MMC-BASED CONVERTERS FOR MVDC APPLICATIONS

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INTRODUCTION

Non technical one...
INSTRUCTORS

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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
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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

Dr. Alexandre Christe

Experience:

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Education:

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Education:

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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
RESEARCH FOCUS

MVDC Technologies and Systems
▶ System Stability
▶ Protection Coordination
▶ Power Electronic Converters

High Power Electronics
▶ Multilevel Converters
▶ Solid State Transformers
▶ Medium Frequency Conversion

Components
▶ Semiconductor devices
▶ Magnetics
▶ Modeling, Characterization

Power Density [kW/l]
Efficiency [%]

All Designs
Filtered designs
Designs with standard core and wire
Filtered standard designs
Selected design

98.6 98.8 99 99.2 99.4 99.6 99.8 100
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 Lunch

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

After the Lunch

5) Galvanically Isolated Modular Converter
   ▶ Magnetic Integration
   ▶ Design Optimization
   ▶ Sub-Module Design

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

7) MMC-Based DC-DC STC Converter
   ▶ Scott Transformer Connection
   ▶ Bidirectional vs. Unidirectional
   ▶ Design and Control

8) 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
  
  \[ \frac{P}{Q} \approx \frac{3}{1} \]
  
  Example: \( @ \cos(\phi) = 0.95 \)

- 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

<table>
<thead>
<tr>
<th></th>
<th>Total AC system cost</th>
<th>Losses</th>
<th>Terminal cost</th>
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▲ High voltage cable

- Power conductor
- Conductor screen
- Insulation
- Insulation screen
- Conducting shield
- Jacket

\[ \Delta R_s \Delta L \]

\[ \Delta R_p, \Delta C \]

\[ \Delta R_p \]

\[ \Delta L \]

MVDC/LVDC

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

EPE2019, Genova, Italy

Power Electronics Laboratory | 10 of 156

September 02, 2019
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\(_{dc}\)
- DC loads (including UPS)
- Expected efficiency increase

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

LVDC ships
- Variable frequency generators \(\Rightarrow\) maximum efficiency of the internal combustion engines
- Commercial products by ABB & Siemens

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

\(\uparrow\) From mercury arc rectifiers to modern HVDC systems

\(\uparrow\) Specialized vessels with LVDC distribution

\(\uparrow\) 1500V PV inverter - step towards the MVDC
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dc beneficial for medium / high power applications
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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⇒ 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!
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]**
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
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 $\approx 2\%$ (!) [7]
▶ Drawn solution is not the unique possibility

 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]
MEDIUM OR LOW FREQUENCY CONVERSION?

**MVDC integration challenge**
- MVDC-LVAC galvanically isolated conversion system

**Desired conversion features**
- High efficiency
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- Modularity
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**Laboratory prototype ratings**
- $S = 0.5$ MVA
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▲ Generic SST illustration for MVDC-LVAC conversion

⇒ 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

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 \( e_x = \sum_{i=1}^{N_{cells}} s_{xi} v_{C_{xi}} \) (switched model) or \( e_x = m_x v_{C_{xi}} \) (average model)

Submodule capacitor voltages

\[
\frac{d}{dt} \begin{bmatrix} v_{C_{SP}} \\ v_{C_{SN}} \end{bmatrix} = \frac{1}{C_{br}} \begin{bmatrix} m_p & 0 \\ 0 & m_n \end{bmatrix} \begin{bmatrix} i_p \\ i_n \end{bmatrix}
\]

First transformation

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

Second transformation

\[
\begin{bmatrix} v_{C_{ΣP}} \\ v_{C_{ΣN}} \end{bmatrix} = \begin{bmatrix} 1 & 1/2 \\ -1/2 & 1/2 \end{bmatrix} \begin{bmatrix} v_{C_{SP}} \\ v_{C_{SN}} \end{bmatrix} \quad \leftrightarrow \quad \begin{bmatrix} v_{C_{SP}} \\ v_{C_{SN}} \end{bmatrix} = \begin{bmatrix} 1/2 & -1/2 \\ 1/2 & 1 \end{bmatrix} \begin{bmatrix} v_{C_{ΣP}} \\ v_{C_{ΣN}} \end{bmatrix}
\]

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

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

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

\[ v_{CM}(t) = \sum_i v_{CM,i} \cos(i3\omega t) \]

the CM voltage

\[ I_{dc} \]

the dc-link current

\[ i_g(t) = i_g \cos \left( \omega t + \varphi - \frac{2\pi(k - 1)}{3} \right) \]

the ac grid current

\[ i_{circ}(t) = \sum_{\delta I} i_{circ,i} \cos \left( \delta I 2\omega t + \theta I - \frac{2\pi(k - 1)}{3} \right) \]

the circulating current

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

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

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

Transformation

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

- $p_\Sigma$ only contains even harmonics
- $p_\Delta$ only contains odd harmonics

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

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

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

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

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

W/o common mode

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

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

W/ common mode

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

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

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

which means 2nd and 4th harmonics (at least!)
W/o common mode

W/ common mode

▲ MMC relevant waveforms without injection of the common mode voltage

▲ MMC relevant waveforms with injection of the common mode voltage
BRANCH CAPACITANCE SELECTION

Branch energy ripples

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

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

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

<table>
<thead>
<tr>
<th>Case #</th>
<th>CM</th>
<th>2\textsuperscript{nd} (+ 4\textsuperscript{th}) harmonic</th>
<th>Energy requirement [kJ/MVA]</th>
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<td>○</td>
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<tr>
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<td>27.2</td>
</tr>
<tr>
<td>4</td>
<td>●</td>
<td>●</td>
<td>24.8</td>
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</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)
COMMON CONTROL LOOPS WITH OTHER VSC’S: POSITIVE/NEGATIVE SEQUENCE EXTRACTION (PNSE)

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 $\alpha\beta$ frame
- No additional filters required (with SOGI, LPF on $\alpha$ 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

**PR in αβ frame [13]**

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

▲ Proportional Integral regulator in $dq$ frame

▲ 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

Common VSC control
Specific MMC control
Modulation indices
calculation methods
MMC SPECIFIC CONTROL LOOPS: ENERGY CONTROL (EC)

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

**Vertical balancing**
- Using a fundamental ac component

\[ v_{c2}^a \rightarrow \mathbf{F} \rightarrow K_{p,vert} \rightarrow i_{\text{circ,vert,abc}} \]

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

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

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]
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]

$$m_p = \frac{V_B/2 - e_B^*/2 - e_L^*}{\dot{v}_{CΣP}}$$

$$m_n = \frac{V_B/2 - e_B^*/2 + e_L^*}{\ddot{v}_{CΣn}}$$
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]

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

▲ 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

(a) No CCC

(b) CCSC / CCC dc circ

(c) 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, $v_{C\Sigma}$ is not properly controller on reactive power steps (it settles to a value close to $V_{C\Sigma 0}$)
- 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 $v_{C\Sigma}$ 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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- 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
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- 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
Circulating currents are canceling out at the terminals.
the final choice depends on the application requirements / acceptable compromises between complexity and performance
MMMC MODULATION METHODS

Variety of options are available...
Choice and motivations for the choice completely different for an HVDC design compared to MVDC!

<table>
<thead>
<tr>
<th>Classification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Carrier-based</strong></td>
<td>PS-PWM [20], LS-PWM (PD-PWM, etc.), SVM [21]</td>
</tr>
<tr>
<td><strong>Programmed</strong></td>
<td>SHE [22], OPP [23], [24]</td>
</tr>
<tr>
<td><strong>Decision based</strong></td>
<td>NLM, FTB [25]</td>
</tr>
</tbody>
</table>
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 $2N_{\text{cells}} + 1$ modulation

Remark $\mu\text{C}$ denotes either a microcontroller, an FGPA, 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

APOD-PWM
- Phase switching pattern without strong harmonic at switching frequency
- Line switching pattern with distinctive carrier side bands
- Higher THD
SINGLE-CARRIER PWM (I)

**Aim**
- Reduce PWM computation requirement
- Flexibility of the modulator irrespectively of the number of cells or the LS-PWM type

**LS-PWM carriers**
- Carrier band “height” determined by the number of cells
- Carrier phase determined by the modulation type
  - 0° phase-shift for PD-PWM
  - 180° phase-shift for neighboring carriers with APOD-PWM
  - 180° phase-shift for the upper half carriers with POD-PWM

**Background work**
- Originally proposed in [26] for MMC with PD-PWM
- Detailed in [27] for FC with PD-PWM
- Extended and generalized for MMC in [8]

**Principle**
- Only the carrier where the reference belongs is active
- The *interesting* signal can be simply retrieved with the reminder from a floor function
- The *boring* signal is an offset called quantizer
- The level-shifted PWM method is obtained by selecting the right carrier with the function $f(u)$

**Restriction**
- Sorting algorithm and alike branch balancing schemes based on the instantaneous number of inserted cells per branch
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 [28]

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

**Restricted sorting [29]**

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

---

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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

![Diagram of cell balancing with distributed modulators](image)
HIGH PERFORMANCE PWM MODULATION METHODS

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

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

\(e_{ap}, e_{an}, e_{Ba}, e_{La} [kV]\)

\(v_{Cap}, v_{Can} [V]\)

\(I_{dc}, i_{ap}, i_{an}, i_{ga}, i_{circ,a} [A]\)

\(f_{sw,cell} = 375\,\text{Hz}\)
HIGH PERFORMANCE PWM MODULATION METHODS

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

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

\[ f_{\text{sw,cell}} = 375 \text{ Hz} \]
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 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

SM designed at PEL
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

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

SM designed at PEL

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MODULAR MULTILEVEL CONVERTER POWER SCALING

- Series connection of HB/FB Submodules (SMs)
- Flexible in terms of voltage scaling
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Branch equivalent circuit with its voltage waveform

SM designed at PEL

- Modular Multilevel Converter

MMC power scaling

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

MMC branch voltage scaling

A converter operating at this point?

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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

▲ MMC power scaling

▶ 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

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

- MMC power scaling
- MMC branch voltage scaling

- SM designed at PEL
Modular Multilevel Converter

Series connection of HB/FB Submodules (SMs)
Flexible in terms of voltage scaling
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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

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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

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

How to increase current capacity?

SM designed at PEL
COMMON MMC CURRENT CAPACITY INCREASE METHODS

▲ Paralleling semiconductor modules

▲ Paralleling SMs

▲ Paralleling converters
COMMON MMC CURRENT CAPACITY INCREASE METHODS

▲ Paralleling semiconductor modules

▲ Paralleling SMs

▲ Paralleling converters

▲ Exemplary cell design; Current capacity - \(3I_{\text{rated}}\)
COMMON MMC CURRENT CAPACITY INCREASE METHODS

▲ Paralleling semiconductor modules

▲ Paralleling SMs

▲ Paralleling converters

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

▲ Paralleling semiconductor modules

▲ Paralleling SMs

▲ Paralleling converters

△ Exemplary cell design; Current capacity $I_{\text{rated}}$

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

▲ Paralleling SMs

▲ Exemplary cell design; Current capacity - \( I_{\text{rated}} \)

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

▲ Paralleling converters

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

Paralleled MMC branches ⇒ System simplification

▲ Cell designed for paralleling

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

▲ 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

▲ MMC with paralleled (sub)branches

▲ Branch equivalent circuit

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

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

**MMC with paralleled (sub)branches**

![Diagram of MMC with paralleled (sub)branches]

**Branch equivalent circuit**

![Diagram of branch equivalent circuit]

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

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

---

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

![Diagram of equivalent circuit]
MMC with paralleled (sub)branches

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

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

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

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

\[ i_{A} = \sum_{i=1}^{M} i_{A,i} \]

\[ i_{B} = \sum_{i=1}^{M} i_{B,i} \]

\[ i_{C} = \sum_{i=1}^{M} i_{C,i} \]

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

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

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

\[ L_a \]

\[ v_{br} \]

\[ L_{br,i} \]

\[ R_{br,i} \]

\[ i_{br,i} \]

\[ i_{A,i} \]

\[ i_{B,i} \]

\[ i_{C,i} \]

\[ V_{pA\Sigma} \]

\[ V_{pB\Sigma} \]

\[ V_{pC\Sigma} \]

\[ V_{in} \]

\[ i_{A} \]

\[ i_{B} \]

\[ i_{C} \]

\[ A \]

\[ B \]

\[ C \]
MODELING

▲ MMC with paralleled (sub)branches

Branch equivalent circuit

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

Equivalent circuit \equiv 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

\[
\overline{v_{br}} = \frac{1}{M} \sum_{i=1}^{M} v_{br,i} \\
\overline{Z_{br}} = \frac{1}{M} Z_{br,i}
\]
Definition of variables identical to the 3PH-MMC

- \( i_c = \frac{i_p + i_n}{2} \) - Leg common-mode current
- \( i_0 = i_p - i_n \) - 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
- $v_c = \frac{v_{nΣ} + v_{pΣ}}{2}$ - Leg common-mode voltage
- $v_s = \frac{v_{nΣ} - v_{pΣ}}{2}$ - Leg differential voltage

Well known 3PH-MMC control logic is retained!
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?
\[ L_{br} \frac{d}{dt} \left( i_{br,i} - \frac{i_{br}}{M} \right) + R_{br} \left( i_{br,i} - \frac{i_{br}}{M} \right) = \bar{v}_{br,i} - v_{br,i} \]

Should \( v_{br,i} \) be chosen like:
\[ v_{br,i} = \bar{v}_{br,i} + \Delta v_{br,i} \]

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

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

\[ i_{br,i} \xrightarrow{[M]} \sum_{i} \Delta i_{br,i} \xrightarrow{H_{\Delta i}} [M] \Delta v_{br,i} \]

▲ SBR current balancing controller
### Equivalent circuit of the branch

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

Should \( v_{br,i} \) be chosen like: \( v_{br,i} = v_{br,i}^\text{\(\tilde{\phi}\)} + \Delta v_{br,i} \)

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

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

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

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

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

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

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

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

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

Current balancing is not enough!

SBR powers are different \( \Rightarrow \) capacitor energy (voltage) divergence
Typical voltage/current waveforms of a (sub)branch

(Sub)branch power equation

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

Taylor series expansion

\[ P_{sbr} = P_{sbr}^{nom} + \frac{\Delta P_{DC}^{sbr}}{\frac{1}{2} V_{DC}^{sbr} \Delta i_{DC}^{sbr}} + \frac{\Delta P_{AC}^{sbr}}{\Delta L_{sbr}} \]

depends on \( \Delta L_{sbr} \)
Typical voltage/current waveforms of a (sub)branch

(Sub)branch power equation

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

\[ = V_{DC_{sbr}}I_{DC_{sbr}} + v_{sbr}i_{sbr} \]

Taylor series expansion

\[ P_{sbr} = P_{sbr}^{\text{nom}} + \frac{\Delta P_{DC_{sbr}}}{2} + \frac{\Delta P_{AC_{sbr}}}{\Delta L_{sbr}} \]

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

(Sub)branch power equation

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

\[ = V_{DC,sbr}^D C + i_{sbr}^D C \]

Taylor series expansion

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

\[ \approx \frac{1}{2} V_{DC}^D C \Delta i_{sbr}^D C \]

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

⇒ SBR energy control through SBR currents mismatches
**CONTROL - SBR BALANCING**

![Typical voltage/current waveforms of a (sub)branch](image)

- **Typical voltage/current waveforms of a (sub)branch**

  (Sub)branch power equation

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

  Taylor series expansion

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

  \[ = V_{DC}^{DC} \Delta i_{sbr}^{DC} \]

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

- **SBR energy control through SBR currents mismatches**

Reminder

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

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

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

- **SBR energy balancing**

  ![SBR energy balancing diagram](image)

  SBR energy controller

  \[ \sum_{i=1}^{M} \Delta v_{br,i} = H_{\Delta i}(H_{\Delta W} \left( M \cdot \frac{1}{M} \sum_{i=1}^{M} W_{br,i} - \sum_{i=1}^{M} W_{br,i,avg} \right) + H_{\Delta W} \left( M \cdot \frac{1}{M} \sum_{i=1}^{M} i_{br,i} - \sum_{i=1}^{M} i_{avg} \right) = 0 \]
Typical voltage/current waveforms of a (sub)branch

(Sub)branch power equation

\[ P_{sbr} = \frac{v_{sbr}i_{sbr}}{s} = V_{DC}^2 + V_{sbr}i_{sbr} \]

Taylor series expansion

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

\[ \Delta P_{DC}^{br} \text{ depends on } \Delta I_{br} \]

Reminder

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

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

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

SBR energy balancing

SBR energy controller

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

<table>
<thead>
<tr>
<th>Parameter</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>

#### Doubling the converter rated power

#### Tripling the converter rated power

\(\text{SBR energy balancing OFF}\)

#### Power profile used to test SBR energy balancing control
<table>
<thead>
<tr>
<th>Rated power ($P$)</th>
<th>Input voltage ($V_{in}$)</th>
<th>No. of cells/SBR ($N$)</th>
<th>Cell rated voltage ($V_{cell}$)</th>
<th>Cell capacitance ($C_{cell}$)</th>
<th>No. of paralleled SBRs ($M$)</th>
<th>SBR inductance ($L_{br}$)</th>
<th>SBR resistance ($R_{br}$)</th>
<th>Sw. frequency ($f_{sw}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left 1MW</td>
<td>5kV</td>
<td>5</td>
<td>1kV</td>
<td>0.83mF</td>
<td>2</td>
<td>5mH</td>
<td>60mΩ</td>
<td>999Hz</td>
</tr>
<tr>
<td>Right 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 (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?
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?

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

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?

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

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

\[ V_{DC} \]

\[ \text{Energy error} \quad \text{Controller TF} \quad \text{several kV} \]

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

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

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

\[ S^* = 0 \]

\[ \text{controller ON} \quad \text{controller reactivation} \]

\[ \text{References provided by the SBR energy balancing controller (M = 2)} \]

\[ \text{References provided by the SBR energy balancing controller (M = 3)} \]

\[ \text{SBR energy balancing OFF} \]
The SIMULATION RESULTS section discusses two relevant questions:

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

Additionally, references provided by the SBR energy balancing controller are noted:

- \( \Delta I^*_{br,i} = \Delta W_{br,i} \cdot \frac{2}{V_{DC}} \) energy error
- Controller TF
- several kV

### References

- \( \Delta I^*_{PA,1,A} \)
- \( \Delta I^*_{PA,2,A} \)
- \( \Delta I^*_{PA,3,A} \)

**Modest response!**

\( \Delta I^*_{br,i} < 10\% \hat{i}_{br} \)

**EPE2019, Genova, Italy**

September 02, 2019

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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?

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

\[\Delta I_{br,i}; i = \sum_{i=1}^{M} \Delta I_{br,i} \text{ (Modest response!)}\]

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

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

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

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

- \( \Delta I_{br,i}^* < 10\% \hat{i}_{br} \) (Modest response!)
- \( \sum_{i=1}^{M} \Delta I_{br,i}^* = 0 \)
- \( \sum_{i=1}^{M} \Delta V_{br,i}^* = 0 \) \( \Rightarrow \) no interference with higher control loops

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

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

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

\[
\Delta W_{br,i} \text{ Energy error} \quad \text{Controller TF} \quad \text{several kV}
\]

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

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

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

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

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

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

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

\[\Rightarrow \text{No need for SM current rating upgrade!}\]
MODULATION CONSIDERATIONS

...impact on the voltage quality
PRELIMINARY CONSIDERATIONS

\[ V_{A0} = s(t) \cdot V_{C,1} \]
\[ = [m(t) + s(\theta_1) + s(\theta_2)] V_{C,1} \]
\[ = \frac{V_{C}^+}{2} + \hat{m} \frac{V_{C}^+}{2} \cos(\omega t) + H_1(\omega t) \]

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

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

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

Time [ms]

▲ PSC modulation example with one HB module
PRELIMINARY CONSIDERATIONS

\[ V_{A0} = V(t) \cdot V_{C,2} \]
\[ = \left[ m_2(t) + m(t) \theta_1 + m(t) \theta_2 \right] V_{C,2} \]
\[ = \frac{V_C + \Delta V_C}{2} + \left( V_C^* + \Delta V_C \right) \frac{m}{2} \cos(\omega t) + H_2(\omega t) \]

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

\[ V_{C,1} \]
\[ V_{C,2} \]
\[ V_L,1 \]
\[ V_L,2 \]
\[ i_L,1 \]
\[ i_L,2 \]

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

PSC modulation example with one HB module
PRELIMINARY CONSIDERATIONS

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

\[ = [m_3(t) + st(\theta_1) + st(\theta_2)]V_{C,3} \]

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

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

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

▲ PSC modulation example with one HB module
Preliminary Considerations

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

\[ = \left[ m(t) + \frac{\dot{m}(t)}{2} \cos(\omega t) + \frac{\ddot{m}(t)}{2} \cos(2\omega t) \right] V_{C,3} \]

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

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

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

\[ v_{A0} = s(t) \cdot V_{C,3} \]
\[ = \left[ m_3(t) + \frac{\text{st}(\theta_1) + \text{st}(\theta_2)}{2} \right] V_{C,3} \]
\[ = \frac{V_C^*}{2} + \hat{m} \frac{V_C^*}{2} \cos(\omega t) + H_3(\omega t) \]

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

Closed loop control of the MMC utilizes similar procedure, where

\[ m_{(n,p)} = \frac{v_{C,n}^* \pm v_{S}^*}{v_{(n,p)} \Sigma} \]

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

\[ V_{C,1}, V_{C,2}, V_{C,3}, v_{l,1}, v_{l,2}, v_{l,3}, i_{l,1}, i_{l,2}, i_{l,3} \]

\( \pm 10\% \) variations

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

Time [ms]

\[ m(t) \quad i_{br} \]

\[ V_C \quad sgn \]

Additional compensation of modulation index

\[ m(t) \quad i_{br} \]

Voltage bal.
**PRELIMINARY CONSIDERATIONS**

\[ v_{A0} = sw(t) \cdot V_{C,3} \]
\[ = \left[ m_3(t) + \frac{\text{st}(\theta_1) + \text{st}(\theta_2)}{2} \right] V_{C,3} \]
\[ = \frac{V_C^*}{2} + \hat{m} \frac{V_C^*}{2} \cos(\omega t) + H_3(\omega t) \]

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

Closed loop control of the MMC utilizes similar procedure, where

\[ m_{(n,p)} = \frac{v_{C}^* \pm v_s^*}{v_{(n,p)\Sigma}} \]

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

\[ v_{SM} [\text{kV}] \]

\[ 0.78 \quad 0.79 \quad 0.8 \quad 0.81 \quad 0.82 \]

\[ 0.78 \quad 0.79 \quad 0.8 \quad 0.81 \quad 0.82 \]

**PSC modulation example with one HB module**

**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)
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)
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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 $\theta_c = 0$
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
Synchronous switching of branches $\Rightarrow (N+1)$-level modulation

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

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

AC voltage spectrum improvement depends on parity of $N$
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)

▲ $(N+1)$-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

▲ MMC leg utilizing two parallel SBRs (an exemplary case)
▲ $2(N + 1)$-level modulation
There are two relevant phase-shifts:

- $\delta$ - phase shift between two carrier sets within two SBRs belonging to adjacent branches
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▲ MMC leg utilizing two parallel SBRs (an exemplary case)

▲ $(MN + 1)$-level modulation
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▲ MMC leg utilizing two parallel SBRs (an exemplary case)

▲ (2MN + 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

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**
LUNCH BREAK

Well deserved...
Before the Lunch

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

After the Lunch

5) Galvanically Isolated Modular Converter
   - Magnetic Integration
   - Design Optimization
   - Sub-Module Design

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

7) MMC-Based DC-DC STC Converter
   - Scott Transformer Connection
   - Bidirectional vs. Unidirectional
   - Design and Control

8) 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)
GALVANICALLY ISOLATED MODULAR CONVERTER

Interleaved and Stacked variants
Open End Winding MMC [30]

- Only one branch per phase-leg
- No CM voltage injection
- No current decoupling
- DC bias in trafo → zig-zag trafo [31]

Isolated dc/dc converter [32]

- DC bias cancellation for any operating point
- Two-phase at least
TRANSFORMER INTEGRATION PROPOSALS IN THE LITERATURE

Open End Winding MMC [30]

- Only one branch per phase-leg
- No CM voltage injection
- No current decoupling
- DC bias in trafo \rightarrow zig-zag trafo [31]

Isolated dc/dc converter [32]

- DC bias cancellation for any operating point
- Two-phase at least

 proper transformer configuration required
Multi-windings trafo
- Unification of proposals [33] & [34]
- Dc bias cancellation is effective for any operating point
- Different dc voltage levels can be accommodated with the same branch design
Method

- Carried out once via terminal mapping
- \( v = L \frac{di}{dt} + Ri \)

\[
\mathbf{L} = \begin{bmatrix}
L_{\sigma,HV} + L_{HV} & L_{HV} & M_{LV} \\
L_{HV} & L_{\sigma,HV} + L_{HV} & M_{LV} \\
M_{LV} & M_{LV} & L_{\sigma,LV} + L_{LV}
\end{bmatrix}
\]

\[
\mathbf{R} = \begin{bmatrix}
R_{HV} & 0 & 0 \\
0 & R_{HV} & 0 \\
0 & 0 & R_{LV}
\end{bmatrix}
\]

iGIMC

- \( v_1 = v_i \)
- \( v_2 = -v_i \)
- \( v_3 = v_L \)

\( i_1 = i_i \)  
\( i_2 = -i_r \)  
\( i_3 = -i_g \)

Result:

- \( v_B = e_l + e_r + R_{HV} (i_i + i_r) + L_{\sigma,HV} \left( \frac{d}{dt}i_i + \frac{d}{dt}i_r \right) \)
- \( 0 = -e_l + e_r + R_{HV} (-i_i + i_r) + (L_{\sigma,HV} + 2L_{HV}) \left( -\frac{d}{dt}i_i + \frac{d}{dt}i_r \right) \)
- \( + 2M_{LV} \frac{d}{dt}i_g - 2v_{CM} \)
- \( v_L = M_{LV} \left( \frac{d}{dt}i_i - \frac{d}{dt}i_r \right) - (L_{\sigma,LV} + L_{LV}) \frac{d}{dt}i_g - R_{LV}i_g \)

sGIMC

- \( v_1 = v_p \)
- \( v_2 = -v_n \)
- \( v_3 = v_L \)

\( i_1 = i_p \)  
\( i_2 = -i_n \)  
\( i_3 = -i_g \)

Result:

- \( v_B = e_p + e_n + R_{HV} (i_p + i_n) + L_{\sigma,HV} \left( \frac{d}{dt}i_p + \frac{d}{dt}i_n \right) \)
- \( 0 = -e_p + e_n + R_{HV} (-i_p + i_n) + (L_{\sigma,HV} + 2L_{HV}) \left( -\frac{d}{dt}i_p + \frac{d}{dt}i_n \right) \)
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- \( v_L = M_{LV} \left( \frac{d}{dt}i_p - \frac{d}{dt}i_n \right) - (L_{\sigma,LV} + L_{LV}) \frac{d}{dt}i_g - R_{LV}i_g \)
GIMC MODELING

Method
- Carried out once via terminal mapping
- \( \mathbf{v} = L \frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i} + \mathbf{R} \mathbf{i} \)

\[
\mathbf{L} = \begin{bmatrix}
  L_\sigma,\text{HV} + L_{\text{HV}} & L_{\text{HV}} & M_{\text{LV}} \\
  L_{\text{HV}} & L_\sigma,\text{HV} + L_{\text{HV}} & M_{\text{LV}} \\
  M_{\text{LV}} & M_{\text{LV}} & L_\sigma,\text{LV} + L_{\text{LV}}
\end{bmatrix}
\]

\[
\mathbf{R} = \begin{bmatrix}
  R_{\text{HV}} & 0 & 0 \\
  0 & R_{\text{HV}} & 0 \\
  0 & 0 & R_{\text{LV}}
\end{bmatrix}
\]

\[
\mathbf{i}_{\text{GIMC}}
\]

\[
\begin{align*}
  \mathbf{v}_1 &= \mathbf{v}_i \\
  \mathbf{v}_2 &= -\mathbf{v}_r \\
  \mathbf{v}_3 &= \mathbf{v}_L \\
  \mathbf{i}_1 &= \mathbf{i}_i \\
  \mathbf{i}_2 &= -\mathbf{i}_r \\
  \mathbf{i}_3 &= -\mathbf{i}_g \\
\end{align*}
\]

Result:
\[
\begin{align*}
  \mathbf{v}_B &= \mathbf{e}_i + \mathbf{e}_r + R_{\text{HV}} (\mathbf{i}_i + \mathbf{i}_r) + L_\sigma,\text{HV} \left( \frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i}_i + \frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i}_r \right) \\
  0 &= -\mathbf{e}_i + \mathbf{e}_r + R_{\text{HV}} (-\mathbf{i}_i + \mathbf{i}_r) + (L_\sigma,\text{HV} + 2L_{\text{HV}}) \left( -\frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i}_i + \frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i}_r \right) \\
  &+ 2M_{\text{LV}} \frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i}_g - 2\mathbf{v}_{\text{CM}} \\
  \mathbf{v}_L &= M_{\text{LV}} \left( \frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i}_i - \frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i}_r \right) - (L_\sigma,\text{LV} + L_{\text{LV}}) \frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i}_g - R_{\text{LV}} \mathbf{i}_g
\end{align*}
\]

\[
\mathbf{i}_{\text{GIMC}}
\]

Result:
\[
\begin{align*}
  \mathbf{v}_B &= \mathbf{e}_p + \mathbf{e}_n + R_{\text{HV}} (\mathbf{i}_p + \mathbf{i}_n) + L_\sigma,\text{HV} \left( \frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i}_p + \frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i}_n \right) \\
  0 &= -\mathbf{e}_p + \mathbf{e}_n + R_{\text{HV}} (-\mathbf{i}_p + \mathbf{i}_n) + (L_\sigma,\text{HV} + 2L_{\text{HV}}) \left( -\frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i}_p + \frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i}_n \right) \\
  &+ 2M_{\text{LV}} \frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i}_g - 2\mathbf{v}_{\text{CM}} \\
  \mathbf{v}_L &= M_{\text{LV}} \left( \frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i}_p - \frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i}_n \right) - (L_\sigma,\text{LV} + L_{\text{LV}}) \frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i}_g - R_{\text{LV}} \mathbf{i}_g
\end{align*}
\]

sGIMC

\[
\mathbf{i}_{\text{sGIMC}}
\]

Result:
\[
\begin{align*}
  \mathbf{v}_1 &= \mathbf{v}_p \\
  \mathbf{v}_2 &= -\mathbf{v}_n \\
  \mathbf{v}_3 &= \mathbf{v}_L \\
  \mathbf{i}_1 &= \mathbf{i}_p \\
  \mathbf{i}_2 &= -\mathbf{i}_n \\
  \mathbf{i}_3 &= -\mathbf{i}_g
\end{align*}
\]

Result:
\[
\begin{align*}
  \mathbf{v}_B &= \mathbf{e}_p + \mathbf{e}_n + R_{\text{HV}} (\mathbf{i}_p + \mathbf{i}_n) + L_\sigma,\text{HV} \left( \frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i}_p + \frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i}_n \right) \\
  0 &= -\mathbf{e}_p + \mathbf{e}_n + R_{\text{HV}} (-\mathbf{i}_p + \mathbf{i}_n) + (L_\sigma,\text{HV} + 2L_{\text{HV}}) \left( -\frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i}_p + \frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i}_n \right) \\
  &+ 2M_{\text{LV}} \frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i}_g - 2\mathbf{v}_{\text{CM}} \\
  \mathbf{v}_L &= M_{\text{LV}} \left( \frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i}_p - \frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i}_n \right) - (L_\sigma,\text{LV} + L_{\text{LV}}) \frac{\mathbf{d}}{\mathbf{d}t} \mathbf{i}_g - R_{\text{LV}} \mathbf{i}_g
\end{align*}
\]

same as for conventional MMC
GIMC OPERATION

- Inverter mode operation

- sGIMC

- iGIMC
**GIMC OPERATION**

- **Inverter** mode operation

- **sGIMC**

- **iGIMC**

- $i_\mu$ does not contain a dc component
MAGNETIC COMPONENTS DESIGN

How much gain with the integrated magnetic component?
**Design space**

- Target: $L_{br} = 2.5 \text{ mH}$
- $i_{br,\text{rms}} = 56.7 \text{ A}$
- $J = 2 \text{ A/mm}^2$

**Analytical designs**

- $L_{\text{Welsby}} = \frac{\mu_0 N^2 na^2}{b} \left(1 + \frac{0.9}{\pi} + 0.32 \frac{c}{a} + 0.84 \frac{c}{b}\right) [\text{H}]$
- Cost function: $J_{\text{cost}} = \sqrt{\left(\frac{l_{\text{wire}}}{10}\right)^2 + V_{\text{tot}}^2}$

**Optimal design**

- $N_{\text{turns}} = 132, N_{\text{layers}} = 12, r_{\text{int}} = 42.4 \text{ mm}$
- $V_{\text{tot}} \approx 61$
- $P_{\text{losses}} = 130 \text{ W}$

- COMSOL frequency analysis @ 0.1 Hz (B-field / H-field)
- Impedance between 0.1 Hz and 100 kHz
LFT DESIGN

Design

- Three-limb dry-type transformer
- Short-circuit impedance > 5%
- Silicon steel (M19 from AK Steel): \( B_{\text{max}} = 1.2 \, \text{T} \Rightarrow \mu_s = 1.37 \% \)
- \( V_{12t} = 10 \, \text{V} \)
- \( J_{HV} = 2.5 \, \text{A/mm}^2, J_{LV} = 2 \, \text{A/mm}^2 \)

Core's permeance model

- Single unknown: \( w_w = \frac{4\mu_0 \mu_r A_c - P_c^* (6 + \pi) d_c}{(4 + 6\alpha)^2 P_c^*} \)

Best design

- \( w_w = 214.4 \, \text{mm and } \alpha = 4 \)
- \( V_{\text{tot}} = 481.7 \, \text{V} \)
- \( P_{w,HV} = 79.08 \, \text{W and } P_{w,LV} = 30.93 \, \text{W per phase} \)

- Leakage H-field in COMSOL @ 50 Hz (← phase a / → phase b)
- Time domain simulations (← no-load / → short-circuit)
GIMC TRANSFORMER DESIGN

Degree of freedom
- HV windings interleaving
- Leakage inductance (i.e., branch inductance) tuning

Best design
- \( w_w = 259.8 \text{ mm and } \alpha = 4 \)
- \( V_{\text{tot}} = 573.11 \)
- \( P_{w,\text{HV}} = 63.29 \text{ W and } P_{w,\text{LV}} = 30.93 \text{ W} \)

\[ L_{\sigma,\text{HV}} = \{83.33, 108.21, 83.33\} \text{ [mH]} \]
\[ L_{\sigma,\text{HV}} = \{25.57, 31.17, 25.57\} \text{ [mH]} \]

Leakage H-fields
- Time domain simulations (← no-load / → short-circuit)
GIMC TRANSFORMER DESIGN

Degree of freedom
▶ HV windings interleaving
▶ Leakage inductance (i.e., branch inductance) tuning

Best design
▶ $w_w = 259.8 \text{ mm}$ and $\alpha = 4$
▶ $V_{\text{tot}} = 573.1\text{ l}$
▶ $P_{w,\text{HV}} = 63.29 \text{ W}$ and $P_{w,\text{LV}} = 30.93 \text{ W}$

$L_{\sigma,\text{HV}} = \{83.33, 108.21, 83.33\} \text{ [mH]}$

$L_{\sigma,\text{HV}} = \{25.57, 31.17, 25.57\} \text{ [mH]}$

Leakage H-fields
▶ Time domain simulations (+ no-load / + positioning)
**MAGNETIC COMPONENTS COMPARISON**

**Case 1 MMC**
- 6 branch inductors + conventional LFT

<table>
<thead>
<tr>
<th>Branch inductors</th>
<th>Transformer</th>
</tr>
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<tr>
<td>volume</td>
<td>losses</td>
</tr>
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<td>6× 6 l</td>
</tr>
<tr>
<td>GIMC</td>
<td>-</td>
</tr>
</tbody>
</table>

**Case 2 GIMC**
- no branch inductors + multi-windings transformer

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**Magnetic Components Comparison**

**Case 1 MMC**
- 6 branch inductors + conventional LFT

**Case 2 GIMC**
- no branch inductors + multi-windings transformer

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<td>6 x 6 l</td>
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<tr>
<td>GIMC</td>
<td>-</td>
</tr>
</tbody>
</table>

⇒ volume + cost reduction & efficiency increase with the integrated magnetic component
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-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)

<table>
<thead>
<tr>
<th>Controlability</th>
<th>Grid Tx</th>
<th>SST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>$\eta \geq 99%$</td>
<td>$P_y$</td>
</tr>
<tr>
<td>Q compensation</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Fault tolerance</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Size</td>
<td>Bulky</td>
<td>Compact</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 [35], [36]
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 $\Rightarrow$ 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

$\begin{align*}
V_i & \quad L_{\sigma 1} & R_{\sigma 1} & L_{\sigma 2}' & R_{\sigma 2}' & L_m & R_m & V_o \\
I_i & \quad & & & & & & I_o
\end{align*}$

$\Rightarrow$ 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:

- 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:

- 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

\( V \) vs. \( f \)

\( R \) vs. \( f \)

\( Lm \)

\( R_{LL} \)

\( V_1 \)

\( V_2 \)

\( I_1 \)

\( N_1 : N_2 \)

\( MFT \)

\( L_{\sigma 1} \)

\( L'_{\sigma 2} \)

\( R_{\sigma 1} \)

\( R'_{\sigma 2} \)

\( N_1 : N_2 \)

\( L_{m} \)

\( V'_{2} \)

\( V'_{1} \)

\( I_1 \)

\( \phi \)

\( \pi \)
**MFT ACCURATE PARAMETERS CONTROL**

**DAB Converter:**
- Leakage Inductance
- Controllability of the power flow
- Higher than \( L_{o,min} \):
  \[
  L_{o,min} = \frac{V_{DC1} V_{DC2} \phi_{min} (\pi - \phi_{min})}{2 P_{out} \pi^2 f_s n}
  \]
- Magnetizing Inductance is normally high

**SRC**
- Leakage inductance is part of resonant circuit
- Must match the reference:
  \[
  L_{o,ref} = \frac{1}{\omega_0^2 C_r}
  \]
- 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

**Series Resonant Converter:**
- \( V_{1,2} \) square
- \( I \) non-sinusoidal

**DAB**
- \( V_{1,2} \) square
- \( I \) non-sinusoidal

**Magnetizing Inductance**
- 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

Different structures employed depending upon the voltage level

Bulk power processing

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

ISOP Structure

Bulk power processing concept
**COMMON PEBB CONFIGURATIONS**

**Dual-Active Bridge**

\[ P = P(\varphi) \]

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

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

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

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

**Resonant Converters**

\[ v_{AB} \quad v_{CD} \quad P = P(\varphi) \]

\[ i_T \quad L_\gamma \]

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

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

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

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

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

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

Power equation

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

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

Power equation

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

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

Switching cycle

\[ \omega t = \pi \]

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

Power equation

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\[ = m_{T} V_{in} V_{o} \frac{\omega L_{\Sigma} \varphi}{\pi} \left( 1 - \frac{1}{\pi} \right) \]

Switching cycle

ωt = π Dead-time

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

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Switching cycle

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

Power equation

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

Switching cycle

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

Power equation

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

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

Switching cycle

\[
\omega t = 2\pi \text{ Dead-time}
\]

\[
\omega t = 2\pi
\]

▲ 1PH-DAB with its relevant waveforms

---

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

Power equation

\[
P = \frac{1}{T} \int_{0}^{T} v_{AB} i_T dt = m_T V_{in} V_o \frac{\omega L}{\sum \phi} \left( 1 - \frac{|\phi|}{\pi} \right)
\]

Switching cycle

Main features

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

▲ 1PH-DAB with its relevant waveforms

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3-PHASE DAB

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

Power Equation

\[ P = \frac{3}{T} \int_{0}^{T} v_{an}i_{an} \, dt \]

\[ = m_{T} \frac{4}{3} V_{in} V_{o} \omega L_{\Sigma} \varphi \left( \frac{1}{2} - \frac{3|\varphi|}{8\pi} \right) \]

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

\[ v_{pa} = m_{T} \frac{2v'_{sa} - v'_{sb} - v'_{sc}}{3} \]

▲ 3PH-DAB with its relevant waveforms

1-PH vs 3-PH DAB

<table>
<thead>
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<th>In/Out current ripple</th>
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THREE-PHASE (3PH) DAB

Power Equation

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

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

1-PH vs 3-PH DAB

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<td>😞</td>
</tr>
</tbody>
</table>

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

▲ Observed DAB-based system

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

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

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

▲ Controlled current source behavior!

▲ DAB equivalent circuit seen from the controlled side

▲ Output voltage control loop

\[ P \frac{S}{\overline{S}} = \frac{4\pi - 3\varphi}{2\pi \sqrt{\frac{4\pi - \varphi}{\pi}}} \]

Almost Linear!

Region of interest

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ABRUPT PHASE ANGLE CHANGES? (I)

- Six step modulation
- Limited number of voltage states

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

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

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

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

? Current shape in the $ab$ plane?
ABRUPT PHASE ANGLE CHANGES? (I)

- Six step modulation
- Limited number of voltage states

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

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

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

\[
i = \begin{cases} 
\hat{i}_0 + \frac{\hat{V}}{L \omega} e^{j(k+1)\frac{\pi}{3}}, & \omega t \in \left[ (k-1) \frac{\pi}{3}, (k-1) \frac{\pi}{3} + \varphi \right] \\
\hat{i}_0 + \frac{\hat{V}}{\omega L} \varphi \sin \left( (k+1) \frac{\pi}{3} \right), & \omega t \in \left[ (k-1) \frac{\pi}{3} + \varphi, k \frac{\pi}{3} \right]
\end{cases}
\]

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

Current slides along a hexagon!

- Either side of the 3PH-DAB
- DAB equivalent circuit

Current shape in the $a\beta$ plane?
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 [38], [39]
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 [38], [39]

What if the phase angle gets abruptly changed?
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 [38], [39]

? What if the phase angle gets abruptly changed?

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

Inverse $\alpha\beta0$ transformation:

$$
\begin{bmatrix}
    i_{\alpha,offs} \\
    i_{\beta,offs} \\
    i_{b,offs}
\end{bmatrix}
= 
\begin{bmatrix}
    1 & 0 & 1 \\
    -\frac{1}{2} & \sqrt{3}/2 & 1 \\
    -\frac{1}{2} & -\sqrt{3}/2 & 1
\end{bmatrix}
\begin{bmatrix}
    i_{\alpha,hex} \\
    i_{\beta,hex} \\
    0
\end{bmatrix}
$$

? Time constant $L_\Sigma/R_\Sigma$ determines asymmetric components decay!
ABRUPT PHASE ANGLE CHANGES? (III)

Safe way of achieving phase angle change (I)

Applied phase angle sequence:

\[ \varphi_1 \Rightarrow \frac{\varphi_1 + \varphi_2}{2} \Rightarrow \frac{\varphi_1 + \varphi_2}{2} \Rightarrow \frac{\varphi_1 + \varphi_2}{2} \Rightarrow \varphi_2 \]

- Angle change!
- Transition time = \( \frac{T}{2} \)
- Transition end

Safe way of achieving phase angle change (II)

Applied phase angle sequence:

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

- Angle change!
- Transition time = \( \frac{T}{3} \)
- Transition end
MEDIUM VOLTAGE DC-DC

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

- Series connection of switches [40]
- Series connection of switches with snubbers
- Two voltage levels ($n_{LVL} = 2$)
- Two-Level voltage waveforms

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

- Quasi Two-Level (Q2L) Converter [41], [42]
- 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**

- Inserted
- Bypassed
- Blocked

**Full-Bridge submodule and its allowed states**

- Inserted #1
- Inserted #2
- Bypassed #1
- Bypassed #2
- Blocked
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

\[ P_{sq} = \frac{\hat{V}^2}{2 \omega L} \left( 1 - \frac{\phi}{\pi} \right) \]
\[ P_{sine} = \frac{\hat{V}^2}{2 \omega L} \sin(\phi) \]

\[ \hat{V}^2 \]

\[ V_{in} \]

\[ V_{o} \]

\[ MFT \]

\[ \text{AC/DC} \]

\[ \text{DC/AC} \]

\[ \text{MMT-based 1PH-DAB} \ [43] \]

\[ \text{MMT-based 3PH-DAB} \]
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- Energy balancing
- Q2L mode & capacitors sizing
- Engagement within bipolar grids

\[ V_{in} - V_{in}^2 - V_{in}^2 - V_{in}^2 \]

▲ MMC-based 1PH-DAB [43]

▲ MMC-based 3PH-DAB
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
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!

- MMC operating as a two level converter and its relevant waveforms
MMC ENERGY BALANCING AND QUASI SQUARE WAVE OPERATION (II)

Quasi Square Wave operation

- Intentional displacement among gating signals
- Control of MFT voltage slopes \( \frac{dV}{dt} \)
- Control of SMs' voltages

\[
G = \frac{V_{omT}}{V_{in}}
\]

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

▲ Charge received by a SM depending upon the gate signal [44]
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.

▲ MMC operating with quasi square voltages and its relevant waveforms

▲ Charge received by a SM depending upon the gate signal [44]

⇒ 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>
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<td>-100</td>
<td>-50</td>
</tr>
</tbody>
</table>

SM voltages sorting (ascending): SM\(_2\) 1050, SM\(_1\) 1200, SM\(_3\) 1150
MMC-BASED DAB SORTING FOR N = 3 (EXAMPLE)

- $V_{SM}(k)$ - SMs voltages measured in the observed switching period
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<th>SM₃</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1200</td>
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</tr>
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</tr>
<tr>
<td>$\Delta V_{SM}$</td>
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<td>-50</td>
</tr>
</tbody>
</table>

SM voltages sorting (ascending)

- $V_{SM}(k)$
  - SM₁: 1200
  - SM₂: 1050
  - SM₃: 1150

Delta $V_{SM}$ sorting (descending)

- $\Delta V_{SM}$
  - Signal 2: 100
  - Signal 1: -50
  - Signal 3: -100
MMC-BASED DAB SORTING FOR N = 3 (EXAMPLE)

- \( V_{\text{SM}}(k) \) - SMs voltages measured in the observed switching period
- \( V_{\text{SM}}(k-1) \) - SMs voltages measured in the previous switching period
- \( \text{Gate}(k-1) \) - Gate signals assigned in the previous switching period
- \( \Delta V_{\text{SM}} \) - 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></th>
<th>SM(_1)</th>
<th>SM(_2)</th>
<th>SM(_3)</th>
</tr>
</thead>
<tbody>
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SM voltages sorting (ascending):

- 1050 \( \rightarrow \) SM\(_2\)
- 1150 \( \rightarrow \) SM\(_3\)
- 1200 \( \rightarrow \) SM\(_1\)

Gate signal assignment:

- Signal 3 \( \rightarrow \) SM\(_1\)
- Signal 2 \( \rightarrow \) SM\(_2\)
- Signal 1 \( \rightarrow \) SM\(_3\)
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)
QUASI TWO-LEVEL (Q2L) CONVERTER

- MMC-alike structure
- Branch inductors removed!
- SM = Main Switch + Active Snubber
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▲ Example of the Q2L Converter transition (N=3)

 שלי Every dwell interval introduces new resonant parameters to the circuit!
QUASI TWO-LEVEL (Q2L) CONVERTER

- MMC-alike structure
- Branch inductors removed!
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- Sequential insertion/bypassing of SMs

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

▲ Quasi Two-Level Converter
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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
MMC-BASED DC-DC CONVERTERS UTILIZING SCOTT TRANSFORMER CONNECTION

Medium Frequency Conversion, High Power, Redundancy ...
CONVERSION OF AC LINES INTO DC

- Transmission capacity increase
- Employment of the existing conductors
- No change in tower foundations
- Possible tower head adjustment
- Possible isolator assemblies adjustment

Llanfair PG Substation
Bangor Substation
• Vac = 2 x 33kV
• Pac = 24.8MW

DC
AC
Llanfair PG Substation
Bangor Substation
• Vdc = 27kV
• Pdc = 30.5MW

(+), (-) pole

▲ Angle DC Project - UK

▲ Conversion of two typical AC lines into DC [45], [46], [47], [48]
Provided ratings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage ($V_{in}$)</td>
<td>$\pm 20$kV</td>
</tr>
<tr>
<td>Output voltage ($V_o$)</td>
<td>1.5kV</td>
</tr>
<tr>
<td>Rated power ($P_{nom}$)</td>
<td>10MW</td>
</tr>
<tr>
<td>Operating frequency ($f$)</td>
<td>1kHz</td>
</tr>
</tbody>
</table>

Redundancy

Converter structure considering given grid nature?

- Topology
- Operating principles and control
- Operating frequency
- Sizing principles considering given ratings
- Constraints
- Behavior under faults

▲ Generic structure of a converter to be employed within a bipolar grid
Features:

- Both stages switching at MFT operating frequency
- DAB operating principles
- Independent operation of the MMCs (ideally)
- Bidirectional topology
- Bipolar DC grids interface
- Redundant under faulty operating conditions
- Medium frequency operation

Drawbacks?

- Twelve arm inductors (or six coupled inductors)
- Magnetic coupling (circulating currents)
ORIGIN OF THE CIRCULATING CURRENTS

Bidirectional Topology

Unidirectional Topology
ORIGIN OF THE CIRCULATING CURRENTS

Bidirectional Topology

Unidirectional Topology

\[ V_s \neq V_p \Rightarrow \text{Circulating currents!} \]
**ORIGIN OF THE CIRCULATING CURRENTS**

**Bidirectional Topology**

**Unidirectional Topology**

However, magnetic coupling is what provides the means for the currents to circulate between windings.

⇒ $v_s \neq v_p \Rightarrow$ **Circulating currents!**

‡ Magnetic coupling is to be avoided!
BIDIRECTIONAL TOPOLOGY

Q4 operation
MMC-BASED BIDIRECTIONAL DC-DC CONVERTER EMPLOYING STC\textsuperscript{2}

▲ Scott Transformer Connection

- 3PH 3W Tx $\rightarrow$ 2 x 1PH Tx
- Number of MMC branches reduction ($N_L \downarrow$)
- Ability to operate in a pure rectifier mode
- Medium frequency operation

▲ MMC-Based High Power DC-DC Converter Employing Scott Transformer Connection [50]

---

Operating principles

▶ MMCs independent operation

\[ V_{T1} = m_{T1} \frac{V_{AB} - V_{CA}}{2} \]
\[ V_{T2} = m_{T2} V_{BC} \]

▶ Suitable HV side voltages (\( V_{c1}, V_{c2} \))?

▶ DAB behavior (phase modulated converter)

\[
P_1 = \frac{V_2^2 m_{T1}^2}{\omega L_a} \left( \frac{1}{2} - \frac{3|\varphi_1|}{8\pi} \right)
\]
\[
P_2 = \frac{V_2^2 m_{T2}^2}{\omega L_a} \left( \frac{2}{3} - \frac{|\varphi_2|}{2\pi} \right)
\]

\[
\left( m_{T1} = \frac{2}{\sqrt{3}} m_{T2} \right) \land \left( \varphi_1 = \varphi_2 \right) \\
\Rightarrow P_1 = P_2
\]

▶ Bidirectional topology

▶ Fundamental frequency switching

▶ Redundant under faults

▲ Converter idealized operating waveforms
**OPERATION UNDER FAULTS**

▲ Converter operation in the case of "Minus" DC pole malfunction

▲ Converter operation in the case of "Plus" DC pole malfunction
3PH-DAB equivalent model

\[ v_{xyz} = v_{ABC} e^{j\phi} \]
\[ L^* = \frac{L_a}{2m^2T^2} \]

Linearization

SSC equivalent circuit seen from the LV side

\[ V_o i_R = 2 \frac{m^2_{T1} V_o^2}{\omega L_a} \phi \left( \frac{1}{2} - \frac{3\phi}{8\pi} \right) \]
Linearized!

\[ i_R = \frac{7m^2_{T1} V_o^2}{8\omega L_a} \phi \]
3PH-DAB equivalent model

\[ v_{xyz} = v_{ABC} e^{j\phi} \]
\[ L_1^* = \frac{I_n}{2mT} \]

Linearization

\[ v_L = v_L^* \]
\[ i_L = i_L^* \]
\[ R_o \]
\[ C_o \]

STC-based SST Control block scheme

SSC equivalent circuit seen from the LV side

\[ V_0i_R = 2 \frac{mT_1 V_0^2}{\omega L_a} \left( \frac{1}{2} - \frac{3\phi}{8\pi} \right) \]
\[ \Rightarrow i_R = 7mT_1 V_0^* \frac{\phi}{8\omega L_a} \]
3PH-DAB equivalent model

\[ v_{xyz} = v_{ABC} e^{j\phi} \]

\[ L^* = \frac{L_a}{2m T_2} \]

Linearization

\[ V_o i_R = 2 \frac{m_{T1} V_o^2}{\omega L_a} \phi \left( \frac{1}{2} - \frac{3\phi}{8\pi} \right) \]

\[ \Rightarrow i_R = \frac{7m_{T1} V_o^2}{8\omega L_a} \phi \]

STC-based SST Control block scheme

What if \( P_1 \neq P_2 \) for any reason?
### 3PH-DAB equivalent model

\[ v_{xyz} = v_{ABC} e^{j\phi} \]

\[ L^*_\gamma = \frac{L_a}{2m_2} \]

### Linearization

\[ V_o i_R = 2 \frac{m_1^2 V_0^2}{\omega L_a} \left( \frac{1}{2} - \frac{3\varphi}{8\pi} \right) \]

\[ \Rightarrow i_R = \frac{7m_1^2 V_0^2}{8\omega L_a} \varphi \]

\[ \Delta P_{T1}^{lin} = 7V_0^2 m_1^2 \frac{16\omega L_a}{\Delta \varphi_1} \]

\[ \Delta P_{T2}^{lin} = 7V_0^2 m_2^2 \frac{12\omega L_a}{\Delta \varphi_2} \]

### STC-based SST Control block scheme

### Power balance loop

Additional control compensates small power mismatches!
### Table 1  Simulated system ratings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Input voltage ($V_{in}$)</td>
<td>±20kV</td>
</tr>
<tr>
<td>Output voltage ($V_o$)</td>
<td>1.5kV</td>
</tr>
<tr>
<td>Rated power ($P_{nom}$)</td>
<td>10MW</td>
</tr>
<tr>
<td>Operating frequency ($f$)</td>
<td>1kHz</td>
</tr>
</tbody>
</table>

- $i_{i1}$ → MMC$_1$ input current
- $i_{i2}$ → MMC$_2$ input current
- $i_{in}$ → neutral conductor current
- $i_{T1}$ → T$_1$ P-winding current
- $i_{T2}$ → T$_2$ P-winding current
- $i_{S}$ → LV stage 3PH-currents
- $i_{R}$ → SSC output current
- $V_o$ → load voltage
- $i_o$ → load current
- $i_{rev}$ → LV side current injection
- $V_{T1}$ → T$_1$ P-winding voltage
- $V_{T2}$ → T$_2$ P-winding voltage
- $i_{in1}$ → MMC$_1$ input current
- $i_{in2}$ → MMC$_2$ input current
- $i_n$ → neutral conductor current
- $i_{T1}$ → T$_1$ P-winding current
- $i_{T2}$ → T$_2$ P-winding current
- $i_s$ → LV stage 3PH-currents
- $i_R$ → SSC output current
- $V_o$ → load voltage
- $i_o$ → load current
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- $V_{T1}$ → T$_1$ P-winding voltage
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▲ Converter operating waveforms during five fundamental cycles
UNIDIRECTIONAL TOPOLOGY

Simplifying the low voltage power stage
MMC-BASED HIGH POWER UNIDIRECTIONAL DC-DC CONVERTER

- No magnetic coupling between Tx windings
- Parameters mismatch robustness
- Sinusoidal operation mode!

^ MMC-based High-Power Unidirectional DC-DC Converter

▲ Converter idealized operating waveforms
Adverse effects of the arm inductance

- Output voltage drop
- Increased commutation time
**Adverse effects of the arm inductance**

- Output voltage drop
- Increased commutation time

\[ L_{\gamma \Sigma} = 0 \quad \text{vs} \quad L_{\gamma \Sigma} \neq 0 \]

\[ i_A \quad \text{(Phase inductance effect on diode rectifier current waveform)} \]

**MMC branch inductors might limit converter operating frequency!**
Adverse effects of the arm inductance

- Output voltage drop
- Increased commutation time

Benefits of arm inductors coupling

- Reduced AC side inductance (ideal voltage source behavior)
- Increased DC side inductance (lower input current ripple)
- Reduced output voltage drop (reduced rectifier commutation time)

Phase inductance effect on diode rectifier current waveform

AC/DC equivalent circuits of a MMC leg with coupled inductors (ideal coupling)

MMC branch inductors might limit converter operating frequency!
OPERATION UNDER FAULTS

▲ Converter operation in the case of "Minus" DC pole malfunction

▲ Converter operation in the case of "Plus" DC pole malfunction
### Table 2  Simulated system ratings

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</thead>
<tbody>
<tr>
<td>Input voltage ($V_{in}$)</td>
<td>$\pm 20kV$</td>
</tr>
<tr>
<td>Output voltage ($V_o$)</td>
<td>1.5kV</td>
</tr>
<tr>
<td>Rated power ($P_{nom}$)</td>
<td>10MW</td>
</tr>
<tr>
<td>Operating frequency (f)</td>
<td>250Hz</td>
</tr>
</tbody>
</table>

- $i_T$ → LV-stage 3PH - currents
- $i_{in1}$ → MMC$_1$ input current
- $i_{in2}$ → MMC$_2$ input current
- $V_1$ → MMC$_1$ AC voltage
- $V_2$ → MMC$_2$ AC voltage
- $i_R$ → DR output current
- $i_o$ → load current
- $V_o$ → load voltage
- $i_{T1}$ → T$_1$ P-winding current
- $i_{T2}$ → T$_2$ P-winding current
- $V_{T1}$ → T$_1$ P-winding voltage
- $V_{T2}$ → T$_2$ P-winding voltage
- $V_R$ → DR output voltage

▲ Converter operating waveforms
- $i_T \rightarrow$ LV-stage 3PH - currents
- $i_{in1} \rightarrow$ MMC$_1$ input current
- $i_{in2} \rightarrow$ MMC$_2$ input current
- $V_1 \rightarrow$ MMC$_1$ AC voltage
- $V_2 \rightarrow$ MMC$_2$ AC voltage
- $i_R \rightarrow$ DR output current
- $i_o \rightarrow$ load current
- $V_o \rightarrow$ load voltage
- $i_{T1} \rightarrow$ T$_1$ P-winding current
- $i_{T2} \rightarrow$ T$_2$ P-winding current
- $V_{T1} \rightarrow$ T$_1$ P-winding voltage
- $V_{T2} \rightarrow$ T$_2$ P-winding voltage
- $V_R \rightarrow$ DR output voltage

▲ Converter operating waveforms during five fundamental cycles
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 DC Source Topology

▲ Pumped Hydro Storage Plants - Research Platform

▲ MMC-Based AC/AC Converter for Pump Hydro Applications
MMC demonstrator ratings are:
- 500 kVA
- $\pm 10 \text{kV}_d \leftrightarrow 2 \times 3.3 \text{kV}_a$
- 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)
MMC – CONVERTER LAYOUT

MMC demonstrator ratings are:

- 500 kVA
- 10 kV\textsubscript{dc} ↔ 400 V\textsubscript{ac} or 6.6 kV\textsubscript{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)

![Flexible DC Source Converter Layout](image-url)
**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

**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
INSULATION COORDINATION OF A MV CONVERTER PROTOTYPE (I)

System partitioning

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

Zones definition

- Zone 1 (ins. coord. inside a SM's enclosure) system voltage: 1 kV<sub>ac</sub>
- Zone 2 (ins. coord. branch)
  - Horizontal system voltage: 1 kV<sub>ac</sub>
  - Vertical system voltage: 3.6 kV<sub>ac</sub>
- Zone 3 (ins. coord. branch - cabinet (at GND)) system voltage: 6.6 kV<sub>ac</sub>
- Zone 4 (ins. coord. for LV circuits) system voltage: 0.4 kV<sub>ac</sub>

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."

EPE2019, Genova, Italy

Power Electronics Laboratory | 141 of 156
Zone 3 (2 out of $2^{10}$ combinations)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Minimal value [mm]</th>
<th>Actual design value [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_b$</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>$d_{C,c}$</td>
<td>60</td>
<td>93</td>
</tr>
<tr>
<td>$d_{L,r}$</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]
**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 $C_{\text{sm}} = 2.25 \text{ mF}$
- Protection devices: Bypass thyristor, relay and OVD
- Current and voltage measurements
- Hybrid balancing circuitry
- Hardware reconfiguration (HR)

▲ MMC Submodule Structure: Yellow parts - Control PCB

▲ 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

▲ MMC Submodule Structure: Yellow parts- Control PCB

▲ 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 [51]
- BH curve for CF297
- Jiles-Atherton parametrization

Planar trao design

Matlab design tool

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

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September 02, 2019
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
- UVLO turn-on threshold
- Shut-down (slow dv/dt from Delta power-supply used to emulate the cell)
- Steady-state operation

V_{cell}, V_{CMD}, V_{GD1,3}, V_{+5V}, UVLO turn-on threshold

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September 02, 2019
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)
**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**)

![Diagram of MMC submodule](image)

- MMC Submodule

![Diagram of control boards](image)

- Control board trimming ⇒ Adjusted Control card

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MMCCONTROL 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.

▲ High Power DC-DC Converter Employing Scott Transformer Connection
REFERENCES

REFERENCES


THANK YOU FOR YOUR ATTENTION

Tutorial pdf can be downloaded from:

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