia

Education:
- 2008: PhD, Liverpool 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
Online since February 2014
12 PhD, 1 Scientist, 1 Postdoc, 1 Secretary
http://pel.epfl.ch
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

Possible future MVDC grids and its links with existing grids
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

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)

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

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

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 ($R_y \downarrow \Rightarrow P_y \uparrow$)

- Cheaper solution ("Break-even distance")

- Underwater cable transmission

- No need for synchronization (Marine applications)

- Direct integration of Renewable Energy Sources

- Challenges $\Rightarrow$ DC Transformer/Protection?

▲ Cost comparison between AC and DC systems

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

Datacenters
- 380 V\text{dc}
- DC loads (including UPS)
- Expected efficiency increase

Large PV powerplants
- 1500 V\text{dc} PV central inverters
- Higher number of series-connected panels per string

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

Open challenges
- DC breaker
- Conversion blocks missing
- Protection coordination

▲ From mercury arc rectifiers to modern HVDC systems

▲ Specialized vessels with LVDC distribution

▲ 1500V PV inverter - step towards the MVDC
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- From mercury arc rectifiers to modern HVDC systems
- DC beneficial for medium / high power applications
- Specialized vessels with LVDC distribution

380 V\text{dc}
1500 V\text{dc} PV inverter - step towards the MVDC
EMERGING MVDC APPLICATIONS

Installations
- ABB HVDC Light demo: 4.3 km/±9 kVdc [1]
- Tidal power connection: 16 km/10 kVdc (based on MV3000 & MV7000) [2]
- Unidirectional oil platform connection in China: 29.2 km/±15 kVdc [3]

Projects
- Angle DC: conversion of 33 kV MVac line to ±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
  - < ±50 kVdc

- RXPE Smart VSC-MVDC
  - 1 - 10 MVAR
  - ±5 - ±50 kVdc
  - 40 - 200 km
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▶ RXPE Smart VSC-MVDC
  ▶ 1 - 10 MVAr
  ▶ ±5 - ±50 kVdc
  ▶ 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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⇒ Modularity provides obvious benefits in high power applications!
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]
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]
**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 $\approx 2 \%$ (1) [7]
- Drawn solution is not the unique possibility

**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]
MEDIUM OR LOW FREQUENCY CONVERSION?

MVDC integration challenge
- MVDC-LVAC galvanically isolated conversion system

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SST approach
- VSI on LVAC side of SST reduces efficiency by $\approx 2\%$ (!) [7]
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Solution with MMC + LFT has higher efficiency

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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

مصر

Functionality wise, only $L_{br}$ is required!

Ee2019, Novi Sad, Serbia
SUBMODULE TYPES

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

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

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

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

where \( e_x = \sum_{i=1}^{N_{\text{cells}}} s_x v_{Cni} \) (switched model) or \( e_x = m_x v_{C\Sigma x} \) (average model)

Submodule capacitor voltages

\[
\frac{d}{dt} \begin{bmatrix} v_{C\Sigma p} \\ v_{C\Sigma n} \end{bmatrix} = \frac{1}{C_{br}} \begin{bmatrix} m_p & 0 \\ 0 & m_n \end{bmatrix} \begin{bmatrix} i_p \\ i_n \end{bmatrix}
\]

First transformation

\[
\begin{bmatrix} i_{circ} \\ i_g \\ e_B \\ e_L \end{bmatrix} = \begin{bmatrix} 1/2 & 1/2 \\ 1 & -1 \\ 1 & 1 \\ -1/2 & 1/2 \end{bmatrix} \begin{bmatrix} i_p \\ i_n \\ e_p \\ e_n \end{bmatrix} \quad \leftrightarrow \quad \begin{bmatrix} i_p \\ i_n \\ e_p \\ e_n \end{bmatrix} = \begin{bmatrix} 1 & 1/2 \\ 1 & -1/2 \\ 1/2 & -1 \\ 1/2 & 1 \end{bmatrix} \begin{bmatrix} i_{circ} \\ i_g \\ e_B \\ e_L \end{bmatrix}
\]

Second transformation

\[
\begin{bmatrix} v_{\Sigma} \\ v_{Cg} \\ m_{\Sigma} \\ m_{\Delta} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ -1/2 & 1/2 \\ 1/2 & 1 \end{bmatrix} \begin{bmatrix} v_{C\Sigma p} \\ v_{C\Sigma n} \\ v_{Cg} \end{bmatrix} \quad \leftrightarrow \quad \begin{bmatrix} v_{C\Sigma p} \\ v_{C\Sigma n} \\ v_{Cg} \end{bmatrix} = \begin{bmatrix} 1/2 & -1 \\ 1/2 & 1 \end{bmatrix} \begin{bmatrix} v_{\Sigma} \\ v_{Cg} \\ m_{\Sigma} \\ m_{\Delta} \end{bmatrix}
\]
Decoupled MMC model with main and secondary paths
\[ e_{p/n}(t) = \frac{V_{dc}}{2} + (v_g(t) + v_{CM}(t)) - \left( R_{br}i_{p/n}(t) + L_{br} \frac{d}{dt}i_{p/n}(t) - M_{br} \frac{d}{dt}i_{n/p}(t) \right) \]

\[ i_{p/n}(t) = \frac{l_{dc}}{3} \pm \frac{i_g(t)}{2} + i_{circ}(t) \]

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

\[ v_{CM}(t) = \sum_i \tilde{v}_{CM,i} \cos(i3\omega t) \]
the CM voltage

\[ l_{dc} \]
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

\[ i_{circ}(t) = \sum_{i \neq l} \hat{i}_{circ,i} \cos \left( i2\omega t + \theta_l - \frac{2\pi(k-1)}{3} \right) \]
the circulating current

with \( k \in \{1, 2, 3\} \) the phase number.
POWER EQUATIONS (II)

Generic formulation

\[ p_{p/n}(t) = e_{p/n}(t)p_{p/n}(t) \]

\[
p_{p/n}(t) = \frac{V_{dc}/dc}{6} \pm \frac{V_{dc}/g(t)}{4} + \frac{i_{circ}(t)(v_g(t) + V_{CM}(t))}{2} - \frac{i_g(t)(v_g(t) + V_{CM}(t))}{2} + i_{circ}(t)(v_g(t) + V_{CM}(t)) - \left( R_{br}p_{p/n}(t)^2 + L_{br}p_{p/n}(t) \frac{dp_{p/n}(t)}{dt} - M_{br}p_{p/n}(t) \frac{dp_{p/n}(t)}{dt} \right)
\]

Transformation

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

- \( p_\Sigma \) only contains even harmonics
- \( p_\Delta \) only contains odd harmonics

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

\[
p_\Delta(t) = -\frac{V_{dc}/i_g(t)}{8} + i_{circ}(t)(v_g(t) + V_{CM}(t)) - \frac{i_{circ}(t)(v_g(t) + V_{CM}(t))}{6} + i_{circ}(t)(v_g(t) + V_{CM}(t)) - \frac{i_{circ}(t)(v_g(t) + V_{CM}(t))}{2}
\]

Reminder

Zero net energy balance
\[ \int_0^T p_\Sigma \, dt = 0 \]

Insight provided

- Circulating current optimization (in steady state!)
- Converter energy requirement
- Converter safe operating area (a bit optimistic though)
First discussed in [10].
Without passives!

**W/o circulating current**

\[
p_Z(t) = \frac{l_{dc}V_{dc}}{3} - i_g \cos(\omega t + \phi) + \frac{\hat{i}_g \hat{V}_g \cos(\phi)}{2} - \frac{\hat{i}_g \hat{V}_g \cos(2\omega t + \phi)}{2} + \frac{i_{circ}(t)}{V_{dc}} = 0
\]

\[
\Rightarrow i_{dc} = \frac{3\hat{i}_g \hat{V}_g \cos(\phi)}{2V_{dc}}
\]

**W/o common mode**

\[
p_Z(t) = V_{dc}l_{dc} + V_{dc}i_{circ}(t) - \frac{i_g \hat{V}_g \cos(\phi)}{2} - \frac{i_g \hat{V}_g \cos(2\omega t + \phi)}{2} = 0
\]

\[
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\]

\[
\Rightarrow i_{circ}(t) = \frac{\hat{i}_g \hat{V}_g \cos(2\omega t + \phi)}{2V_{dc}}
\]

**W/ common mode**

\[
p_Z(t) = -i_g \cos(\omega t + \phi) + \frac{\hat{i}_g \hat{V}_g \cos(\phi)}{2} - \frac{\hat{i}_g \hat{V}_g \cos(2\omega t + \phi)}{2} + i_{circ}(t)V_{dc} + \frac{l_{dc}V_{dc}}{3} = 0
\]

\[
\Rightarrow i_{dc} = \frac{3\hat{i}_g \hat{V}_g \cos(\phi)}{2V_{dc}}
\]

\[
\Rightarrow i_{circ}(t) = \frac{\hat{i}_g \left[2 \cos(\omega t + \phi) + \hat{V}_g \cos(2\omega t + \phi)\right]}{2V_{dc}}
\]

which means 2\textsuperscript{nd} and 4\textsuperscript{th} harmonics (at least!)
CIRCULATING CURRENT OPTIMIZATION (II)

W/o common mode

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>$e_{ap}$, $e_{an}$, $v_{C\Sigma ap}$, $v_{C\Sigma an}$ [kV]</th>
<th>$i_{ap}$, $i_{an}$, $i_{ga}$, $i_{circ,a}$ [A]</th>
<th>$p_{\Sigma a}$, $p_{\Delta a}$ [MW]</th>
</tr>
</thead>
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<tr>
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<td>0</td>
<td>-0.1</td>
<td>0</td>
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<tr>
<td>0.01</td>
<td>0</td>
<td>-0.1</td>
<td>0</td>
</tr>
<tr>
<td>0.02</td>
<td>0</td>
<td>-0.1</td>
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<td>-0.1</td>
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<td>-0.1</td>
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</table>

W/ common mode

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<td>0</td>
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<td>0</td>
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▲ MMC relevant waveforms without injection of the common mode voltage

▲ MMC relevant waveforms with injection of the common mode voltage
Branch energy ripples

\[ \Delta W_{br,+} = \frac{1}{2} C_{br} v_{C\Sigma,\text{max}}^2 - \frac{1}{2} C_{br} v_{C\Sigma,0}^2 \]

\[ \Delta W_{br,-} = \frac{1}{2} C_{br} v_{C\Sigma,0}^2 - \frac{1}{2} C_{br} v_{C\Sigma,\text{min}}^2 \]

Energy requirement \( k_{ac} = 0.9, v_{C\Sigma,0}^* = V_{dc} \) and \( \epsilon_{V_{C\Sigma}} = 10\% \)

<table>
<thead>
<tr>
<th>Case #</th>
<th>CM</th>
<th>2(^{nd}) (+ 4(^{th})) harmonic</th>
<th>Energy requirement [kJ/MVA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td>45.6</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>46.3</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>27.2</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td>24.8</td>
</tr>
</tbody>
</table>

Time domain waveforms \( \varphi = -\pi/2 \) (worst case)
MMC CONTROL METHODS

Similarities and differences with other voltage source converters
MMC CONTROL LAYERS

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

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

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

Decoupled Double Synchronous Reference Frame (DDSRF) [12]

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

Double Second-Order Generalized Integrator (DSOGI)

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

\[
K_{p,\text{gcc}} e_{L,dq} / \text{uni2605}
\]

**Proportional Integral regulator in \(dq\) frame**

**PR in \(\alpha\beta\) frame [13]**
- Track ac components in a stationary reference frame
- Delay compensation with \(\phi_h = h \omega_1 T_d\)

\[
K_{p,\text{gcc}} + K_{1,\text{gcc}} \frac{s \cos(\phi_1) - \omega_1 \sin(\phi_1)}{s^2 + \omega_1^2} e_{L,\alpha\beta} / \text{uni2605}
\]

**Proportional Resonant regulator in \(\alpha\beta\) 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

\[ V_B^* \rightarrow u^2 \rightarrow \frac{a_d C_d}{2} \rightarrow \frac{a_{id}}{S} \rightarrow P^* \]

- DC voltage control

\[ \Sigma_{VC} \Delta_{VC} \]

- Overall MMC control structure

Common VSC control
Specific MMC control
Modulation indices calculation methods

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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

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

where $\theta_L$ is the load current angle
MMC SPECIFIC CONTROL LOOPS: CIRCULATING CURRENT CONTROL (CCC)

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]
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]

\[
\begin{align*}
    m_p &= \frac{V_B/2 - e^*_B/2 - e^*_L}{v_{c\Sigma 0}^*} \\
    m_n &= \frac{V_B/2 - e^*_B/2 + e^*_L}{v_{c\Sigma 0}^*}
\end{align*}
\]
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]

\[
m_p = \frac{V_B/2 - e_B^*/2 - e_L^*}{\dot{v}_{CSP}}
\]

\[
m_n = \frac{V_B/2 - e_B^*/2 + e_L^*}{\dot{v}_{CSn}}
\]
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]

\[
\begin{align*}
    m_p &= \frac{V_B/2 - e_B^*/2 - e_L^*}{v_{CΣP}^E} \\
    m_n &= \frac{V_B/2 - e_B^*/2 + e_L^*}{v_{CΣn}^F}
\end{align*}
\]

▲ Hybrid voltage 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.

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...
CURRENTS IN INVERTER MODE

No CCC

CCSC / CCC dc circ

CCSC / CCC + 2nd circ inj

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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, $v_{CΣ}$ is not properly controller on reactive power steps (it settles to a value close to $V_{CΣ0}$)
▶ With the direct modulation w/o CCSC, the energies are shifted between the phase-legs (thanks to the uncontrolled circulating current) ⇒ 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 $v_{CΣ}$ 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

Few comments:

▶ With the direct modulation, $v_{CΣ}^\Sigma$ is not properly controller on reactive power steps (it settles to a value close to $V_{CΣ0}^\Sigma$)

▶ With the direct modulation w/o CCSC, the energies are shifted between the phase-legs (thanks to the uncontrolled circulating current) ⇒ 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 $v_{CΣ}^\Sigma$ dynamics are sluggish (increased voltage variation & lightly damped oscillatory response)

▶ BPFs tuning is affecting the performance of the hybrid voltage control method

⇒ the branch energy control offers mitigated performances
Few comments:

- LPF filter bandwidth 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
Few comments:

- LPF filter bandwidth 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

⇒ 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
the final choice depends on the application requirements / acceptable compromises between complexity and performance.
MMC MODULATION METHODS

Variety of options are available...
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
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 $2N_{\text{cells}} + 1$ modulation

Remark μC denotes either a microcontroller, an FPGA, or a combination of both.
CARRIER-BASED MODULATION

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

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

Results with OPPs from [24]

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]

⇒ maximum performance without compromising the switching frequency
SORTING ALGORITHMS

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 $f_{\text{sort}}$
▶ All switching signals can be modified

Restricted sorting [27]

▶ The sorting algorithm is triggered when a switching transition occurs
▶ 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
HIGH PERFORMANCE PWM MODULATION METHODS

Enhanced restricted sorting algorithm \((N + 1)\)

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

\[ e_{ap}, e_{an}, e_{Ba}, e_{La} \text{ [kV]} \]
\[ v_{Cap}, v_{CAn} \text{ [V]} \]
\[ i_{dc}, i_{ap}, i_{an}, i_{ga}, i_{circ,a} \text{ [A]} \]

\( f_{sw,cell} = 375 \text{ Hz} \)

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Enhanced restricted sorting algorithm \( (N + 1) \)

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

\( \hat{f}_{\text{sw,cell}} = 375 \text{ Hz} \)
COFFEE BREAK

Well deserved...
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

- 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

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

Branch equivalent circuit with its voltage waveform

Existing SM design is assumed

Branch voltage scaling

Modular Multilevel Converter

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Modular Multilevel Converter (MMC) power scaling

- Series connection of HB/FB Submodules (SMs)
- 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

SM designed at PEL
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

A converter operating at this point?

A converter operating at this point?

A converter operating at this point?

Existing SM design is assumed

Linear \( S=f(V) \) change for a given current rating

SM designed at PEL
Modular Multilevel Converter Power Scaling

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- Flexible in terms of voltage scaling
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Branch equivalent circuit with its voltage waveform

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- Linear $S=f(V)$ change for a given current rating

SM designed at PEL

Branch voltage scaling
MODULAR MULTILEVEL CONVERTER POWER SCALING

- 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

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- Linear $S=f(V)$ change for a given current rating

- SM designed at PEL
MODULAR MULTILEVEL CONVERTER POWER SCALING

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

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

- Branch equivalent circuit with its voltage waveform

- SM designed at PEL
Modular Multilevel Converter Power Scaling

- Series connection of HB/FB Submodules (SMs)
- 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
- Current capacity $\uparrow \Rightarrow$ new characteristics

SM designed at PEL

 MMC branch voltage scaling

How to increase current capacity?

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COMMON MMC CURRENT CAPACITY INCREASE METHODS

▲ Paralleling semiconductor modules

▶ Special design considerations

▶ Cell frame size does not change

▶ Possible heat sink oversizing?

▲ Paralleling SMs

▶ Additional inductor is needed

▶ Additional terminal for the capacitors

▶ Special gate driver structure

▲ Paralleling converters

Well known principle

Problem is shifted to the control domain

\[ V_{DC} \]

\[ V_{SM} \]
COMMON MMC CURRENT CAPACITY INCREASE METHODS

▲ Paralleling semiconductor modules

▲ Exemplary cell design; Current capacity \( \cdot 3/\text{rated} \)

▲ Paralleling SMs

▲ Paralleling converters

Electrolytic capacitor
IGBT module
Terminals

Power PCB

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

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

Well known principle
Problem is shifted to the control domain
COMMON MMC CURRENT CAPACITY INCREASE METHODS

▲ Paralleling semiconductor modules

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

▲ Paralleling SMs

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

▲ Paralleling converters

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

▲ Exemplary cell design; Current capacity $\cdot 2I_{\text{rated}}$
COMMON MMC CURRENT CAPACITY INCREASE METHODS

- ParALLEling semiconductor modules
- Exemplary cell design; Current capacity - $I_{\text{rated}}$
- Special design considerations
  - Cell frame size does not change
  - Possible heat sink oversizing?

- ParALLEling SMs
- ParALLEling converters

- Well known principle
- Problem is shifted to the control domain
COMMON MMC CURRENT CAPACITY INCREASE METHODS

- Paralleling semiconductor modules

- Exemplary cell design; Current capacity - $I_{\text{rated}}$
  - Special design considerations
  - Cell frame size does not change
  - Possible heat sink oversizing?

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

- Paralleling converters

Well known principle
- Problem is shifted to the control domain
COMMON MMC CURRENT CAPACITY INCREASE METHODS

- Paralleling semiconductor modules
  - Exemplary cell design; Current capacity \( I_{\text{rated}} \)
  - Special design considerations
  - Cell frame size does not change
  - Possible heat sink oversizing?

- Paralleling SMs
  - Cell designed for paralleling
  - Additional inductor is needed
  - Additional terminal for the capacitors
  - Special gate driver structure

- Paralleling converters
  - Well known principle
  - Problem is shifted to the control domain
  - Paralleled MMC branches ⇒ System simplification

- Paralleling branches
**COMMON MMC CURRENT CAPACITY INCREASE METHODS**

- **Paralleling semiconductor modules**
- **Paralleling SMs**
- **Paralleling converters**
  - Well known principle
  - Problem is shifted to the control domain

Paralleled MMC branches ⇒ System simplification

- Exemplary cell design; Current capacity \( I_{\text{rated}} \)
  - Special design considerations
  - Cell frame size does not change
  - Possible heat sink oversizing?

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

- 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

\[ v_{br} = \frac{1}{M} \sum_{i=1}^{M} v_{br,i} \]

\[ Z_{br} = \frac{1}{M} Z_{br,i} \]
MODELING

 MMC with paralleled (sub)branches

\[ v_{br} = \sum_{i=1}^{M} v_{br,i} \]

\[ Z_{br} = \frac{1}{M} Z_{br,i} \]
MODELING

\[ v_{\text{br}} = \sum_{i=1}^{M} v_{\text{br},i} \]

\[ Z_{\text{br}} = \frac{1}{M} \sum_{i=1}^{M} Z_{\text{br},i} \]

\[ \sum_{i=1}^{M} v_{\text{br},i} = v_{\text{br}_{\Sigma}} \]

\[ Z_{\text{br}} = \frac{1}{M} Z_{\text{br},i} \]

\[ v_{\text{br}_{\Sigma}} = \sum_{i=1}^{M} v_{\text{br},i} \]
MODELING

MMC with paralleled (sub)branches

\[ \Sigma_{i=1}^{M} v_{br,i} Z_{br,i} \]

Branch equivalent circuit

\[ \overline{v_{br}} = \frac{1}{M} \sum_{i=1}^{M} v_{br,i} \]

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

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

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
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
- $v_c = \frac{v_{nΣ} + v_{pΣ}}{2}$ - Leg common-mode voltage
- $v_s = \frac{v_{nΣ} - v_{pΣ}}{2}$ - Leg differential voltage
**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
- $v_c = \frac{v_{nP} + v_{pE}}{2}$ - Leg common-mode voltage
- $v_s = \frac{v_{nE} - v_{pE}}{2}$ - Leg differential voltage

**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
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
- $v_C = \frac{v_{nΣ} + v_{pΣ}}{2}$ - Leg common-mode voltage
- $v_s = \frac{v_{nΣ} - v_{pΣ}}{2}$ - Leg differential voltage

Well known 3PH-MMC control logic is retained!

Standard balancing directions:

- HB $\Rightarrow$ total energies stored within the legs
- VB $\Rightarrow$ total energies stored within the branches belonging to the same leg

Is this enough to keep the whole structure balanced?
CONTROL - SBR BALANCING

\[ i_{br} \]

\[ \begin{align*}
L_{br} \frac{d}{dt} (i_{br,i} - \frac{i_{br}}{M}) + R_{br} (i_{br,i} - \frac{i_{br}}{M}) = v_{br \Sigma} - v_{br,i}
\end{align*} \]

Should \( v_{br,i} \) be chosen like: \( v_{br,i} = \overline{v_{br \Sigma}} + \Delta v_{br,i} \)

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

\( \gt \) Current split can be controlled by means of \( \Delta v_{br,i} \)

\( \gt \) Total branch voltage must not be corrupted!

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

SBR current balancing controller
CONTROL - SBR BALANCING

Equivalent circuit of the branch

\[ L_{br} \frac{d}{dt}\left(i_{br,i} - \frac{i_{br}}{M}\right) + R_{br}\left(i_{br,i} - \frac{i_{br}}{M}\right) = v_{br,i} - v_{br}\]

Should \( v_{br,i} \) be chosen like:

\[ v_{br,i} = \overline{v_{br}} + \Delta v_{br,i} \]

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

- 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

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**CONTROL - SBR BALANCING**

▲ Equivalent circuit of the branch

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

Current split can be controlled by means of $\Delta v_{br,i}$

Total branch voltage must not be corrupted!

Should $v_{br,i}$ be chosen like: $v_{br,i} = \bar{v}_{br} + \Delta v_{br,i}$

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

- SBR current balancing controller

**Current balancing is not enough!**

SBR powers are different $\Rightarrow$ capacitor energy (voltage) divergence

$\sum_{i=1}^{M} \Delta v_{br,i} = 0$
Typical voltage/current waveforms of a (sub)branch

(Sub)branch power equation

\[ P_{sbr} = \frac{v_{sbr}i_{sbr}}{} \]

\[ = V_{DC}^sbr \cdot I_{DC}^sbr + v_{sbr}^\sim i_{sbr}^\sim \]

Taylor series expansion

\[ P_{sbr} = P_{sbr}^{\text{nom}} + \Delta P_{sbr}^{DC} + \Delta P_{sbr}^{AC} \]

\[ \approx \frac{1}{2} V_{DC}^sbr \cdot \Delta I_{DC}^sbr \text{ depends on } \Delta L_{br} \]
**Typical voltage/current waveforms of a (sub)branch**

(Sub)branch power equation

\[
P_{sbr} = \frac{v_{sbr}i_{sbr}}{sbr} = V_{DC}^sbr I_{DC}^{sbr} + \frac{v_{sbr}i_{sbr}}{sbr}
\]

Taylor series expansion

\[
P_{sbr} = P_{sbr}^{\text{nom}} + \Delta P_{sbr}^{\text{DC}} + \Delta P_{sbr}^{\text{AC}}
\]

\[
\approx \frac{1}{2} V_{DC}^sbr \Delta I_{DC}^{sbr} \text{ depends on } \Delta L_{br}
\]

⇒ SBR energy control through SBR currents mismatches
Typical voltage/current waveforms of a (sub)branch

(Sub)branch power equation

\[ P_{sbr} = \frac{v_{sbr} i_{sbr}}{V_{DC} I_{DC}} \]

Taylor series expansion

\[ P_{sbr} = P_{sbr}^{nom} + \Delta P_{sbr}^{DC} + \Delta P_{sbr}^{AC} \]

SBR energy control through SBR currents mismatches

Reminder

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

\[ \bar{v}_{br} = \frac{1}{M} \sum_{i=1}^{M} v_{br,i} = \frac{1}{M} \sum_{i=1}^{M} \left[ \bar{v}_{br,i}^{DC} + \Delta v_{br,i} \right] \]
Typical voltage/current waveforms of a (sub)branch

(Sub)branch power equation

\[ P_{sbr} = \frac{v_{sbr}}{i_{sbr}} = \frac{v_{DC}}{i_{DC}} + \frac{v_{AC}}{i_{AC}} \]

Taylor series expansion

\[ P_{sbr} = P_{sbr}^{nom} + \Delta P_{DC} + \Delta P_{AC} \]

depends on \( \Delta L_{br} \)

\[ \Delta v_{br,i} = \frac{1}{M} \sum_{i=1}^{M} v_{br,i} = \frac{1}{M} \sum_{i=1}^{M} \left( \frac{v_{br,i}^{DC} + \Delta v_{br,i}}{CMV} \right) \]

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

must be respected at all times!

SBR energy balancing

\[ W_{br,i} = \frac{1}{2} \sum_{i=1}^{M} \frac{i_{br,i}^{2}}{V_{DC}} \]

SBR energy controller

\[ \sum_{i=1}^{M} \Delta v_{br,i} = H_{\Delta i} H_{\Delta W} \left( M \cdot \frac{1}{M} \sum_{i=1}^{M} \frac{i_{br,i}^{2}}{W_{avg}} - \sum_{i=1}^{M} \frac{W_{br,i}}{W_{avg}} \right) + H_{\Delta i} \left( M \cdot \frac{1}{M} \sum_{i=1}^{M} \frac{i_{br,i} - \Delta i_{br,i}}{i_{avg}} \right) = 0 \]
**CONTROL - SBR BALANCING**

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

(Sub)branch power equation

\[
P_{\text{sbr}} = \frac{v_{\text{sbr}}}{i_{\text{sbr}}} = V_{\text{DC}}\frac{\Delta i_{\text{sbr}}}{R_{\text{sbr}}} + v_{\text{sbr}}\frac{\Delta i_{\text{sbr}}}{i_{\text{sbr}}}
\]

Taylor series expansion

\[
P_{\text{sbr}} = P_{\text{nom}} + \Delta P_{\text{DC}} + \Delta P_{\text{AC}}
\]

\[
\Delta P_{\text{sbr}} = v_{\text{DC}}\frac{\Delta i_{\text{sbr}}}{R_{\text{sbr}}} + v_{\text{sbr}}\frac{\Delta i_{\text{sbr}}}{i_{\text{sbr}}}
\]

depends on \(\Delta i_{\text{br}}\)

⇒ SBR energy control through SBR currents mismatches

Reminder

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

\[
\bar{v}_{\text{br},i} = \frac{1}{M} \sum_{i=1}^{M} v_{\text{br},i} = \frac{1}{M} \sum_{i=1}^{M} \left[ \frac{v_{\text{br},i}}{\text{CMV}} + \Delta v_{\text{br},i} \right]
\]

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

▲ SBR energy controller

\[
\sum_{i=1}^{M} \Delta v_{\text{br},i} = H_{\Delta}H_{\Delta W}\left(M \cdot \frac{1}{M} \sum_{i=1}^{M} \bar{W}_{\text{br},i} - \sum_{i=1}^{M} \bar{W}_{\text{br},i}\right) + H_{\Delta i}\left(M \cdot \frac{1}{M} \sum_{i=1}^{M} \Delta i_{\text{br},i} - \sum_{i=1}^{M} \bar{i}_{\text{br},i}\right) = 0
\]
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

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

▲ Power profile used to test SBR energy balancing control
## SIMULATION RESULTS

<table>
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<tr>
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<th>Rated power (P)</th>
<th>Input voltage (V&lt;sub&gt;in&lt;/sub&gt;)</th>
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<th>SBR inductance (L&lt;sub&gt;br&lt;/sub&gt;)</th>
<th>SBR resistance (R&lt;sub&gt;br&lt;/sub&gt;)</th>
<th>Sw. frequency (f&lt;sub&gt;sw&lt;/sub&gt;)</th>
</tr>
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<tr>
<td>Left</td>
<td>1MW</td>
<td>5kV</td>
<td>5</td>
<td>1kV</td>
<td>0.83mF</td>
<td>2</td>
<td>5mH</td>
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</tr>
<tr>
<td>Right</td>
<td>1.5MW</td>
<td>5kV</td>
<td>5</td>
<td>1kV</td>
<td>0.83mF</td>
<td>3</td>
<td>5mH</td>
<td>60mΩ</td>
<td>999Hz</td>
</tr>
</tbody>
</table>

▲ Simulation results in case M = 2

▲ Simulation results in case M = 3
SIMULATION RESULTS

Leg A upper and lower SBR currents [A]

Leg A upper and lower SBR voltages [kV]

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 $M = 3$
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?
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?

\[
\Delta I_{br,i}^* = \Delta W_{br,i} \cdot H_{\Delta W} \cdot \frac{2}{V_{DC}}
\]

Energy error
Controller TF
several kV
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?

$$\Delta I_{br,i} = \Delta W_{br,i} \cdot H_{\Delta W} \cdot \frac{2}{V_{DC}}$$

$\Delta W_{br,i}$: Energy error

$H_{\Delta W}$: Controller TF

$V_{DC}$: several kV

$\Delta P_{br,i}$: Controller

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

$\Delta P_{PA,1[A]}$  
$\Delta P_{PA,2[A]}$  
$\Delta P_{PA,3[A]}$

References provided by the SBR energy balancing controller ($M = 3$)

$S = 0$

$0.22A$  
$0.33A$  
$0.13A$

$5.1A$  
$5A$  
$2.77A$

0 0.5 1.5 2 3

controller ON  
controller reactivation  
controller reactivation
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?

\[ \Delta I_{br,i}^* = \Delta W_{br,i}^* \cdot H_{\Delta W} \cdot \frac{2}{V_{DC}} \]

\[ \Delta W_{br,i} \]

Energy error
Controller TF

several kV

\[ \Delta I_{br,i} \]

\[ \Delta I_{br,i} < 10\% \hat{i}_{br} \text{ (Modest response!)} \]

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

References provided by the SBR energy balancing controller (\( M = 3 \))
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?

\[ \Delta I_{br,i}^* = \Delta W_{br,i} / V_{DC} \]

\[ \sum_{i=1}^{M} \Delta I_{br,i}^* = 0 \]

\( \Delta I_{br,i}^* < 10\% \hat{i}_{br} \) (Modest response!)
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?

\[ \Delta I_{br,i}^* = \Delta W_{br,i} \cdot \frac{2}{V_{DC}} \]

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

\[ \Delta I_{PA,1}[A] \]
\[ \Delta I_{PA,2}[A] \]
\[ \Delta I_{PA,3}[A] \]

\[ S = 0 \]
\[ 0.22A \]
\[ 0.33A \]
\[ 0.13A \]
\[ 0.2A \]
\[ 0.5A \]
\[ 2.77A \]
\[ 7.77A \]

\[ \Delta W_{br,i} \]

\[ \Delta I_{br,i} < 10\% \hat{i}_{br} \text{ (Modest response!)} \]

\[ \sum_{i=1}^{M} \Delta I_{br,i}^* = 0 \]

\[ \sum_{i=1}^{M} \Delta v_{br,i}^* = 0 \Rightarrow \text{no interference with higher control loops} \]

**References provided by the SBR energy balancing controller (M = 3)**

\[ \Delta W_{br,i} \text{ AVG} \]

\[ H_{AVG} \]

\[ \Delta P_{DC}^{br,i} \]

\[ \Delta v_{br,i} \text{ AVG} \]

\[ H_{AVG} \]

\[ \Delta v_{br,i} \]
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?

\[ \Delta I_{br,i}^* = \Delta W_{br,i} \cdot \frac{H_{\Delta W}}{V_{DC}} \]

\[ \Delta W_{br,i} \]

Several kV

Energy error

Controller TF

\[ \Delta I_{br,i} \]

\[ \Delta V_{br,i} \]

\[ \sum_{i=1}^{M} \Delta I_{br,i}^* \]

\[ \sum_{i=1}^{M} \Delta V_{br,i} \]

\( \Rightarrow \) No need for SM current rating upgrade!

\[ \Delta I_{br,i} < 10\% \hat{i}_{br} \] (Modest response!)

\[ \sum_{i=1}^{M} \Delta I_{br,i}^* = 0 \]

\[ \sum_{i=1}^{M} \Delta V_{br,i} = 0 \] no interference with higher control loops

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

References provided by the SBR energy balancing controller (\( M = 3 \))
MODULATION CONSIDERATIONS

...impact on the voltage quality
\[ v_{A0} = \text{sw}(t) \cdot V_{C,1} \]
\[ = [m_1(t) + \text{st}(\theta_1) + \text{st}(\theta_2)]V_{C,1} \]
\[ = \frac{V_C^*}{2} + \hat{m} \frac{V_C^*}{2} \cos(\omega t) + H_1(\omega t) \]

\[ m_1(t) = \frac{1}{2} + \frac{\hat{m}}{2} \cos(\omega t) \]
PRELIMINARY CONSIDERATIONS

\[ v_{A0} = s(t) \cdot V_{C,2} = [m_2(t) + s(t_1) + s(t_2)]V_{C,2} \]

\[ = \frac{V_C + \Delta V_C}{2} + (V_C^* + \Delta V_C) \frac{\hat{m}}{2} \cos(\omega t) + H_2(\omega t) \]

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

\[ V_{C,1} \quad V_{C,2} \]
\[ V_{L,1} \quad V_{L,2} \]
\[ i_{L,1} \quad i_{L,2} \]

\[ \pm 10\% \text{ variations} \]

\[ 0 \quad 5 \quad 10 \quad 15 \quad 20 \quad \text{Time [ms]} \]

\[ \Delta \text{ PSC modulation example with one HB module} \]
PRELIMINARY CONSIDERATIONS

\[ v_{A0} = s(t) \cdot V_{C,3} \]

\[ = \left[ m_3(t) + \frac{\mathrm{s}(\theta_1) + \mathrm{s}(\theta_2)}{2} \right] V_{C,3} \]

\[ = \frac{V_C^*}{2} + \hat{m} \frac{V_C^*}{2} \cos(\omega t) + H_3(\omega t) \]

\[ m_3(t) = \left\{ \frac{1}{2} + \frac{\hat{m}}{2} \cos(\omega t) \right\} \frac{V_C}{V_{C,3}} \]
Preliminary Considerations

PSC modulation example with one HB module

\[
\begin{align*}
    \nu_{A0} &= \nu_{W}(t) \cdot \nu_{C,3} \\
    &= \left[ \frac{m_3(t)}{2} \cos(\omega t) \right] \nu_{C,3} \\
    &\quad + \frac{\nu_{C}^*}{2} \left( \frac{m_3(t)}{2} \cos(\omega t) \right)^3 + H_3(\omega t)
\end{align*}
\]

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

\[
    m_3(t) = \left\{ \frac{1}{2} + \frac{\dot{m}}{2} \cos(\omega t) \right\} \frac{\nu_{C}^*}{\nu_{C,3}}
\]

\[
    \begin{align*}
        V_{C,1} &\quad V_{C,2} &\quad V_{C,3} \\
        \nu_{L,1} &\quad \nu_{L,2} &\quad \nu_{L,3} \\
        i_{L,1} &\quad i_{L,2} &\quad i_{L,3}
    \end{align*}
\]

±10% variations

Time [ms]

PSC modulation example with one HB module
**PRELIMINARY CONSIDERATIONS**

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

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

Closed loop control of the MMC utilizes similar procedure, where

\[ m_{(n,p)} = \frac{v_{c,n}^* + v_{c,p}^*}{v_{(n,p)\Sigma}} \]

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

\[ \nu_{A0} = \nu(t) \cdot V_{C,3} \]
\[ = [m_3(t) + m_1(t) + m_2(t)] V_{C,3} \]
\[ = \frac{V_C^*}{2} + \hat{m} \frac{V_C^*}{2} \cos(\omega t) + H_3(\omega t) \]

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

Closed loop control of the MMC utilizes similar procedure, where

\[ m_{(n,p)} = \frac{\nu_{c}^* + \nu_{s}^*}{\nu_{(n,p)}^*} \]

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

\( \nu_{sm}[kV] \)

\( 0.78 \quad 0.79 \quad 0.8 \quad 0.81 \quad 0.82 \)

\( 0.9 \quad 1 \quad 1.1 \)

\( 0 \quad 5 \quad 10 \quad 15 \quad 20 \)

\( 0 \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \quad 12 \quad 14 \quad 16 \quad 18 \quad 20 \)

\( V_{C,1} \quad V_{C,2} \quad V_{C,3} \)

\( \nu_{L,1} \quad \nu_{L,2} \quad \nu_{L,3} \)

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\( \nu_{L,1} \quad \nu_{L,2} \quad \nu_{L,3} \)

\( \nu_{SM}[kV] \)
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

$\Rightarrow$ every SM capacitor is perceived as a stiff voltage source
PSC MODULATION APPLIED TO A SINGLE BRANCH

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- Closed-loop control of the internal quantities
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⇒ every SM capacitor is perceived as a stiff voltage source

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

Obtained voltage waveform in case $m(t) = \frac{1}{2} + \frac{0.95}{2} \cos(2\pi 50t)$ and $\theta_c = 0$
PSC MODULATION APPLIED TO A SINGLE BRANCH

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

\[ m^* \]

\[ C_1, C_2, C_3, C_4 \]

\[ v_{SWY}, v_{SW1} \]

\[ m^* \]

\[ C_1, C_2, C_3, C_4 \]

\[ v_{SWY}, v_{SW1} \]

\[ \text{Time [s]} \]

\[ 0 \quad 5 \quad 10 \quad 15 \quad 20 \]

\[ 0 \quad 2 \quad 4 \]

\[ \text{Synchronous switching} \Rightarrow 2\text{LVL mod.} \]

\[ \text{Asynchronous switching} \Rightarrow (N+1)\text{-LVL mod.} \]

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

 Obtained voltage waveform in case \( m(t) = \frac{1}{2} + \frac{0.95}{2} \cos(2\pi 50t) \) and \( \Theta_c = \frac{2\pi}{3} \)
PSC MODULATION APPLIED TO A REGULAR MMC LEG

Synchronous switching of branches ⇒ \((N + 1)\)-level modulation

Asynchronous switching of branches ⇒ \((2N + 1)\)-level modulation

\[ m^*_n \]

\[ C_{n1}, C_{n2}, C_{n3}, C_{n4} \]

\[ \nu_{n\Sigma} \]

\[ \delta = 0 \]

\[ C_{p1}, C_{p2}, C_{p3}, C_{p4} \]

\[ \delta = \pi / N \]

5 levels

9 levels

\[ \nu_s \]

\[ \nu_c \]

\[ \nu_{p\Sigma} \]

\[ \nu_{n\Sigma} \]

\[ \nu_s \]

\[ \nu_c \]

Time [ms]

Time [ms]

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PSC MODULATION APPLIED TO A REGULAR MMC LEG

Synchronous switching of branches \(\Rightarrow (N + 1)\)-level modulation

Asynchronous switching of branches \(\Rightarrow (2N + 1)\)-level modulation

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.
There are two relevant phase-shifts:

- $\delta$ - phase shift between two carrier sets within two SBRs belonging to adjacent branches
- $\beta$ - phase shift between two carrier sets within two SBRs belonging to the same branch
PSC MODULATION APPLIED TO A MMC LEG WITH TWO PARALLEL SBRS

There are two relevant phase-shifts:

- $\delta$ - phase shift between two carrier sets within two SBRs belonging to adjacent branches
- $\beta$ - phase shift between two carrier sets within two SBRs belonging to the same branch

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

▲ $(2N + 1)$-level modulation
There are two relevant phase-shifts:

- $\delta$ - phase shift between two carrier sets within two SBRs belonging to adjacent branches

- $\beta$ - phase shift between two carrier sets within two SBRs belonging to the same branch
There are two relevant phase-shifts:

- $\delta$ - phase shift between two carrier sets within two SBRs belonging to adjacent branches
- $\beta$ - phase shift between two carrier sets within two SBRs belonging to the same branch

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

▲ (2MN + 1)-level modulation
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

AC voltage quality can be improved by utilizing 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
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)

<table>
<thead>
<tr>
<th>Grid Tx</th>
<th>SST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controlability</td>
<td>No</td>
</tr>
<tr>
<td>Efficiency</td>
<td>$\eta \geq 99%$</td>
</tr>
<tr>
<td>Q compensation</td>
<td>No</td>
</tr>
<tr>
<td>Fault tolerance</td>
<td>No</td>
</tr>
<tr>
<td>Size</td>
<td>Bulky</td>
</tr>
</tbody>
</table>

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

▲ Concept of a modern power system

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

▲ Fast EV charging concept
MFT challenges

- **Skin and proximity effect losses**: impact on efficiency and heating
- **Cooling**: increase of power density ⇒ decrease in size ⇒ less cooling surface ⇒ higher $R_{th}$ ⇒ 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

MFT design is generally challenging and requires multiphysics considerations and multiobjective optimization.
MFT NONSINUSOIDAL POWER ELECTRONIC WAVEFORMS

DAB Converter:

\[ MFT \]

\[ L_{\sigma_1} L'_{\sigma_2} R_{\sigma_1} R'_{\sigma_2} \]

\[ N_1 : N_2 \]

\[ L_m \]

\[ RLV_1 V'_2 \]

\[ I_1 \]

\[ V_1 ; V_2 \] square

\[ I_1 \] non-sinusoidal

Series Resonant Converter:

\[ MFT \]

\[ C r L_{\sigma_1} L'_{\sigma_2} R_{\sigma_1} R'_{\sigma_2} \]

\[ N_1 : N_2 \]

\[ RLL_m V_1 V'_2 \]

\[ I_1 \]

\[ V_1 ; V_2 \] square

\[ I_1 \] sinusoidal

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

\[ \text{Specific AC core losses} \]

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

\[ \text{Harmonics impacting winding losses} \]
**DAB**

- Leakage Inductance
- Controllability of the power flow
- Higher than $L_{a,\min}$:
  \[
  L_{a,\min} = \frac{V_{DC1}V_{DC2}\varphi_{\min}(\pi - \varphi_{\min})}{2P_{out}\pi^2f_sn}
  \]
- Magnetizing Inductance is normally high

**SRC**

- Leakage inductance is part of resonant circuit
- Must match the reference:
  \[
  L_{a,\text{ref}} = \frac{1}{\omega_0^2C_r}
  \]
- Magnetizing inductance is normally high
- Reduced in case of LLC
- Limits the magnetization current to the reference $I_{m,\text{ref}}$
- Limits the switch-off current and losses
  \[
  L_m = \frac{nV_{DC2}}{4f_sl_{m,\text{ref}}}
  \]
- $I_{m,\text{ref}}$ 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..
DC-DC SST - BASIC CONCEPTS

Fractional power processing

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

Different structures employed depending upon the voltage level

Bulk power processing

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

Different structures employed depending upon the voltage level

ISOP Structure

Bulk power processing concept
COMMON PEBB CONFIGURATIONS

**Dual-Active Bridge**

\[ P = P(\varphi) \]

\[ v_{AB}, v_{CD} \]

\[ i_T, L_\gamma \]

**Resonant Converters**

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

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

\[ Q = Q(R_{ac}) \]

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

\[ C_R, L_\gamma, L_m, R_{ac} \]

\[ v_{AB} \]

\[ i_T \]

\[ L_m R_{ac} \]

\[ v_{in}, V_o \]

\[ \text{phase-shifted} \]

\[ \text{variable frequency} \]
1-PHASE DAB

Basic operating principles
SINGLE-PHASE (1PH) DUAL ACTIVE BRIDGE (DAB)

Power equation

\[ P = \frac{1}{T} \int_{0}^{T} v_{AB} i_{T} dt \]

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

1PH-DAB with its relevant waveforms
Power equation

\[
P = \frac{1}{T} \int_{0}^{T} v_{AB} i_T \, dt
\]

\[
= m_T V_{in} V_o \omega L_S \varphi \left( 1 - \frac{|\varphi|}{\pi} \right)
\]

Switching cycle

\[
\omega t = \pi
\]

1PH-DAB with its relevant waveforms
SINGLE-PHASE (1PH) DUAL ACTIVE BRIDGE (DAB)

Power equation

\[ P = \frac{1}{T} \int_0^T v_{AB} i_T \, dt \]

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

Switching cycle

\[ \omega t = \pi \]

Dead-time

1PH-DAB with its relevant waveforms
SINGLE-PHASE (1PH) DUAL ACTIVE BRIDGE (DAB)

Power equation

\[ P = \frac{1}{T} \int_{0}^{T} v_{AB} i_{T} \, dt = m_{T} V_{in} V_{o} \omega L \sum \varphi \left(1 - \left| \varphi \right| \frac{\pi}{\pi} \right) \]

Switching cycle

1PH-DAB with its relevant waveforms
SINGLE-PHASE (1PH) DUAL ACTIVE BRIDGE (DAB)

Power equation

\[ P = \frac{1}{T} \int_{0}^{T} v_{AB} i_{T} \, dt \]

\[ = m_T V_{in} V_o \omega L \sum \phi \left(1 - \frac{|\phi|}{\pi}\right) \]

Switching cycle

1PH-DAB with its relevant waveforms

Main features

- Phase-Modulated converter
- Simple power flow control
- Soft-switching capability
SINGLE-PHASE (1PH) DUAL ACTIVE BRIDGE (DAB)

Power equation

\[ P = \frac{1}{T} \int_{0}^{T} v_{AB} i_T dt \]

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

Switching cycle

Main features

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

1PH-DAB with its relevant waveforms
\[ P = \frac{1}{T} \int_{0}^{T} v_{AB} i_T dt \]

\[ = m_T V_{in} V_o \omega L \phi \left( 1 - \left| \phi \right| \frac{\pi}{\pi} \right) \]

Switching cycle

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

\[ V_{in} \]

▲ 1PH-DAB with its relevant waveforms
3-PHASE DAB

Somewhat more complicated...
THREE-PHASE (3PH) DAB

\[ v_{an} = \frac{2v_{sa} - v_{sb} - v_{sc}}{3} \]

\[ v_{pa} = m_T \frac{2v_{sa}' - v_{sb}' - v_{sc}'}{3} \]

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

\[ = m_T \frac{4}{3} \frac{V_{in} V_o}{\omega L} \left( \frac{1}{2} - \frac{3|\phi|}{8\pi} \right) \]

\[ \phi \]

1-PH vs 3-PH DAB

<table>
<thead>
<tr>
<th>Control Simplicity</th>
<th>Tx utilization</th>
<th>Soft Switching</th>
<th>In/Out current ripple</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-PH DAB</td>
<td>😊</td>
<td>😊</td>
<td>😊</td>
</tr>
<tr>
<td>3-PH DAB</td>
<td>😊</td>
<td>😊</td>
<td>😊</td>
</tr>
</tbody>
</table>

3PH-DAB with relevant waveforms
THREE-PHASE (3PH) DAB

Power Equation

\[ P = \frac{3}{T} \int_0^T v_{an} i_{an} \, dt \]
\[ = m_T \frac{4}{3} V_{in} V_o \omega \Sigma \left( \frac{1}{2} - \frac{3|\varphi|}{8\pi} \right) \]

1-PH vs 3-PH DAB

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<td>😊</td>
<td>😊</td>
<td>😊</td>
<td>😊</td>
</tr>
<tr>
<td>3-PH DAB</td>
<td>😊</td>
<td>😊</td>
<td>😊</td>
<td>😊</td>
</tr>
</tbody>
</table>

⇒ 3PH-DAB is considered favorable!
3PH-DAB CONTROL

- Observed DAB-based system

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

$$\psi_0 i_o = \frac{4m_T V_{in}V_o}{3\omega L} \varphi \left(\frac{1}{2} - \frac{3|\varphi|}{8\pi}\right)$$

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

▶ Controlled current source behavior!

- DAB equivalent circuit seen from the controlled side

- Output voltage control loop

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

Region of interest

Almost linear!
Six step modulation
Limited number of voltage states

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

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

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

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

Current shape in the $\alpha\beta$ plane?
ABRUPT PHASE ANGLE CHANGES? (I)

- Six step modulation
- Limited number of voltage states

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

$V_p = V_k$

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

$L \frac{di}{dt} = V_p - V_s$

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

- Amplitude of the change proportional to $\varphi$
- Phase change in 60° steps

Current slides along a hexagon!
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 $V_s$
- Current vector stepwise phase changes ($60^\circ$)
- Current vector magnitude directly proportional to phase angle
- Current vector slides along the hexagon [31], [32]

What if the phase angle gets abruptly changed?
ABRUPT PHASE ANGLE CHANGES? (II)

Recap

- Limited number of voltage states $V_p$ and $V_s$
- Current vector stepwise phase changes ($60^\circ$)
- 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:

\[
\begin{bmatrix}
i_{\alpha}^{\text{off}} \\
i_{\beta}^{\text{off}}
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & 1 \\
\frac{-1}{2} & \frac{\sqrt{3}}{2} & 1
\end{bmatrix}
\begin{bmatrix}
i_{\alpha,\text{hex}}^{\text{off}} \\
i_{\beta,\text{hex}}^{\text{off}} \\
0
\end{bmatrix}
\]

Time constant $L_\Sigma/R_\Sigma$ determines asymmetric components decay!

Ee2019, Novi Sad, Serbia

October 23, 2019
ABRUPT PHASE ANGLE CHANGES? (III)

Applied phase angle sequence:

\[ \varphi_1 \xrightarrow{\frac{\varphi_1 + \varphi_2}{2}} \varphi_1 \xrightarrow{T \frac{1}{6}} \varphi_2 \xrightarrow{\text{Transition end}} \]

\[ \text{Transition time} = T \frac{1}{6} \]

Applied phase angle sequence:

\[ \varphi_1 \Rightarrow \varphi_2 \Rightarrow \varphi_1 \Rightarrow \varphi_2 \]

\[ \text{Transition time} = T \frac{1}{3} \]
MEDIUM VOLTAGE DC-DC

Extending previously presented concepts...
**HOW TO HANDLE HIGH/MEDIUM VOLTAGES?**

- 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
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

\[
P_{sq} = \frac{V^2}{2 \omega L} (1 - \frac{\varphi}{\pi})
\]

\[
P_{sine} = \frac{V^2}{2 \omega L} \sin(\varphi)
\]

▲ MMC-based 1PH-DAB [36]

▲ MMC-based 3PH-DAB
Basic operation principles are retained
- Easy to comprehend (AC equivalent)

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

$$P = \frac{V_1 V_2}{\omega L \gamma} \sin(\delta)$$
MMC ENERGY BALANCING AND QUASI SQUARE WAVE OPERATION (I)

Ideally, $Q^+ = Q^-$ \(\rightarrow\) Natural balancing

However, reality is different...

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

▲ 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

Balancing algorithm must be employed!
Quasi Square Wave operation

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

\[
G = \frac{V_{o,mT}}{V_{in}}
\]

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

\[\Delta \theta = (N - 1) \Delta \theta\]

▲ Charge received by a SM depending upon the gate signal [37]
MMC ENERGY BALANCING AND QUASI SQUARE WAVE OPERATION (II)

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.

\[ Q_{SM} \]

▲ 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
- $\Delta V_{SM}$ - SM voltage change with respect to the previous switching period

<table>
<thead>
<tr>
<th></th>
<th>SM$_1$</th>
<th>SM$_2$</th>
<th>SM$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{SM}(k)$</td>
<td>1200</td>
<td>1050</td>
<td>1150</td>
</tr>
<tr>
<td>$V_{SM}(k-1)$</td>
<td>1100</td>
<td>1150</td>
<td>1200</td>
</tr>
<tr>
<td>Gate (k-1)</td>
<td>Signal 2</td>
<td>Signal 3</td>
<td>Signal 1</td>
</tr>
<tr>
<td>$\Delta V_{SM}$</td>
<td>100</td>
<td>-100</td>
<td>-50</td>
</tr>
</tbody>
</table>
MMC-BASED DAB SORTING FOR N = 3 (EXAMPLE)

- $V_{SM}(k)$ - SMs voltages measured in the observed switching period
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<tr>
<th></th>
<th>SM&lt;sub&gt;1&lt;/sub&gt;</th>
<th>SM&lt;sub&gt;2&lt;/sub&gt;</th>
<th>SM&lt;sub&gt;3&lt;/sub&gt;</th>
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<td>-100</td>
<td>-50</td>
</tr>
</tbody>
</table>

SM voltages sorting (ascending): SM<sub>2</sub> (1050) → SM<sub>1</sub> (1200) → SM<sub>3</sub> (1150)
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
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<th>$\Delta V_{SM}$</th>
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<tbody>
<tr>
<td>SM$_1$</td>
<td>1200</td>
<td>1100</td>
<td>Signal 2</td>
<td>100</td>
</tr>
<tr>
<td>SM$_2$</td>
<td>1050</td>
<td>1150</td>
<td>Signal 3</td>
<td>-100</td>
</tr>
<tr>
<td>SM$_3$</td>
<td>1150</td>
<td>1200</td>
<td>Signal 1</td>
<td>-50</td>
</tr>
</tbody>
</table>

SM voltages sorting (ascending): $1050_{SM_2}$, $1150_{SM_3}$, $1200_{SM_1}$

$\Delta V_{SM}$ sorting (descending): $100$ $Signal_2$ $-50$ $Signal_1$ $-100$ $Signal_3$
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
- \( \text{Gate}(k-1) \) - Gate signals assigned in the previous switching period
- \( \Delta V_{SM} \) - SM voltage change with respect to the previous switching period
- \( \text{Gate}(k) \) - Gate signal assigned to a SM in the observed switching period

<table>
<thead>
<tr>
<th>SM</th>
<th>( V_{SM}(k) )</th>
<th>( V_{SM}(k-1) )</th>
<th>( \text{Gate}(k) )</th>
<th>( \Delta V_{SM} )</th>
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<tbody>
<tr>
<td>SM_1</td>
<td>1200</td>
<td>1100</td>
<td>Signal 2</td>
<td>100</td>
</tr>
<tr>
<td>SM_2</td>
<td>1050</td>
<td>1150</td>
<td>Signal 3</td>
<td>-100</td>
</tr>
<tr>
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<td>1050</td>
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<thead>
<tr>
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<th>SM_2</th>
<th>Signal 3</th>
<th>SM_3</th>
<th>Signal 1</th>
<th>SM_1</th>
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</thead>
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<tr>
<td>100</td>
<td>-50</td>
<td>-100</td>
<td>1200</td>
<td>1150</td>
<td>1050</td>
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</table>

<table>
<thead>
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<th>Gate signal assignment</th>
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<tr>
<td>SM_2</td>
</tr>
<tr>
<td>SM_3</td>
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</table>
▶ MMC-alike structure
▶ Branch inductors removed!
▶ SM = Main Switch + Active Snubber
▶ Sequential insertion/bypassing of SMs

▲ Example of the Q2L Converter transition (N=3)
QUASI TWO-LEVEL (Q2L) CONVERTER

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

![Diagram of Quasi Two-Level Converter]

▲ Quasi Two-Level Converter

![Diagrams of Q2L Converter Transition (N=3)]

Example of the Q2L Converter transition (N=3)

と言って、毎の待ち時間帯は新しくリゾンティングパラメータを導入します！

每一天居住区間都引出新的共振参数到电路！
QUASI TWO-LEVEL (Q2L) CONVERTER

- MMC-alike structure
- Branch inductors removed!
- SM = Main Switch + Active Snubber
- Sequential insertion/bypassing of SMs
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)
QUASI TWO-LEVEL (Q2L) CONVERTER

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

▲ 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

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

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

- 4Q Robicon
- 4Q Grid Simulator
- ABB ACS2000
- 12-pulse Rectifier
- PHSP Hydraulic Part - Emulation
- PHSP Electric Part - DUT
- PHSP RT-HIL Emulation

- 6 kV MVAC link
- 400V LVAC link
- 10kV MVDC link
- 6kV MV lab
MMC demonstrator ratings are:

- 500 kVA
- 10 kV\text{dc} \leftrightarrow 400 V\text{ac} or 6.6 kV\text{ac}
- 16 low voltage cells per branch \Rightarrow 32 cells per phase (cabinet) \Rightarrow 96 cells in total
- Industrial central controller and communication (ABB AC PEC 800)

\[
\begin{align*}
&\text{control} & & \text{phase-leg 1} & & \text{phase-leg 2} & & \text{phase-leg 3} & & \text{GIMC trafo} \\
&\text{cabinet} & & \text{cabinet} & & \text{cabinet} & & \text{cabinet} & & \text{cabinet}
\end{align*}
\]
MMC – CONVERTER LAYOUT

MMC demonstrator ratings are:

- 500 kVA
- ± 10 kV<sub>dc</sub> ↔ 2 x 3.3 kV<sub>ac</sub>
- 8 low voltage cells per branch ⇒ 16 cells per MMC phase ⇒ 96 cells in total
- Industrial central controller and communication (ABB AC PEC 800)

![Flexible DC Source Converter Layout](image_url)
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

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

▲ CFD simulations of submodule and cabinet
▲ PS-PWM, DC circ
▲ PS-PWM, DC+2\textsuperscript{nd} circ
▲ Time benchmark

\[ P_{c,T,u} \]
\[ P_{c,T,l} \]
\[ P_{c,D,u} \]
\[ P_{c,D,l} \]
\[ P_{on,T,u} \]
\[ P_{on,T,l} \]
\[ P_{off,T,u} \]
\[ P_{off,T,l} \]
\[ P_{rr,D,u} \]
\[ P_{rr,D,l} \]
System partitioning

Control cabinet  Phase-leg 1 cabinet  Phase-leg 2 cabinet  Phase-leg 3 cabinet  GIMC Trafo cabinet

Branch
Phase-leg
10kVdc
400Vac

Multi-windings transformer

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."

Zones definition

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

Zone 2 (ins. coord. branch)
- Horizontal system voltage: 1 kV\textsubscript{ac}
- Vertical system voltage: 3.6 kV\textsubscript{ac}

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

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

Zone 2
- Box at dc- cell's potential (floating)
- Box corner radius: 3 mm
- MKHP (high CTI material) drawer holding 4 cells
Zone 3 (2 out of $2^{16}$ combinations)

Design recap

<table>
<thead>
<tr>
<th>Variable</th>
<th>Minimal value [mm]</th>
<th>Actual design value [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l_b$</td>
<td>6.8</td>
<td>3</td>
</tr>
<tr>
<td>$d_{L,h}$</td>
<td>3.2</td>
<td>15</td>
</tr>
<tr>
<td>$d_{C,h}$</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>$d_{L,v}$</td>
<td>12.5</td>
<td>275</td>
</tr>
<tr>
<td>$d_{C,v}$</td>
<td>60</td>
<td>81.5</td>
</tr>
<tr>
<td>$d_{L,c}$</td>
<td>60</td>
<td>93</td>
</tr>
<tr>
<td>$d_{C,c}$</td>
<td>102</td>
<td>120</td>
</tr>
</tbody>
</table>

Ac dielectric withstand test
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

▲ Drawer holding 4 cell (MKHP material)

▲ AC dielectric withstand test result
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

▲ Developed MMC submodule

▲ MMC Submodule Structure: Yellow parts - Control PCB

October 23, 2019
- Power processing part
- Semikron full-bridge IGBT module 1.2 kV/50 A
- Bank of electrolytic capacitors \( C_{sm} = 2.25 \text{ mF} \)
- Protection devices: Bypass thyristor, relay and OVD
- Current and voltage measurements
- Hybrid balancing circuitry
- Hardware reconfiguration (HR)
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
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

Planar trafo design

Matlab design tool

FEM
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
  - $V_{cell}$, $V_{CMD}$ gets energized
  - UVLO turn-on threshold

- Steady-state operation
  - $V_{cell}$, $V_{CMD}$, $V_{sense}$

- Shut-down (slow $\text{d}v/\text{d}t$ from Delta power-supply used to emulate the cell)
  - $V_{cell}$
  - UVLO turn-off threshold
  - Loss of regulating capability
MMC MECHANICS

▲ MMC CAD development

▲ MMC coupled air-core branch inductors

▲ MMC - Actual mechanical assembly

▲ MMC Submodule thermal heat-run test setup

Honeycomb
DUT
T° Controller
T° Logger

Air flow sensor
- **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 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
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- Certain adjustments need to be made
  - Adjustment of the original MMC submodule?
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- Two connected MMCs as the end goal (**13 RT-Boxes + 96 cells**)

![MMC Submodule](image)

![Control Board](image)

- Control board trimming ⇒ Adjusted Control card

![Diagram](image)

**Ee2019, Novi Sad, Serbia**

October 23, 2019
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)

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

▲ MMC Submodule

▲ Control Board

▲ Power Board
- **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 complete scheme including ABB AC 800PEC industrial controllers
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


THANK YOU FOR YOUR ATTENTION

Tutorial pdf can be downloaded from:

- https://pel.epfl.ch/publications_talks_en