INDEL 2018

MMC-BASED CONVERSION FOR MVDC APPLICATIONS

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Power Electronics Laboratory
Switzerland

POWER ELECTRONIC LABORATORY

Some general information...

SHORT BIO

Experience

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

Education

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

INDUSTRIAL RESEARCH PROJECTS (PERSONAL BACKGROUND)

ABB Medium Voltage Drives

2013 – 2014 R&D Platform Manager ACS 6000

ABB Corporate Research

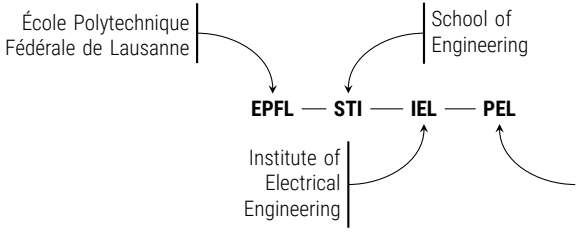
2011 – 2013 Voltage Isolation Voltage Adaptation - VIVA

2010 – 2011 Power Electronics Traction Transformer - PETT

2009 – 2010 Advanced Power Supply Technology - APST

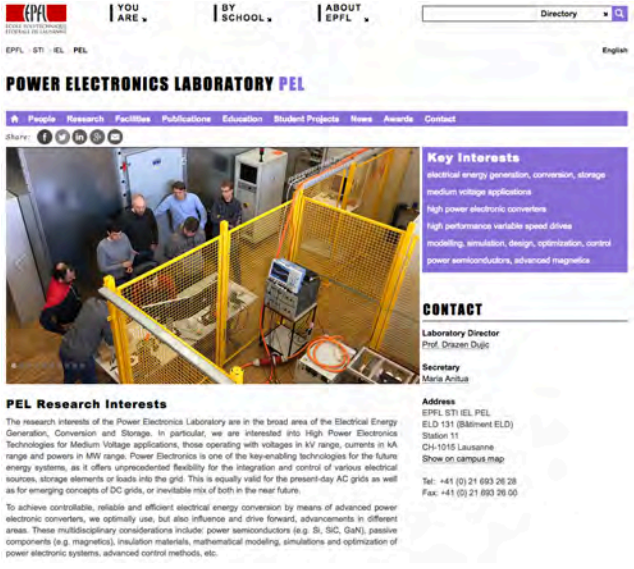
2009 – 2010 New Hardware Platform for Robotics - YuMi

POWER ELECTRONICS LABORATORY AT EPFL



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

Competence Centre

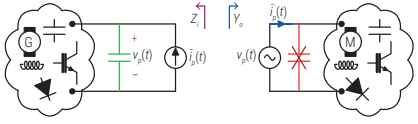


RESEARCH FOCUS

MVDC Technologies and Systems

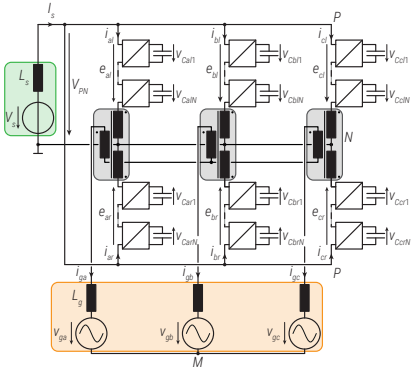
- System Stability
- Protection Coordination
- Power Electronic Converters

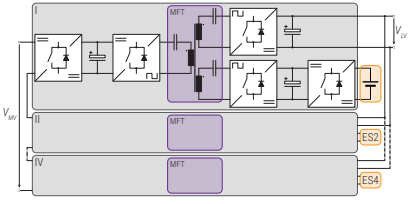
MVDC
ENERGY CONVERSION TECHNOLOGIES AND SYSTEMS



High Power Electronics

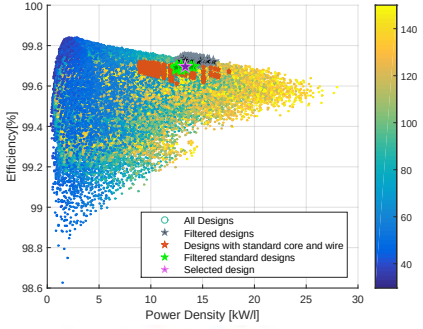
- Multilevel Converters
- Solid State Transformers
- Medium Frequency Conversion





Characterization

- Semiconductor devices
- Magnetic components
- Systems



MVDC TECHNOLOGIES AND SYSTEMS

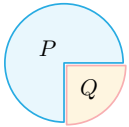
Future electrical energy generation, conversion and storage technologies

WHY DC OR MVDC?

- No reactive power

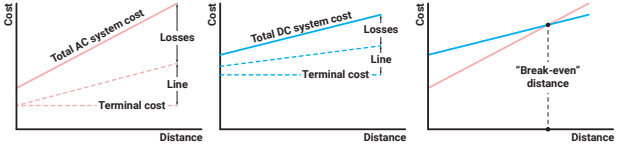
Example: @ $cos(\varphi) = 0.95$

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

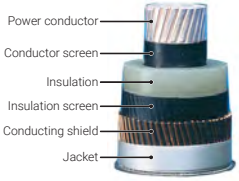


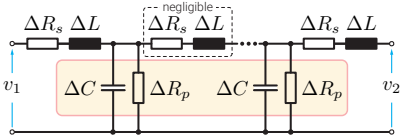
  - No constraints imposed upon transmission distance
  - Transmission capacity increase
  - Lower transmission losses
  - Alleviated stability problems

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

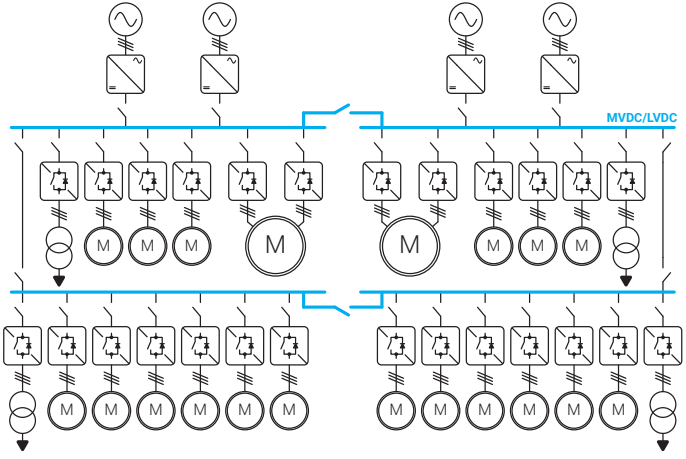


▲ Cost comparison between AC and DC systems





▲ High voltage cable



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

TREND TOWARDS DC

Bulk power transmission

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

▲ From mercury arc rectifiers to modern HVDC systems

LVDC ships

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

▲ Specialized vessels with LVDC distribution

Datacenters

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

Large PV powerplants

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

▲ 1500V PV inverter - step towards the MVDC

Open challenges

- DC breaker
- Conversion blocks missing
- Protection coordination

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Open challenges

- DC breaker
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- Protection coordination

dc beneficial for medium / high power applications

EMERGING MVDC APPLICATIONS

Installations

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

- Unidirectional oil platform connection in China: 29.2 km/±15 kV_{dc} [3]

Projects

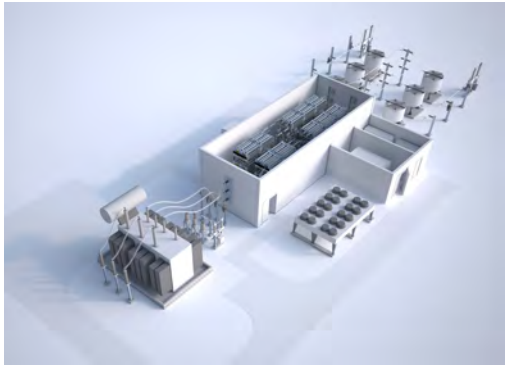
- Angle DC: conversion of 33 kV MVAC line to ±27 kV MVDC [4]

Universities

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

Products

- Siemens MVDC Plus
  - 30 - 150 MW
  - < 200 km
  - < ±50 kV_{dc}



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

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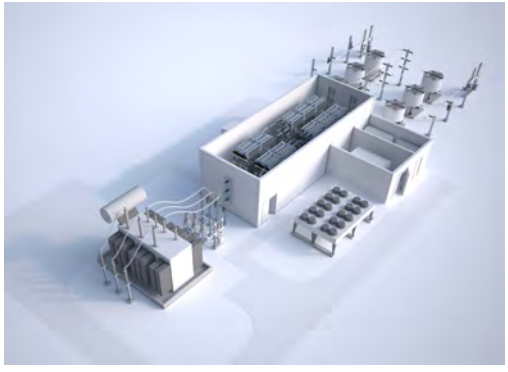

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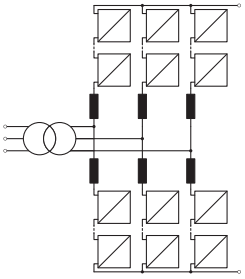
⇒ MVDC is gaining momentum!

TREND TOWARDS HIGHLY MODULAR CONVERTER TOPOLOGIES

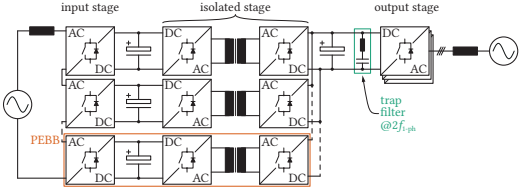
HVDC

- 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



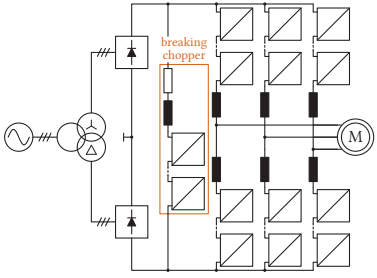
Solid-state transformers (SSTs)

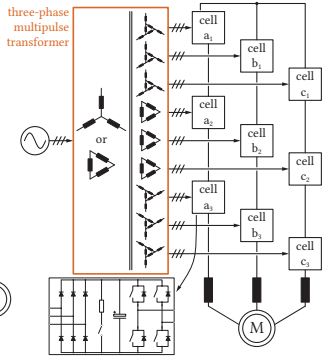
- Power density increase w/ conversion & isolation at higher frequency
- Grid applications / traction transformer w/ different optimization objectives
- MFT design / isolation are the bottlenecks



MV drives

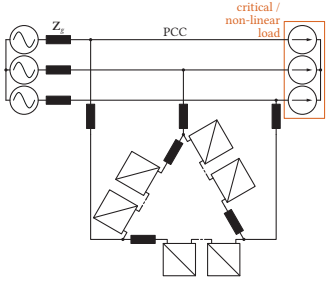
- Monolithic ML topologies (NPC, NPP, FC, ANPC) are not scalable
- Robicon drive → everyone offers it
- Siemens & Benshaw: MMC drive
- Low dv/dt ⇒ motor friendly





FACTS

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



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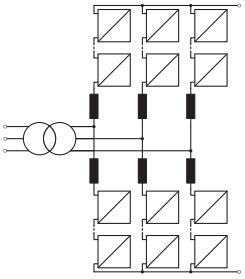

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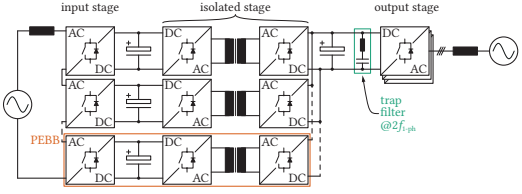

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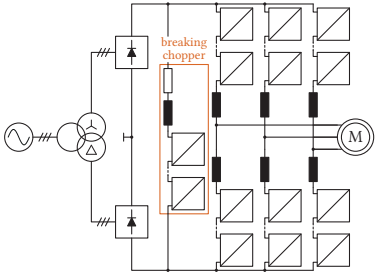

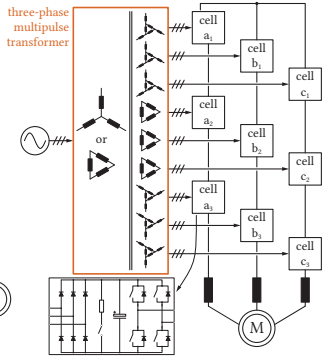

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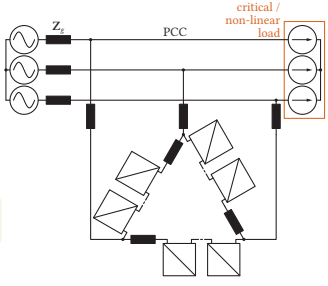


⇒ Modularity provides obvious benefits in high power applications!

MODULAR MULTILEVEL CONVERTER

Fundamental operating principles, modeling, power equations

NOMENCLATURE

Cell

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

Branch

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

Phase-leg

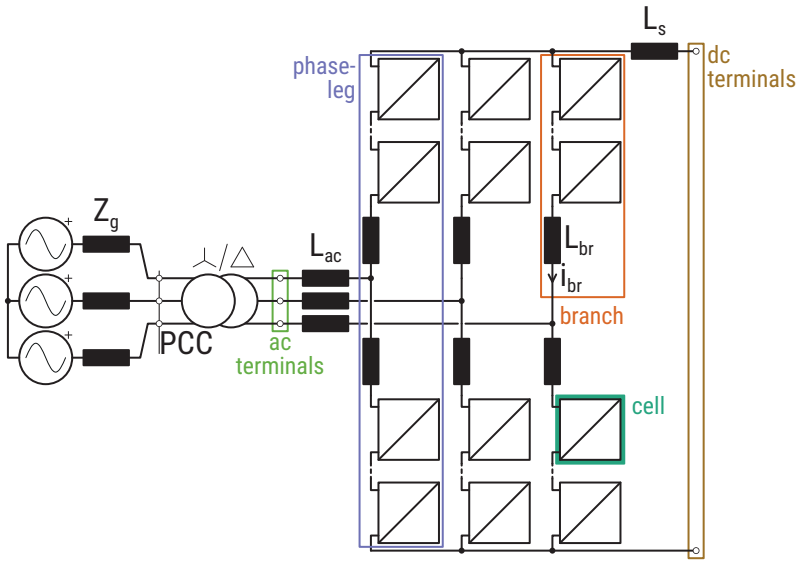
- Comprising two branches

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)

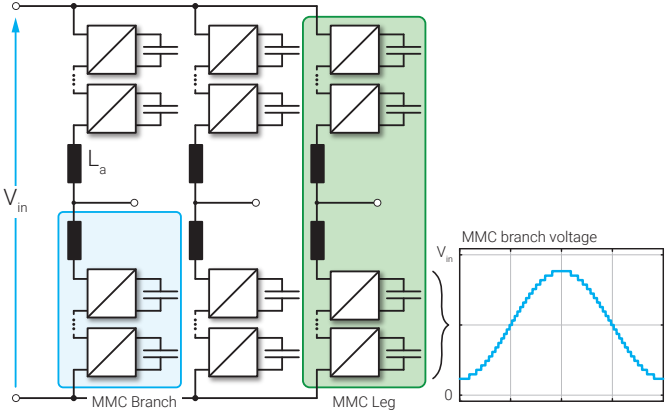


▲ Modular multilevel converter connected to the AC grid through the inductive filter

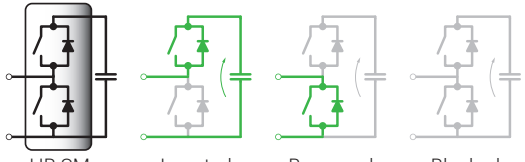
Functionality wise, only L_{br} is required!

MMC CELL TYPES

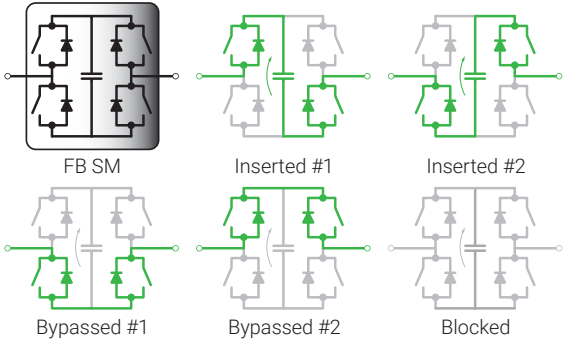
- Variety of conversion possibilities
- Variety of modulations
- Different types of submodules (SMs)
  - Half-Bridge (HB) - 2-level output voltage
  - Full-Bridge (FB) - 3-level output voltage
  - Others...
- Arbitrary voltage waveform generation



▲ Modular Multilevel Converter (MMC)



▲ Half-Bridge submodule and its allowed states



▲ Full-Bridge submodule and its allowed states

KVL equations

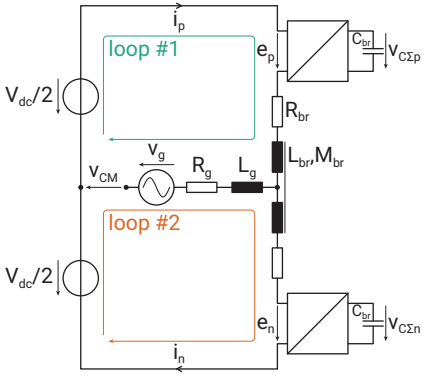
$$\frac{V_{dc}}{2} = e_p + L_{br}\frac{d}{dt}i_p - M_{br}\frac{d}{dt}i_n + R_{br}i_p + L_g\frac{d}{dt}(i_p - i_n) + R_g(i_p - i_n) + v_g + v_{CM}$$

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

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

Cell capacitor voltages

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



▲ Simplified MMC representation for modeling

First transformation

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

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

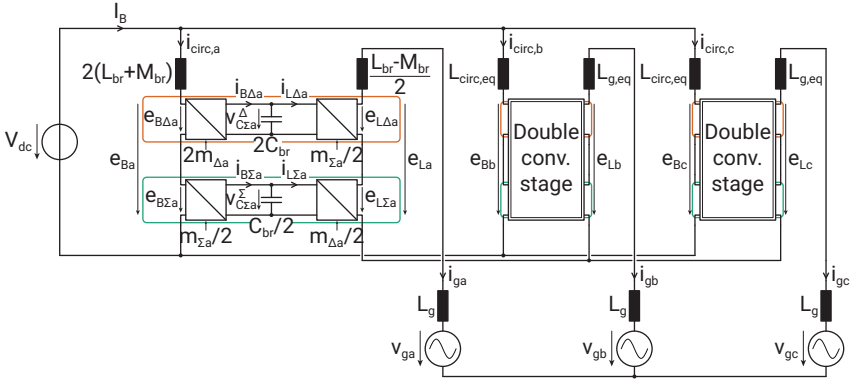
Second transformation

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

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

DECOUPLED MODEL

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



▲ MMC model illustrating decoupled control of AC and DC side

POWER EQUATIONS (I)

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

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

where

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

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

POWER EQUATIONS (II)

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

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

Transformation

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

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

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

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

Reminder

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

Insight provided

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

CIRCULATING CURRENT OPTIMIZATION

- First discussed in [5].
- Without passives!

W/o circulating current

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

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

W/o common mode

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

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

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

W/ common mode

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

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

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

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

BRANCH CAPACITANCE SELECTION

Branch energy ripples

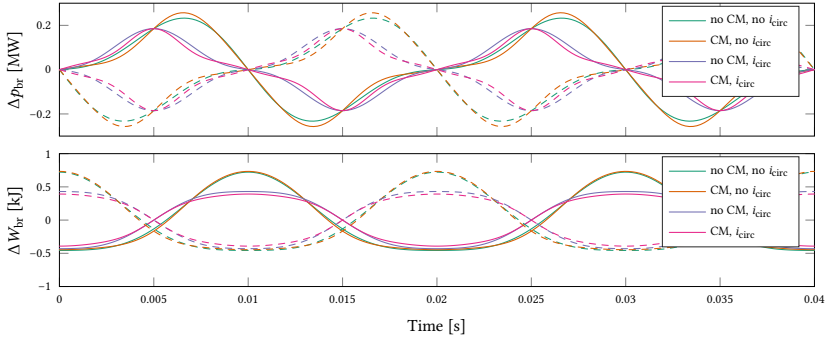
$$\Delta W_{\mathrm{br},+} = \frac{1}{2} C_{\mathrm{br}} v_{C\Sigma,\max}^2 - \frac{1}{2} C_{\mathrm{br}} v_{C\Sigma 0}^{\star 2} \quad \rightarrow \quad C_{\mathrm{br}} = \frac{2\Delta W_{\mathrm{br},+}}{\left[(1+\varepsilon_{v_{C\Sigma}})^2 - 1\right] v_{C\Sigma 0}^{\star 2}}$$

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

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

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

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



MMC CONTROL METHODS

Similarities and differences with other voltage source converters

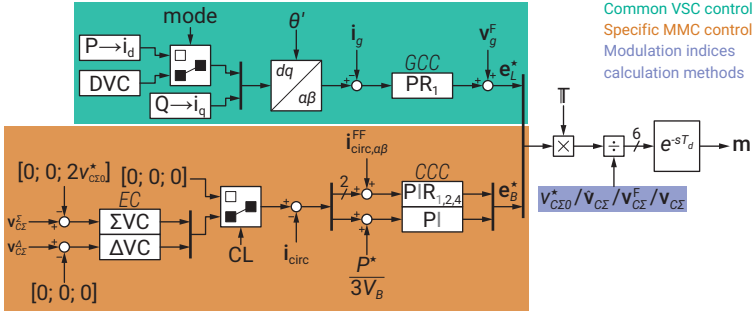
INTRO

Two modes of operation:

1. **Inverter** mode (also called voltage source mode): transferring active power from the dc terminals to the ac terminals
2. **Rectifier** mode (also called current source 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



▲ Simplified MMC control structure

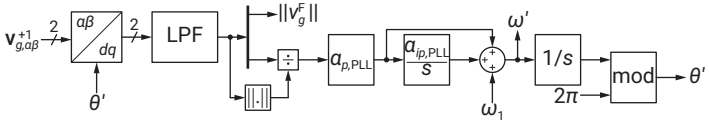
COMMON CONTROL LOOPS: PHASE-LOCKED LOOP (PLL)

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

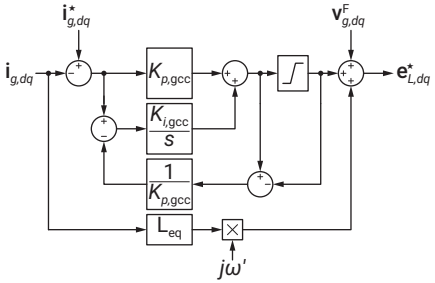


▲ Simple Phase Locked Loop scheme

COMMON CONTROL LOOPS: GRID CURRENT CONTROL (GCC)

PI in *dq* frame

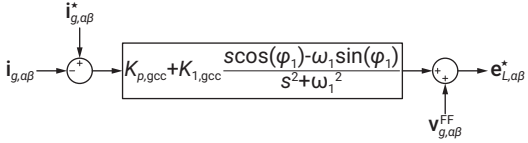
- Track dc components in a rotating reference frame
- Delay compensation by phase advance in the inverse Park transform



▲ Proportional Integral regulator in *dq* frame

PR in *αβ* frame [6]

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

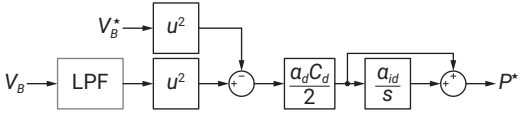


▲ Proportional Resonant regulator in *αβ* frame

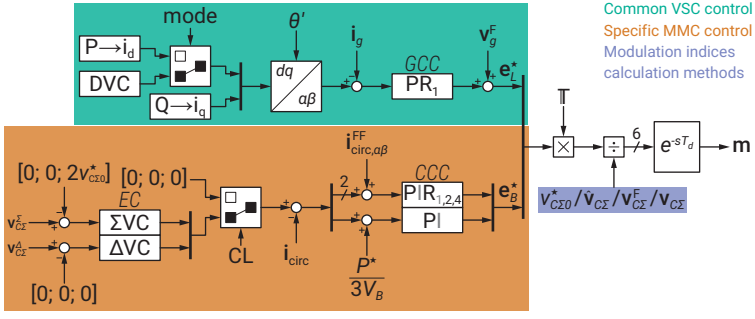
COMMON CONTROL LOOPS: DIRECT VOLTAGE CONTROL (DVC)

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



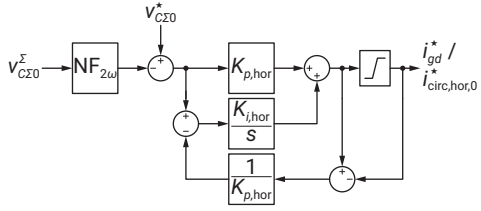
▲ Simplified MMC control structure

MMC SPECIFIC CONTROL LOOPS: ENERGY CONTROL (EC)

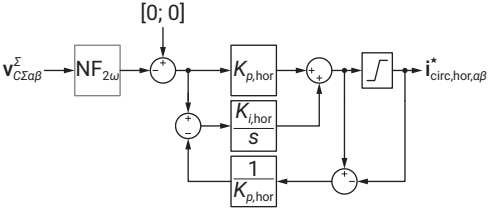
1. **Horizontal balancing**: shift energy between phase-legs using a CM current component
2. **Vertical balancing**: shift energy between branches using a fundamental ac current component

Horizontal balancing

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

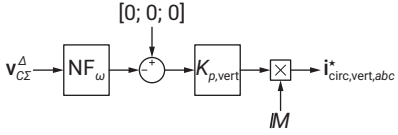


- Optimization of the capacitor voltage ripple with the $\alpha\beta$ components in case notch filters are disabled



Vertical balancing

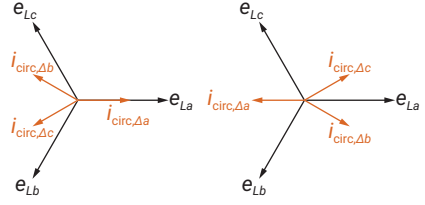
- Using a fundamental ac component



- Major contribution by [7] to cancel the circulating currents from vertical balancing at the dc terminals

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

where θ_L is the load current angle

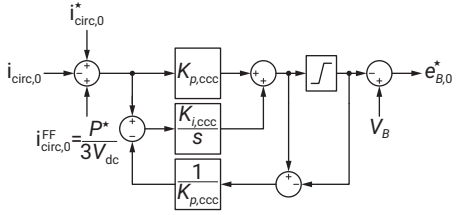


MMC SPECIFIC CONTROL LOOPS: CIRCULATING CURRENT CONTROL (CCC)

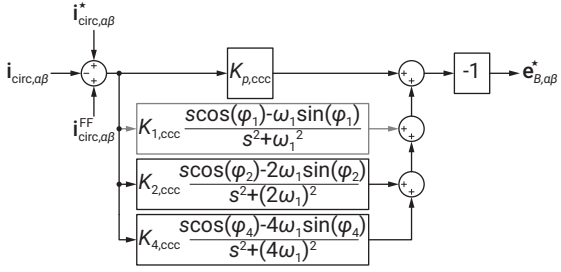
It has been shown in the power equations that the circulating current contains multiple low harmonic frequency components:

- **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 [8]



▲ Circulating Current Controller based on PI regulator



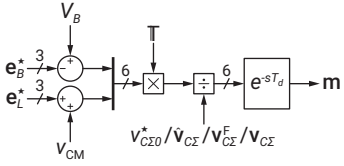
▲ Circulating Current Controller based on multiple PR regulators

MODULATION INDEX CALCULATION METHODS

Direct Modulation

- The modulation indices are calculated from the *desired* dc average value
- **OFF**: energy controllers, odd harm. and integrator on dc in the CCC

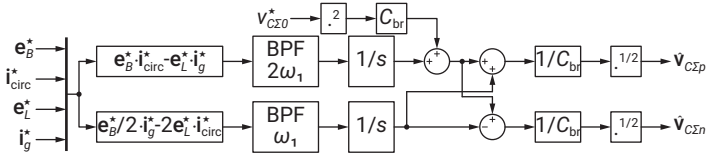
$$m_p = \frac{V_B/2 - e_B^\star/2 - e_L^\star}{v_{C\Sigma 0}^\star} \qquad m_n = \frac{V_B/2 - e_B^\star/2 + e_L^\star}{v_{C\Sigma 0}^\star}$$



Open-Loop Control

- The modulation indices are calculated from *estimates* of the summed branch capacitors in steady-state
- **OFF**: energy controllers, odd harm. and integrator on dc in the CCC

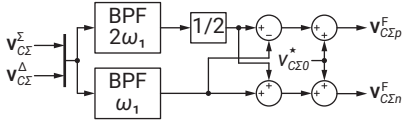
$$m_p = \frac{V_B/2 - e_B^\star/2 - e_L^\star}{\hat{v}_{C\Sigma p}} \qquad m_n = \frac{V_B/2 - e_B^\star/2 + e_L^\star}{\hat{v}_{C\Sigma n}}$$



Hybrid Voltage Control

- The modulation indices are calculated from *filtered values* of the summed branch capacitors measurements
- **OFF**: energy controllers, odd harm. and integrator on dc in the CCC

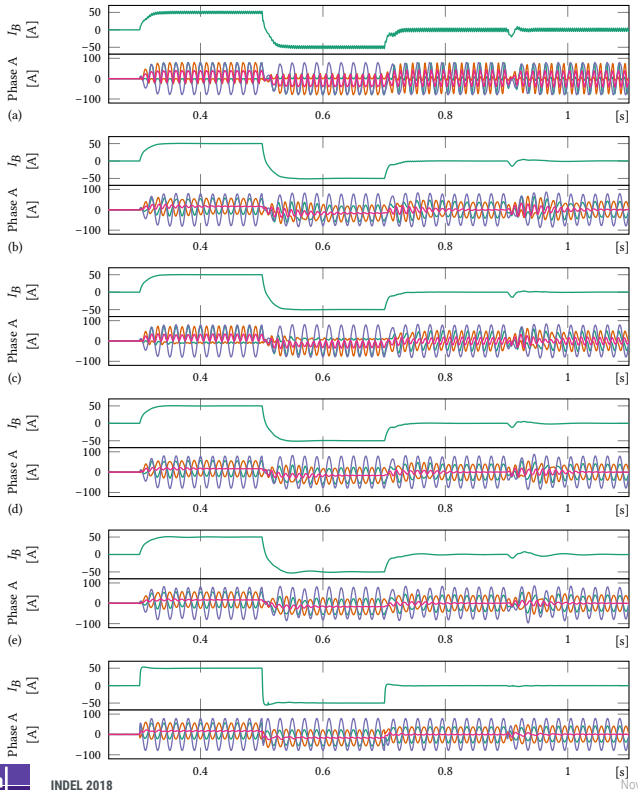
$$m_p = \frac{V_B/2 - e_B^\star/2 - e_L^\star}{v_{C\Sigma p}^F} \qquad m_n = \frac{V_B/2 - e_B^\star/2 + e_L^\star}{v_{C\Sigma n}^F}$$



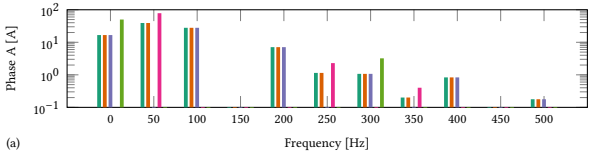
Closed-Loop Control

- The modulation indices are calculated from the *actual measurements* of the summed branch capacitors
- The energy controllers **are enabled**
- The odd harmonics in the circulating current control **are enabled**
- This is by far the most complex control implementation, but at the same time the only method suitable for reaching the best dynamics.

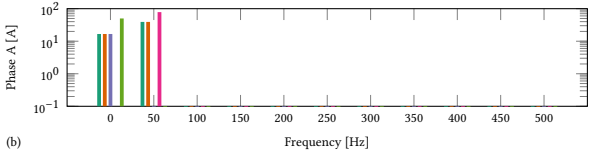
CURRENTS IN INVERTER MODE



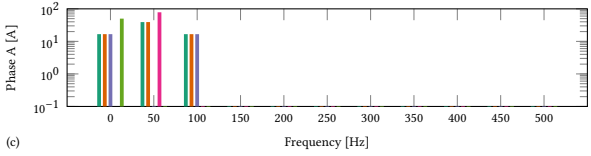
No CCC



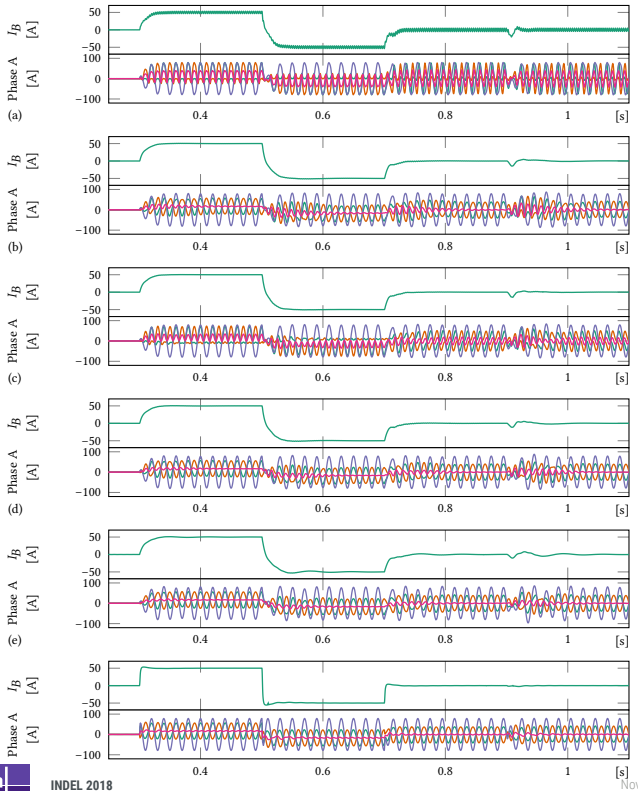
CCSC / CCC dc circ



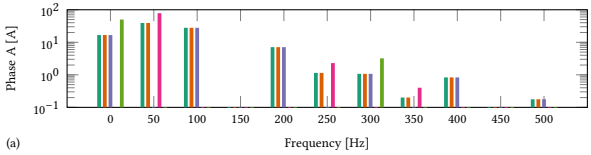
CCSC / CCC + 2nd circ inj



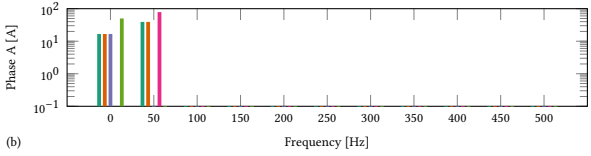
CURRENTS IN INVERTER MODE



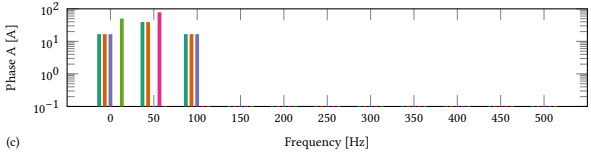
No CCC



CCSC / CCC dc circ

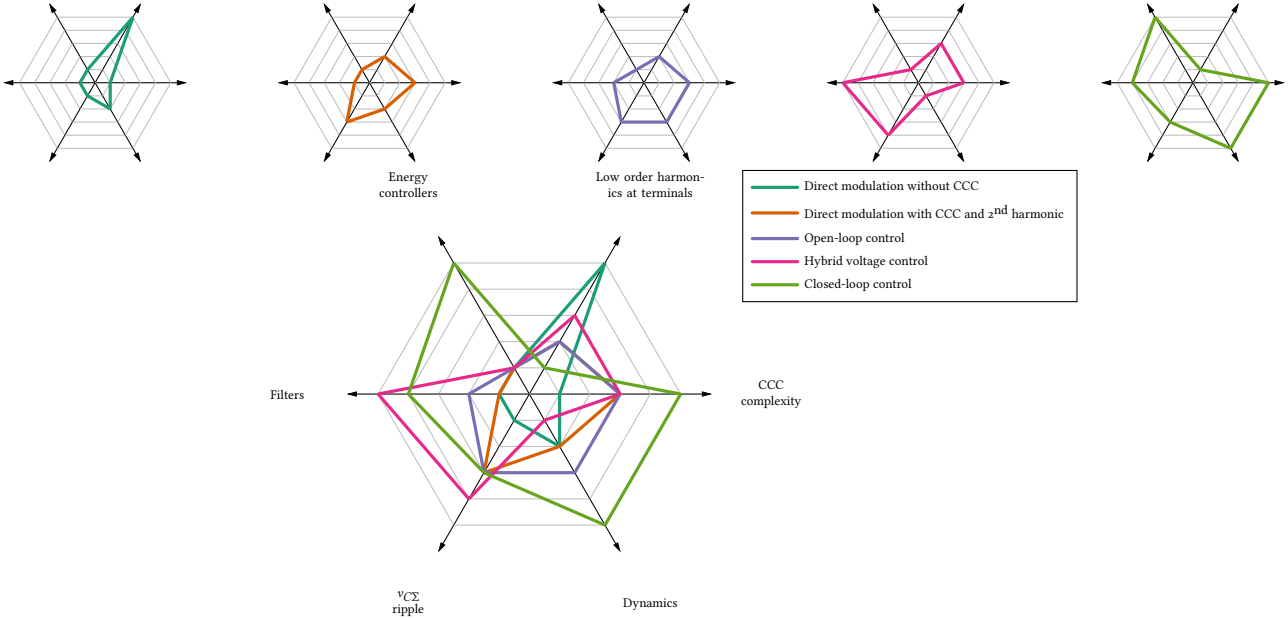


CCSC / CCC + 2nd circ inj



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

CONTROL METHOD PERFORMANCE RATING



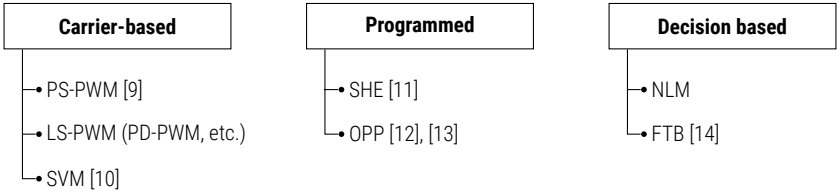
⇒ the final choice depends on the application requirements / acceptable compromises between complexity and performance

MMC MODULATION METHODS

Variety of options are available...

CLASSIFICATION

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

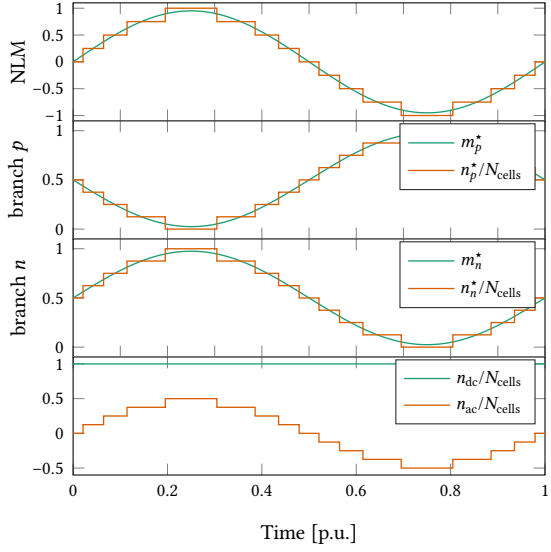


NUMBER OF VOLTAGE LEVELS PER BRANCH

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

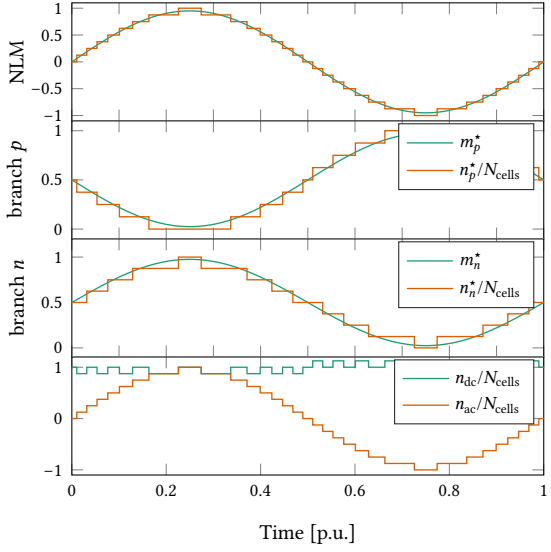
$N + 1$ modulation

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



$2N + 1$ modulation

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



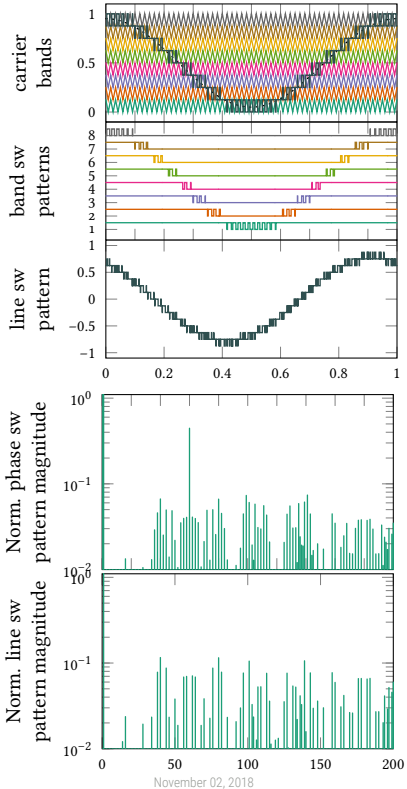
CARRIER-BASED MODULATION

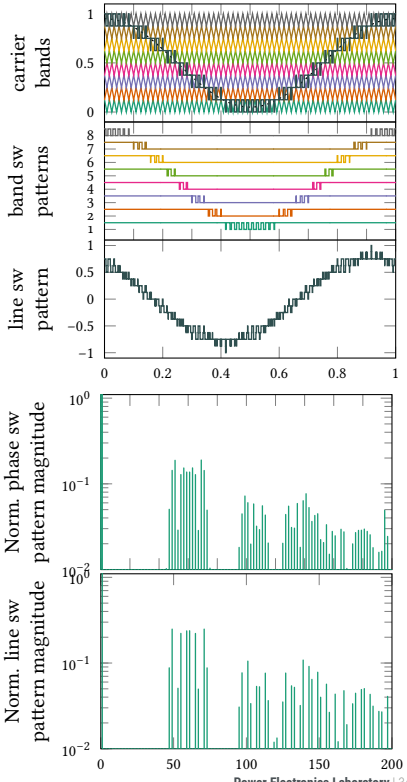
PD-PWM

- 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





SHE AND OPPS

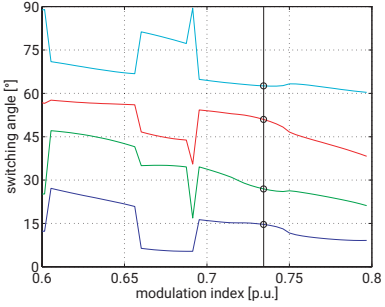
Selective Harmonic Elimination

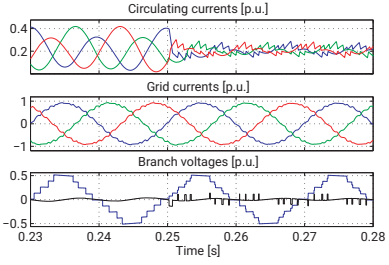
- Cancel one harmonic per switching angle plus 1 angle to set the modulation index over a quarter fundamental period
- Results in continuous switching angles ⇒ linear grid current controller
- $2N + 1$ modulation preferred when it comes to the circulating current control [15]

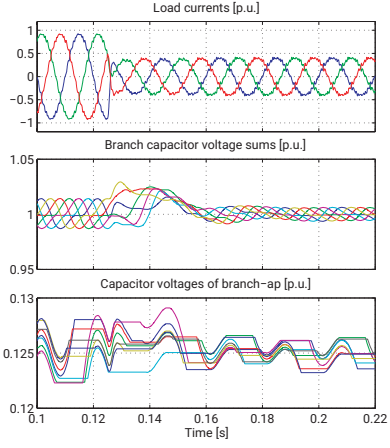
Optimized Pulse Patterns

- 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 [13]

Results with OPPs from [13]





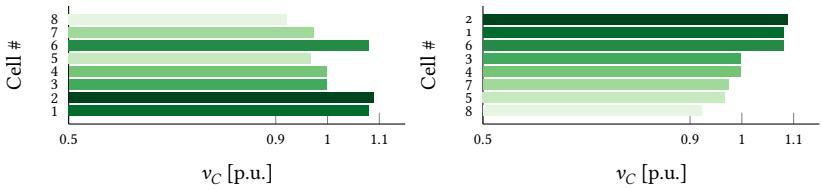


⇒ maximum performance without compromising the switching frequency

SORTING ALGORITHMS

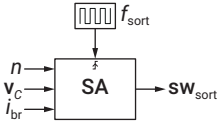
Principle

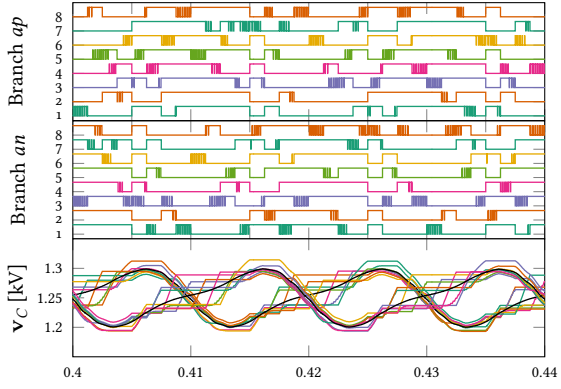
- Depending on the branch current polarity (and switching state), the inserted cells are either charged or discharged



Simple sorting

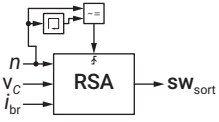
- The sorting algorithm is triggered at f_{sort}
- All switching signals can be modified

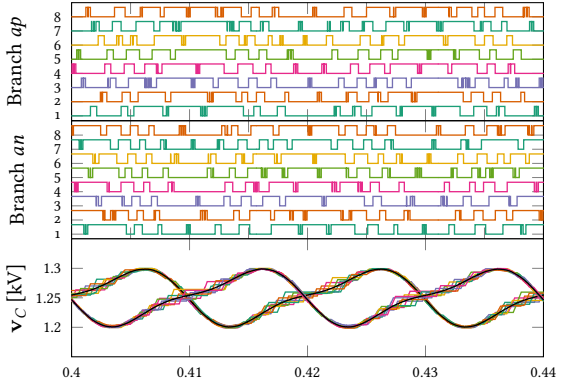




Restricted sorting [16]

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





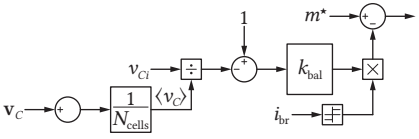
CELL BALANCING WITH DISTRIBUTED MODULATORS

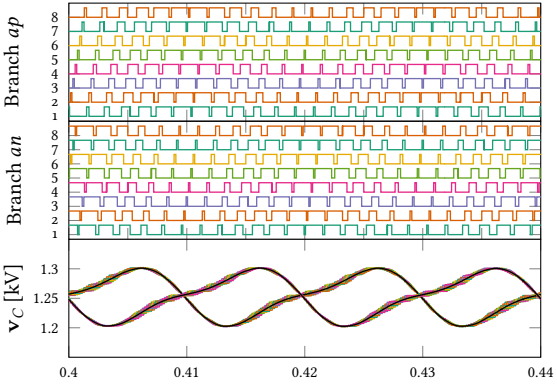
Principle

- The proportional control action cancel out at the branch level

Branch average based

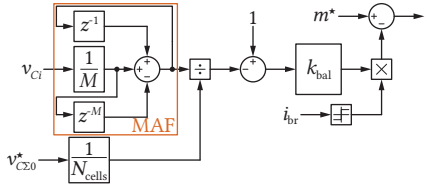
- The *instantaneous* summed branch capacitor average is sent by the branch controller [9]

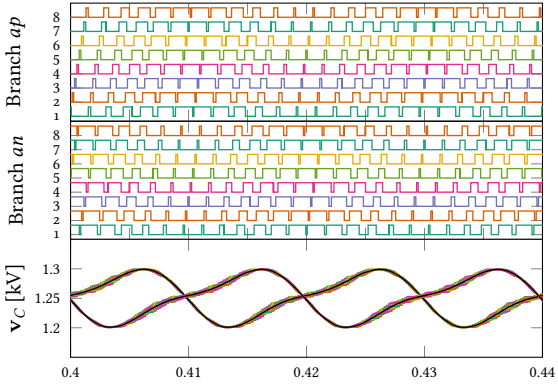




Moving average filter based

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





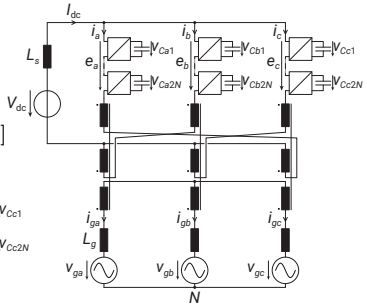
GALVANICALLY ISOLATED MODULAR CONVERTER

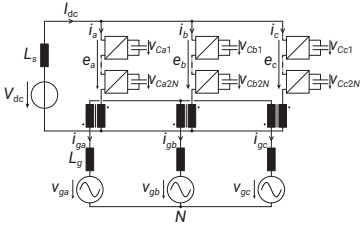
Interleaved and Stacked variants

TRANSFORMER INTEGRATION PROPOSALS IN THE LITERATURE

Open End Winding MMC [17]

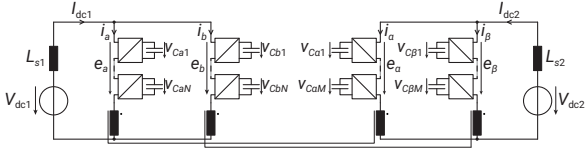
- Only **one** branch per phase-leg
- No CM voltage injection
- No current decoupling
- DC bias in trafo → zig-zag trafo [18]

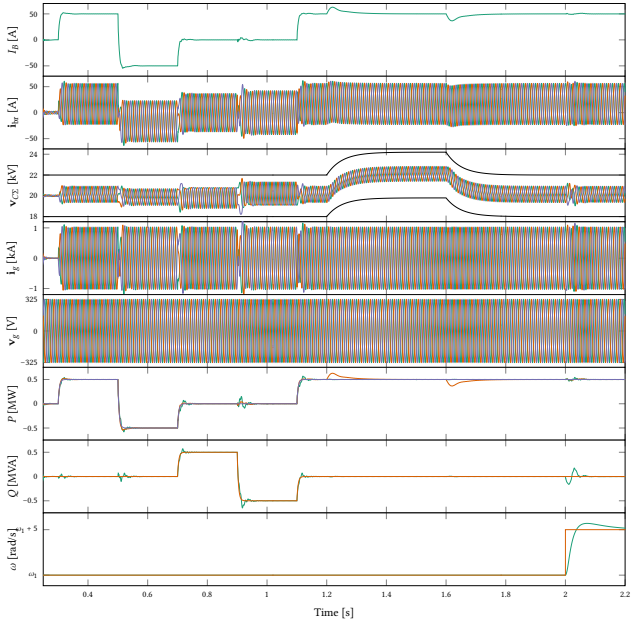




Isolated dc/dc converter [19]

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





TRANSFORMER INTEGRATION PROPOSALS IN THE LITERATURE

Open End Winding MMC [17]

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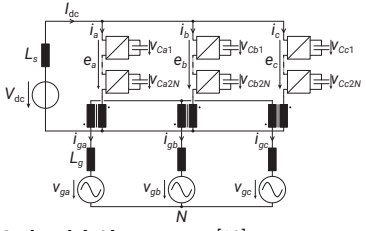
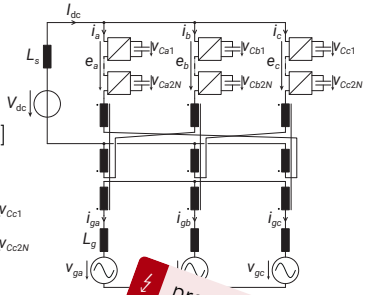
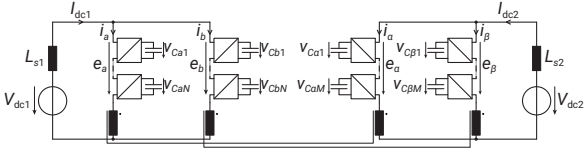


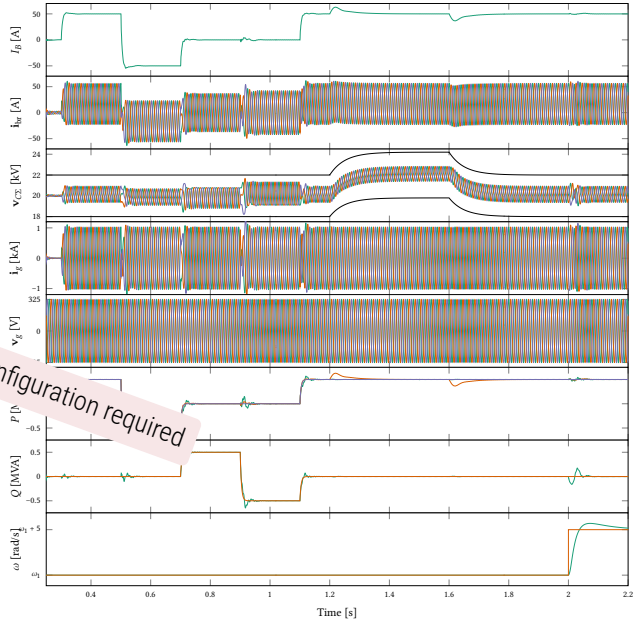


proper transformer configuration required

Isolated dc/dc converter [19]

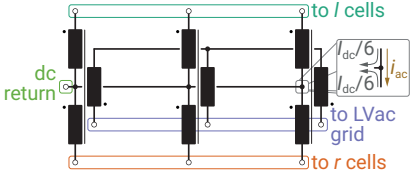
- DC bias cancellation for any operating point
- Two-phase at least





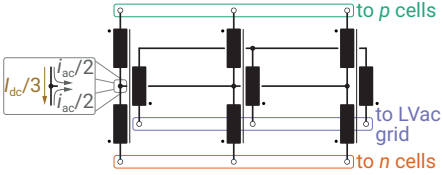
THE GALVANICALLY ISOLATED MODULAR CONVERTER

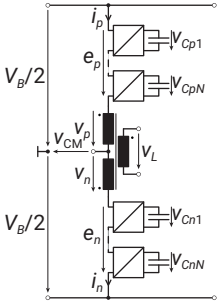
- Multi-windings trafo
- Unification of proposals [20] & [21]
- Dc bias cancellation is effective for any operating point
- Different dc voltage levels can be accommodated with the same branch design

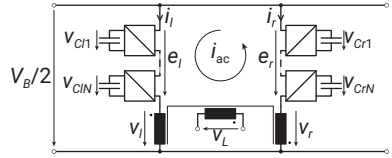


▲ iGIMC trafo

▼ sGIMC trafo







▲ Interleaved GIMC (iGIMC)

◀ Stacked GIMC (sGIMC)

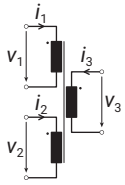
GIMC MODELING

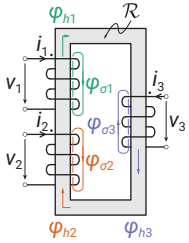
Method

- Carried out once via terminal mapping
- $\mathbf{v} = \mathbb{L}\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{i} + \mathbb{R}\mathbf{i}$

$$\mathbb{L} = \begin{bmatrix} L_{\sigma,\mathrm{HV}} + L_{\mathrm{HV}} & L_{\mathrm{HV}} & M_{\mathrm{LV}} \\ L_{\mathrm{HV}} & L_{\sigma,\mathrm{HV}} + L_{\mathrm{HV}} & M_{\mathrm{LV}} \\ M_{\mathrm{LV}} & M_{\mathrm{LV}} & L_{\sigma,\mathrm{LV}} + L_{\mathrm{LV}} \end{bmatrix}$$

$$\mathbb{R} = \begin{bmatrix} R_{\mathrm{HV}} & 0 & 0 \\ 0 & R_{\mathrm{HV}} & 0 \\ 0 & 0 & R_{\mathrm{LV}} \end{bmatrix}$$





iGIMC

$$v_1 = v_I \qquad i_1 = i_I$$
$$v_2 = -v_r \qquad i_2 = -i_r$$
$$v_3 = v_L \qquad i_3 = -i_g$$

Result:

$$v_B = e_I + e_r + R_{\mathrm{HV}}\left(i_I + i_r\right) + L_{\sigma,\mathrm{HV}}\left(\frac{\mathrm{d}}{\mathrm{d}t}i_I + \frac{\mathrm{d}}{\mathrm{d}t}i_r\right)$$

$$0 = -e_I + e_r + R_{\mathrm{HV}}\left(-i_I + i_r\right) + \left(L_{\sigma,\mathrm{HV}} + 2L_{\mathrm{HV}}\right)\left(-\frac{\mathrm{d}}{\mathrm{d}t}i_I + \frac{\mathrm{d}}{\mathrm{d}t}i_r\right) + 2M_{\mathrm{LV}}\frac{\mathrm{d}}{\mathrm{d}t}i_g - 2v_{\mathrm{CM}}$$

$$v_L = M_{\mathrm{LV}}\left(\frac{\mathrm{d}}{\mathrm{d}t}i_I - \frac{\mathrm{d}}{\mathrm{d}t}i_r\right) - \left(L_{\sigma,\mathrm{LV}} + L_{\mathrm{LV}}\right)\frac{\mathrm{d}}{\mathrm{d}t}i_g - R_{\mathrm{LV}}i_g$$

sGIMC

$$v_1 = v_p \qquad i_1 = i_p$$
$$v_2 = -v_n \qquad i_2 = -i_n$$
$$v_3 = v_L \qquad i_3 = -i_g$$

Result:

$$v_B = e_p + e_n + R_{\mathrm{HV}}\left(i_p + i_n\right) + L_{\sigma,\mathrm{HV}}\left(\frac{\mathrm{d}}{\mathrm{d}t}i_p + \frac{\mathrm{d}}{\mathrm{d}t}i_n\right)$$

$$0 = -e_p + e_n + R_{\mathrm{HV}}\left(-i_p + i_n\right) + \left(L_{\sigma,\mathrm{HV}} + 2L_{\mathrm{HV}}\right)\left(-\frac{\mathrm{d}}{\mathrm{d}t}i_p + \frac{\mathrm{d}}{\mathrm{d}t}i_n\right) + 2M_{\mathrm{LV}}\frac{\mathrm{d}}{\mathrm{d}t}i_g - 2v_{M0}$$

$$v_L = M_{\mathrm{LV}}\left(\frac{\mathrm{d}}{\mathrm{d}t}i_p - \frac{\mathrm{d}}{\mathrm{d}t}i_n\right) - \left(L_{\sigma,\mathrm{LV}} + L_{\mathrm{LV}}\right)\frac{\mathrm{d}}{\mathrm{d}t}i_g - R_{\mathrm{LV}}i_g$$

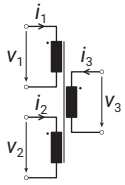
GIMC MODELING

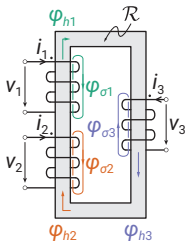
Method

- Carried out once via terminal mapping
- $\mathbf{v} = \mathbb{L}\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{i} + \mathbb{R}\mathbf{i}$

$$\mathbb{L} = \begin{bmatrix} L_{\sigma,\mathrm{HV}} + L_{\mathrm{HV}} & L_{\mathrm{HV}} & M_{\mathrm{LV}} \\ L_{\mathrm{HV}} & L_{\sigma,\mathrm{HV}} + L_{\mathrm{HV}} & M_{\mathrm{LV}} \\ M_{\mathrm{LV}} & M_{\mathrm{LV}} & L_{\sigma,\mathrm{LV}} + L_{\mathrm{LV}} \end{bmatrix}$$

$$\mathbb{R} = \begin{bmatrix} R_{\mathrm{HV}} & 0 & 0 \\ 0 & R_{\mathrm{HV}} & 0 \\ 0 & 0 & R_{\mathrm{LV}} \end{bmatrix}$$





same as for conventional MMC

iGIMC

$$v_1 = v_l \qquad i_1 = i_l$$
$$v_2 = -v_r \qquad i_2 = -i_r$$
$$v_3 = v_L \qquad i_3 = -i_g$$

Result:

$$v_B = e_l + e_r + R_{\mathrm{HV}}(i_l + i_r) + L_{\sigma,\mathrm{HV}}\left(\frac{\mathrm{d}}{\mathrm{d}t}i_l + \frac{\mathrm{d}}{\mathrm{d}t}i_r\right)$$

$$0 = -e_l + e_r + R_{\mathrm{HV}}(-i_l + i_r) + (L_{\sigma,\mathrm{HV}} + 2L_{\mathrm{HV}})\left(-\frac{\mathrm{d}}{\mathrm{d}t}i_l + \frac{\mathrm{d}}{\mathrm{d}t}i_r\right) + 2M_{\mathrm{LV}}\frac{\mathrm{d}}{\mathrm{d}t}i_g - 2v_{\mathrm{CM}}$$

$$v_L = M_{\mathrm{LV}}\left(\frac{\mathrm{d}}{\mathrm{d}t}i_l - \frac{\mathrm{d}}{\mathrm{d}t}i_r\right) - (L_{\sigma,\mathrm{LV}} + L_{\mathrm{LV}})\frac{\mathrm{d}}{\mathrm{d}t}i_g - R_{\mathrm{LV}}i_g$$

sGIMC

$$v_1 = v_p \qquad i_1 = i_p$$
$$v_2 = -v_n \qquad i_2 = -i_n$$
$$v_3 = v_L \qquad i_3 = -i_g$$

Result:

$$v_B = e_p + e_n + R_{\mathrm{HV}}(i_p + i_n) + L_{\sigma,\mathrm{HV}}\left(\frac{\mathrm{d}}{\mathrm{d}t}i_p + \frac{\mathrm{d}}{\mathrm{d}t}i_n\right)$$

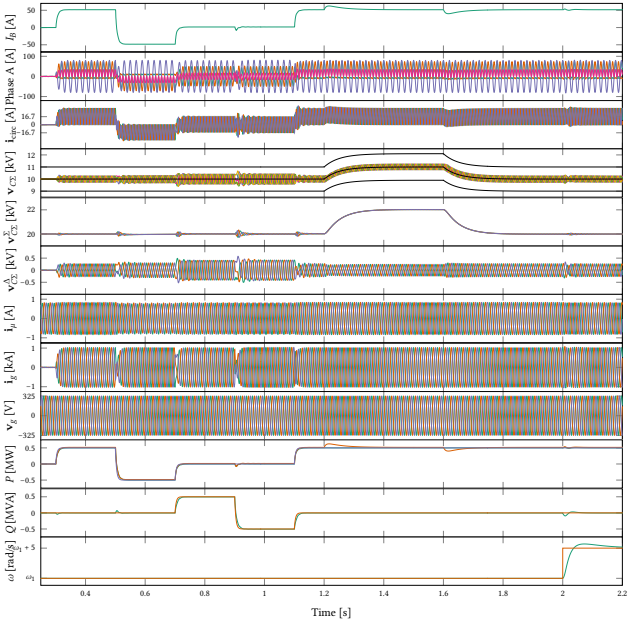
$$0 = -e_p + e_n + R_{\mathrm{HV}}(-i_p + i_n) + (L_{\sigma,\mathrm{HV}} + 2L_{\mathrm{HV}})\left(-\frac{\mathrm{d}}{\mathrm{d}t}i_p + \frac{\mathrm{d}}{\mathrm{d}t}i_n\right) + 2M_{\mathrm{LV}}\frac{\mathrm{d}}{\mathrm{d}t}i_g - 2v_{MO}$$

$$v_L = M_{\mathrm{LV}}\left(\frac{\mathrm{d}}{\mathrm{d}t}i_p - \frac{\mathrm{d}}{\mathrm{d}t}i_n\right) - (L_{\sigma,\mathrm{LV}} + L_{\mathrm{LV}})\frac{\mathrm{d}}{\mathrm{d}t}i_g - R_{\mathrm{LV}}i_g$$

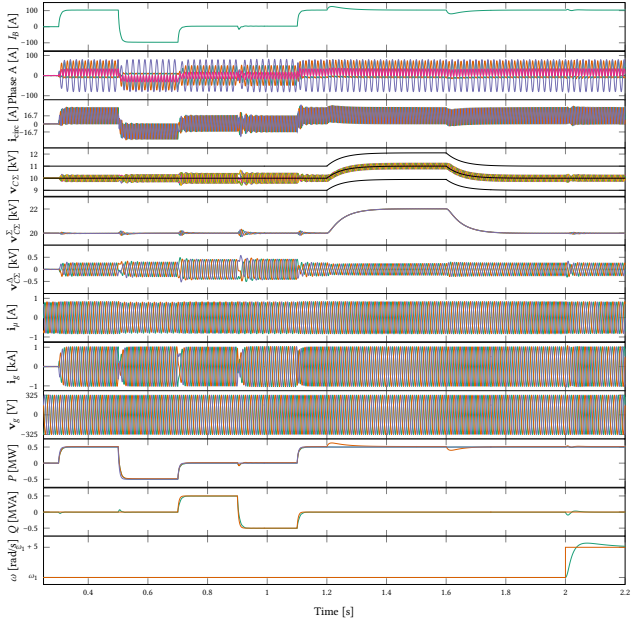
GIMC OPERATION

- **Inverter** mode operation

sGIMC



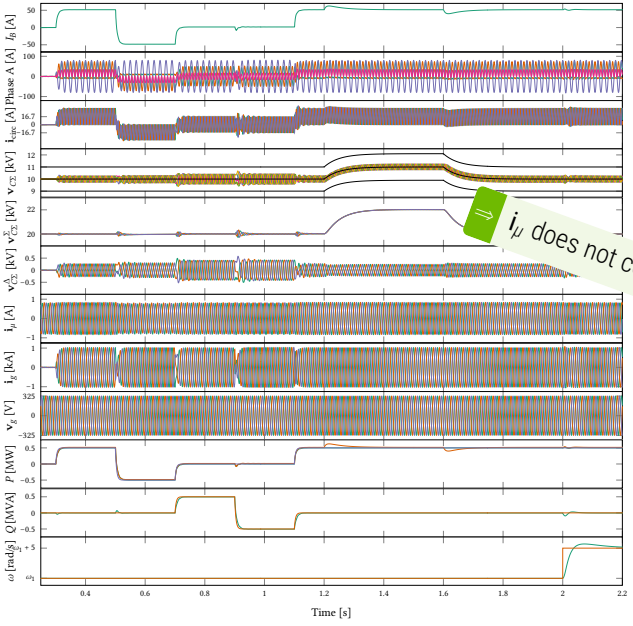
iGIMC



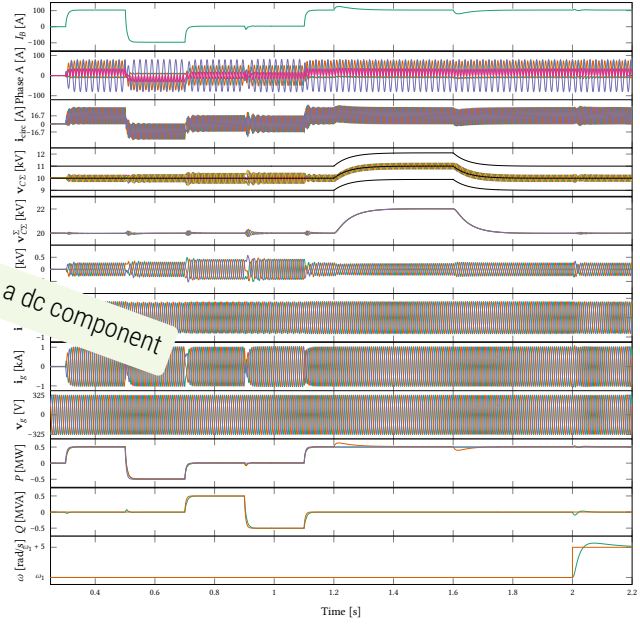
GIMC OPERATION

- **Inverter** mode operation

sGIMC



iGIMC



MAGNETIC COMPONENTS DESIGN

How much gain with the integrated magnetic component?

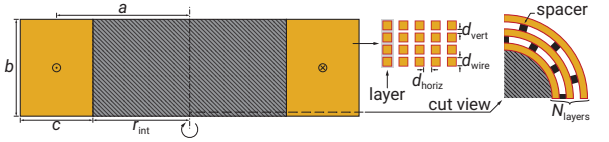
AIR-CORE BRANCH INDUCTOR SIZING

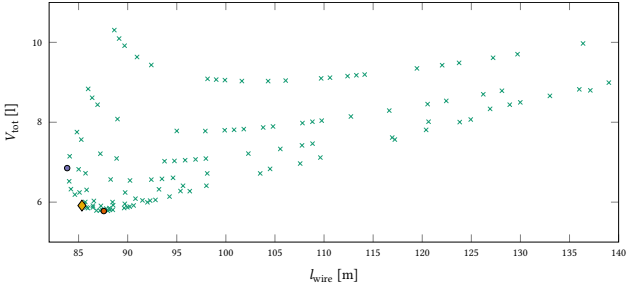
Design space

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

Analytical designs

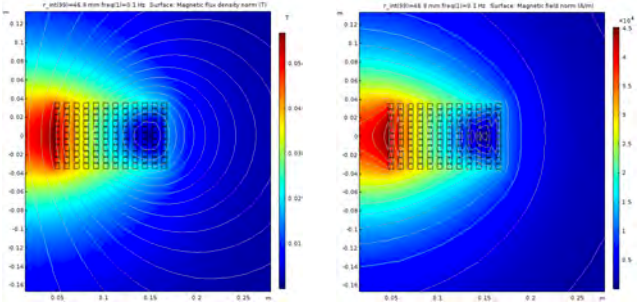
- $L_{Welsby} = \dfrac{\mu_0 N^2 \pi a^2}{b} \dfrac{1}{1 + 0.9\frac{a}{b} + 0.32\frac{c}{a} + 0.84\frac{c}{b}}\,[\text{H}]$
- Cost function: $J_{cost} = \sqrt{\left(\frac{l_{wire}}{10}\right)^2 + V_{tot}^2}$





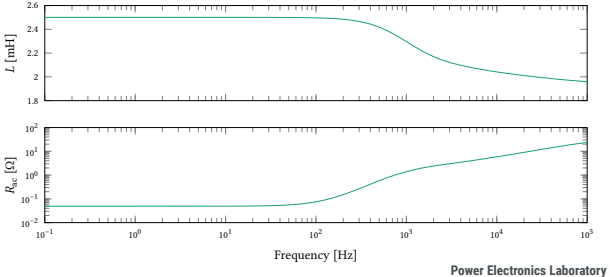
Optimal design

- $N_{turns} = 132$, $N_{layers} = 12$, $r_{int} = 42.4\,\text{mm} \overset{\text{FEM opt}}{\rightarrow} 42.6\,\text{mm}$
- $V_{tot} \approx 6\,\text{l}$
- $P_{losses} = 130\,\text{W}$



▲ COMSOL frequency analysis @ 0.1 Hz (← B-field / → H-field)

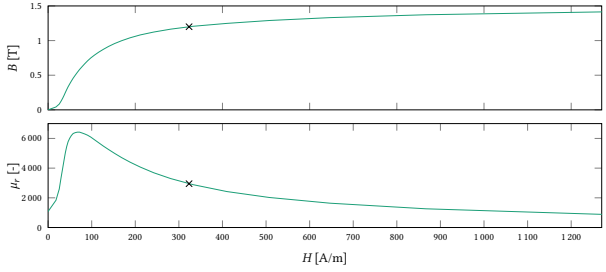
▼ Impedance between 0.1 Hz and 100 kHz

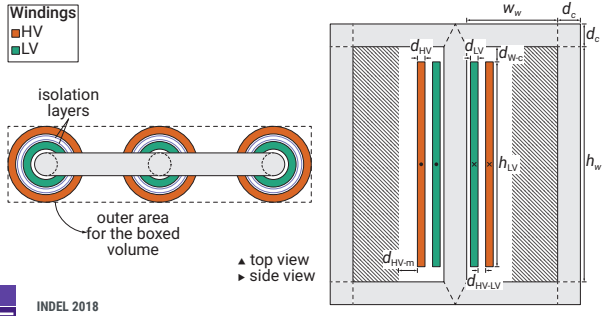


LFT DESIGN

Design

- Three-limb dry-type transformer
- Short-circuit impedance > 5 %
- Silicon steel (M19 from AK Steel): $B_{max} = 1.2\,T \Rightarrow i_\mu = 1.37\,\%$
- $V_{t2t} = 10\,V$
- $J_{HV} = 2.5\,A/mm^2$, $J_{LV} = 2\,A/mm^2$



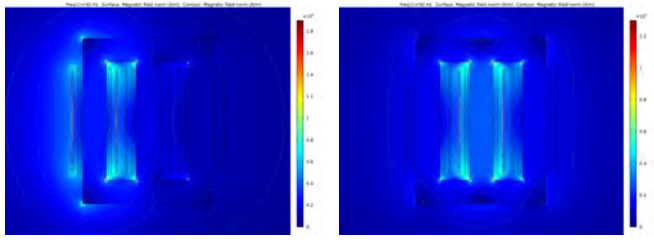


Core's permeance model

- Single unknown: $w_w = \dfrac{4\mu_0\mu_r A_c - \mathcal{P}_c^\star(6+\pi)d_c}{(4+6\alpha)\mathcal{P}_c^\star}$

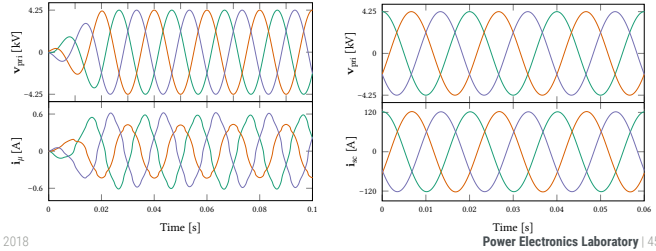
Best design

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



▲ Leakage H-field in COMSOL @ 50 Hz (← phase *a* / → phase *b*)

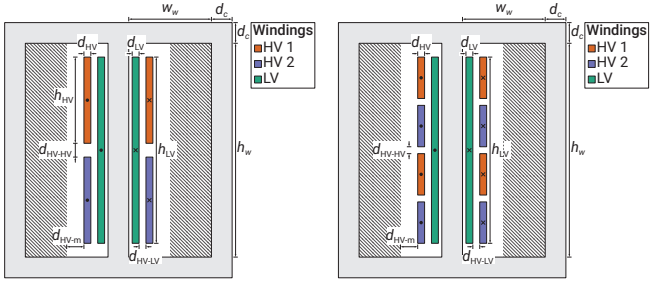
▼ Time domain simulations (← no-load / → short-circuit)



GIMC TRANSFORMER DESIGN

Degree of freedom

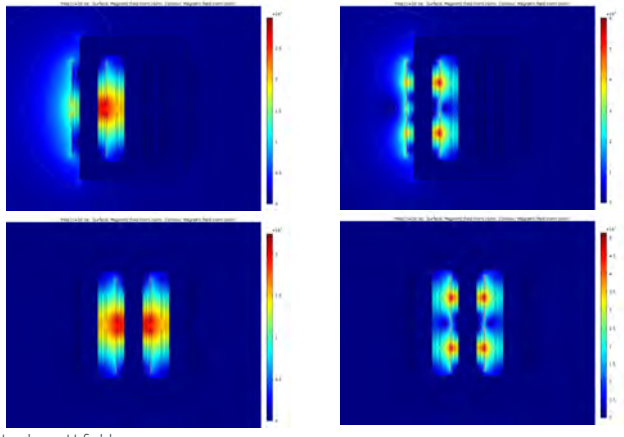
- HV windings interleaving
- Leakage inductance (i.e., branch inductance) tuning



Best design

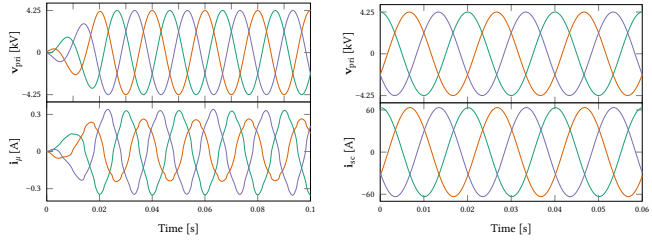
- $w_w = 259.8$ mm and $\alpha = 4$
- $V_{tot} = 573.1$ l
- $P_{w,HV} = 63.29$ W and $P_{w,LV} = 30.93$ W

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



▲ Leakage H-fields

▼ Time domain simulations (← no-load / → short-circuit)



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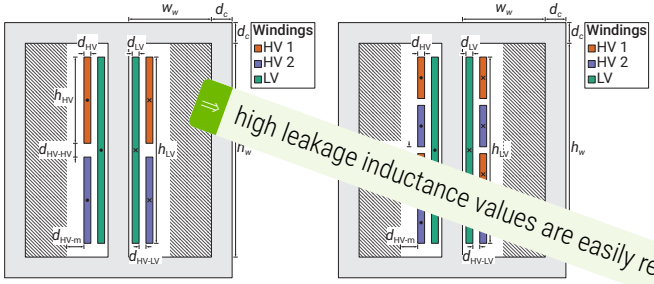

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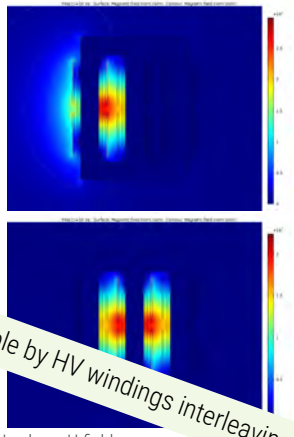

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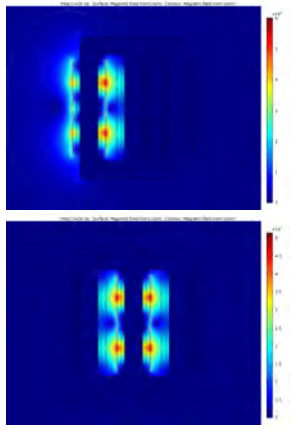
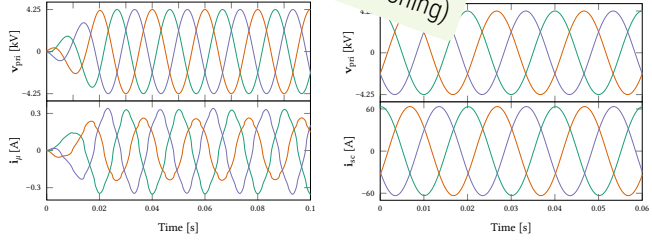


high leakage inductance values are easily reachable by HV windings interleaving (+ positioning)

▲ Leakage H-fields

▼ Time domain simulations (← no-load /



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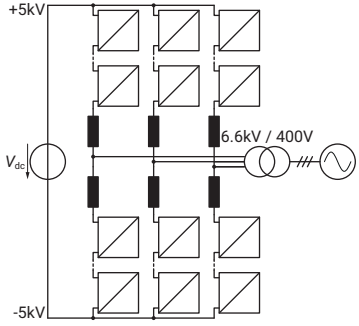
- $P_{w,\mathrm{HV}} = 63.29$ W and $P_{w,\mathrm{LV}} = 30.93$ W

MAGNETIC COMPONENTS COMPARISON

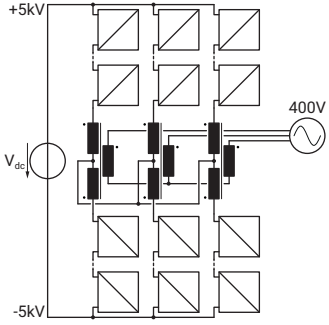
Case 1 MMC

- 6 branch inductors + conventional LFT



Case 2 GIMC

- no branch inductors + multi-windings transformer



	Branch inductors		Transformer	
	volume	losses	volume	losses
DC/3-AC MMC	6× 6 l	780 W (0.156 %)	481.7 l	660 W (0.132 %)
GIMC	-	-	573.1 l	945 W (0.19 %)

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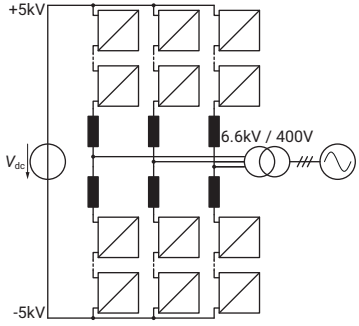

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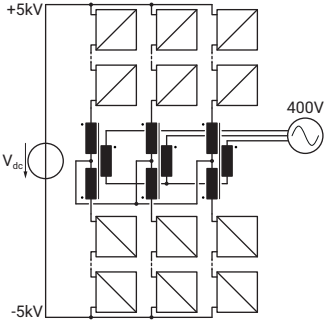

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DC/3-AC MMC	6× 6 l	780 W (0.156 %)	481.7 l	660 W (0.132 %)
GIMC	-	-	573.1 l	945 W (0.19 %)

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

HP DC-DC CONVERTERS

Building blocks of Solid State Transformers

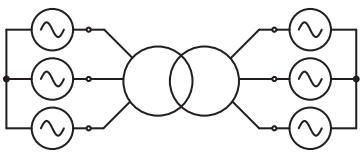
SOLID-STATE TRANSFORMER (SST)

Concept and motivation?

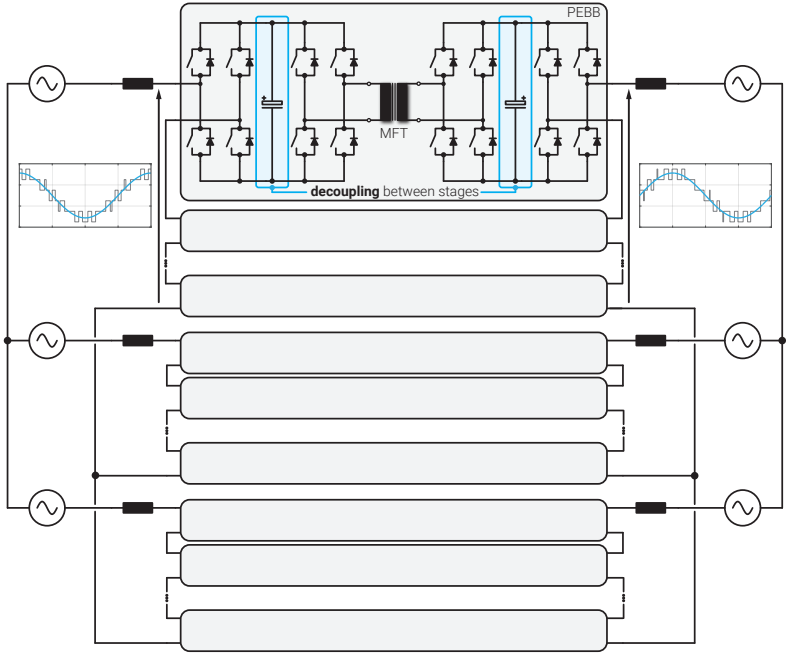
- SST = Switching stages + Isolation
- Firstly envisioned within AC grids
- Power Electronic Building Blocks (PEBBs)
- Conventional transformer vs SST?
- Operating frequency increase **(MFT)**

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

Advantages at the expense of reduced efficiency!



▲ Conventional AC grid transformer



▲ Solid-State Transformer employed with the aim of interfacing two AC systems [22], [23]

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

Characteristics

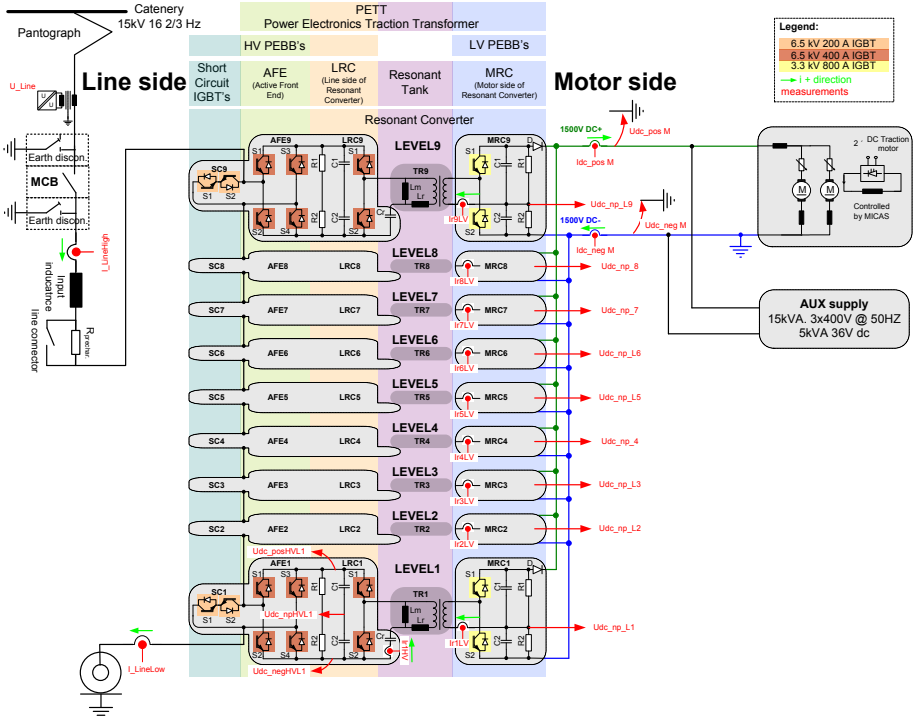
- 1-Phase MVAC to MVDC
- Power: 1.2MVA
- Input AC voltage: 15kV, 16.7Hz
- Output DC voltage: 1500 V
- 9 cascaded stages (n + 1)
- input-series output-parallel
- double stage conversion

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 [24], [25]

SOLID STATE TRANSFORMER FOR TRACTION - DESIGN

Retrofitted to shunting locomotive

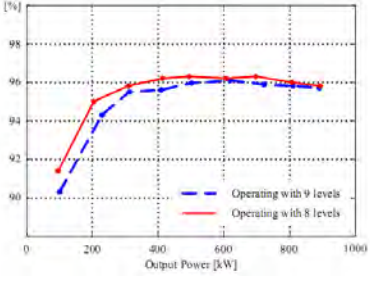
- Replaced LFT + SCR rectifier
- Propulsion motor - 450kW
- 12 months of field service
- No power electronic failures
- Efficiency around 96%
- Weight: ≈ 4.5 t

Technologies

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

Displayed at:

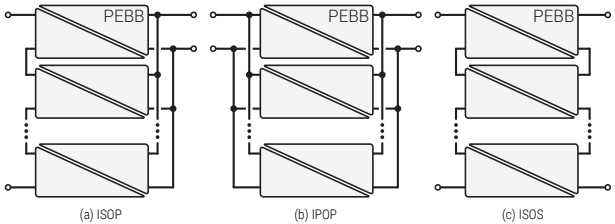
- Swiss Museum of Transport
- https://www.verkehrshaus.ch



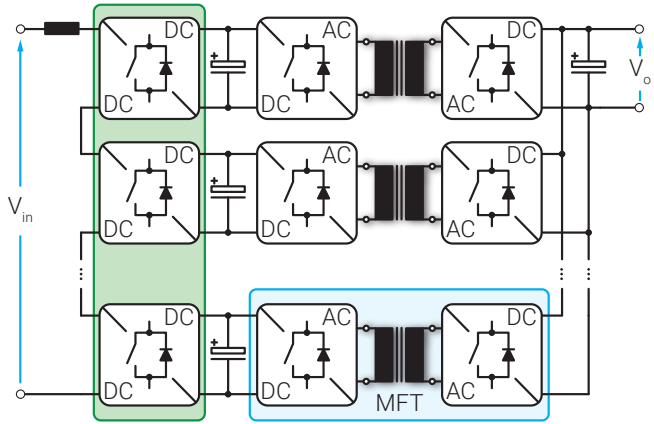
▲ ABB PETT prototype [24], [25]

Fractional power processing

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



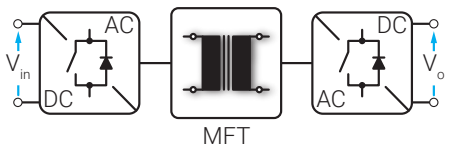
▲ Different structures employed depending upon the voltage level



▲ ISOP Structure

Bulk power processing

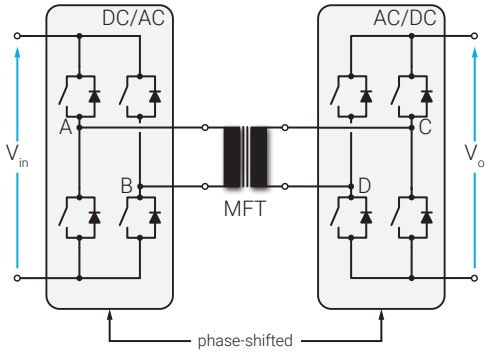
- Single MFT
- Isolation solved only once
- Various configurations/operating principles



▲ Bulk power processing concept

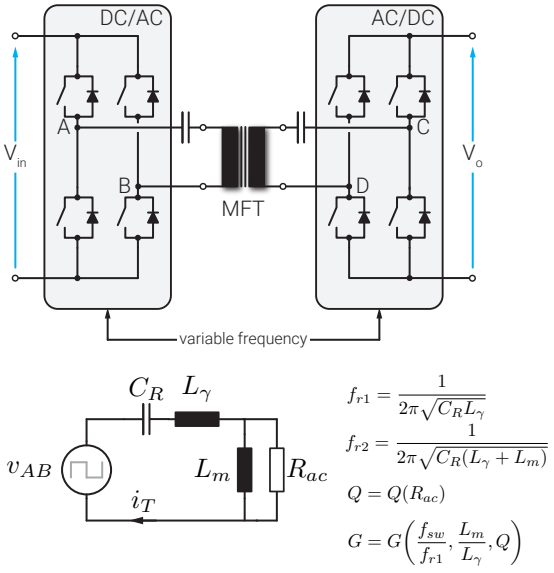
COMMON PEBB CONFIGURATIONS

Dual-Active Bridge



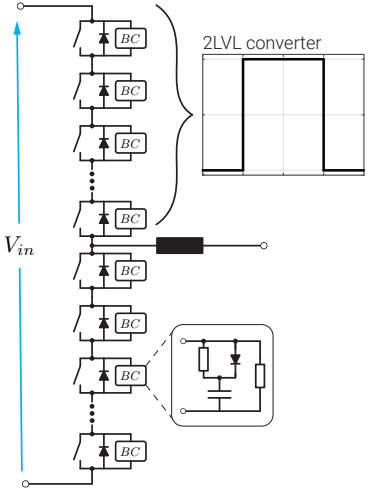
▲ Dual Active Bridge [26]

Resonant Converters



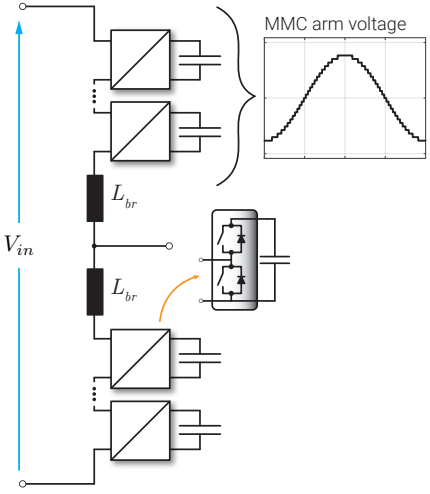
▲ LCL Resonant Converter

HOW TO HANDLE HIGH/MEDIUM VOLTAGES?



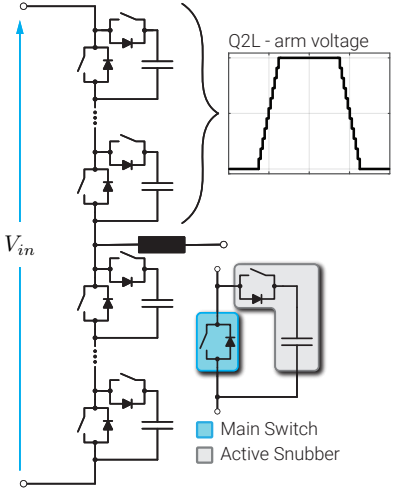
▲ Series connection of switches [27]

- 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

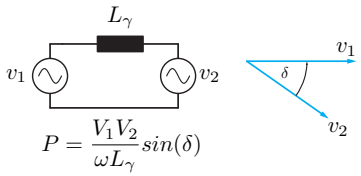


▲ Quasi Two-Level (Q2L) Converter [28], [29]

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

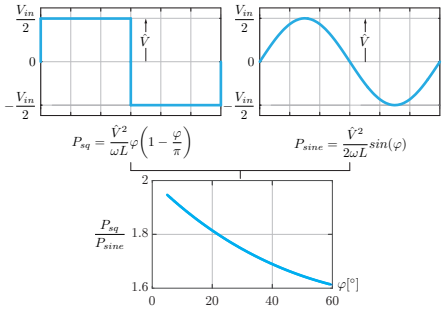
MMC-BASED DUAL ACTIVE BRIDGE (DAB)

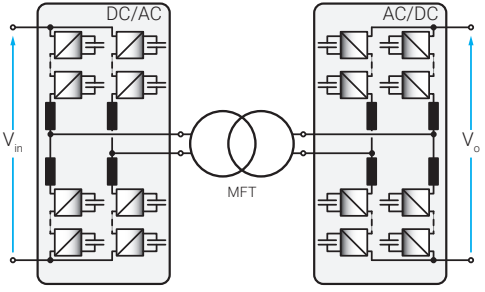
- Basic operation principles are retained
- Easy to comprehend (AC equivalent)



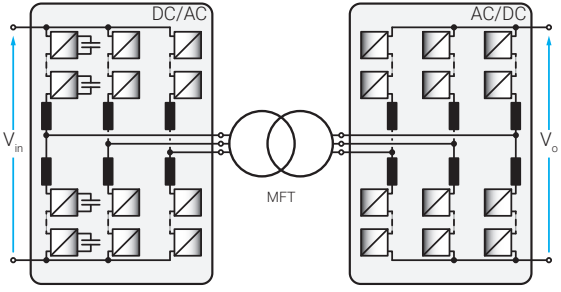
Challenges?

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





▲ MMC-based 1PH-DAB [30]



▲ MMC-based 3PH-DAB

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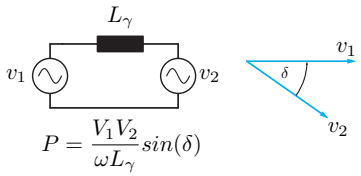

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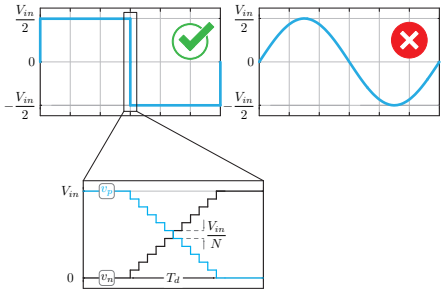

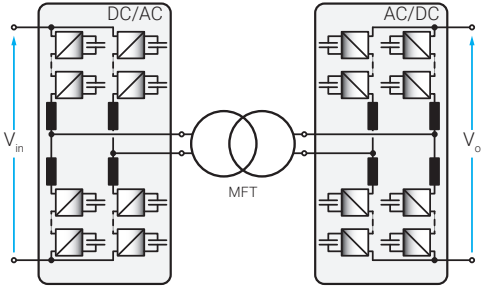

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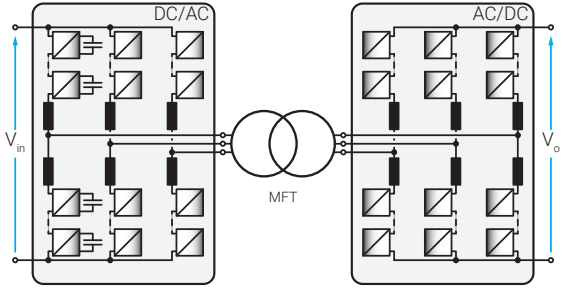
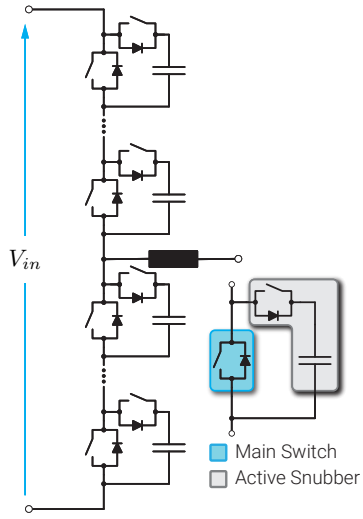


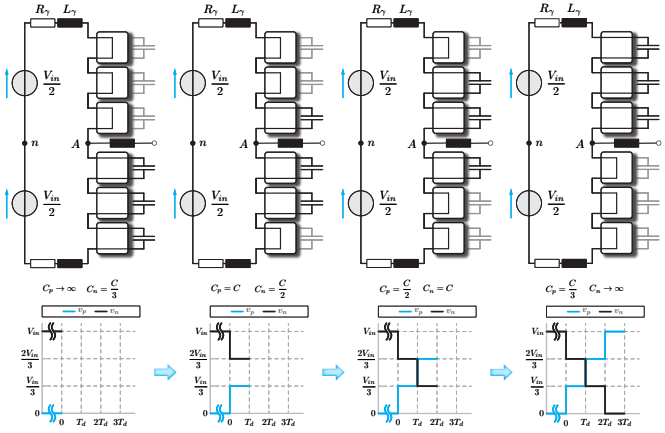
▲ MMC-based 3PH-DAB

QUASI TWO-LEVEL (Q2L) CONVERTER

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



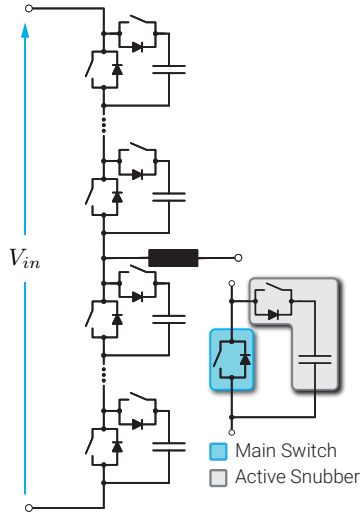
▲ Quasi Two-Level Converter



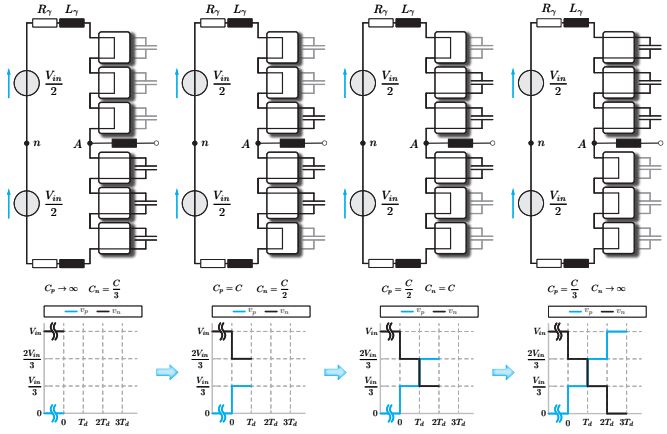
▲ Example of the Q2L Converter transition (N=3)

QUASI TWO-LEVEL (Q2L) CONVERTER

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



▲ Quasi Two-Level Converter



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

Every dwell interval introduces new resonant parameters to the circuit!

QUASI TWO-LEVEL (Q2L) CONVERTER

- MMC-alike structure
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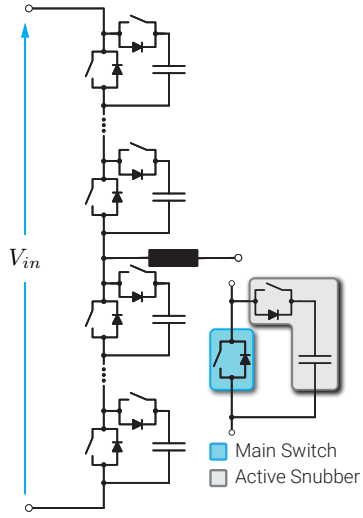
- Sequential insertion/bypassing of SMs



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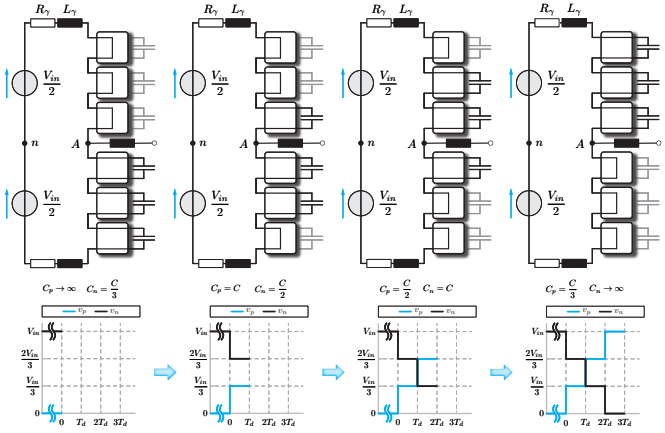
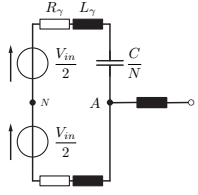


▲ Example of the Q2L Converter transition (N=3)



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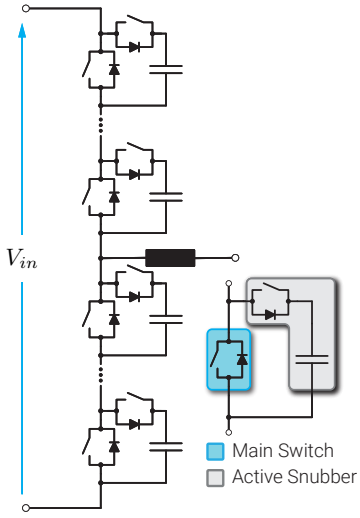
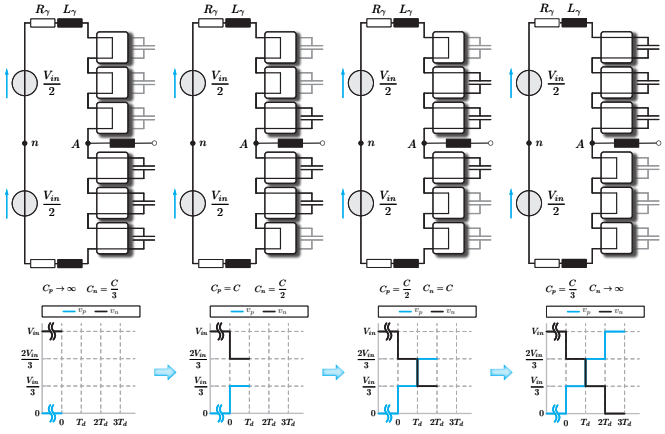
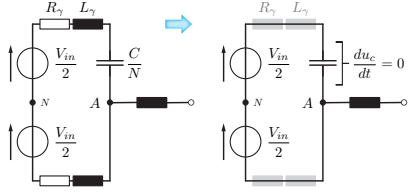


▲ Quasi Two-Level Converter



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



QUASI TWO-LEVEL (Q2L) CONVERTER

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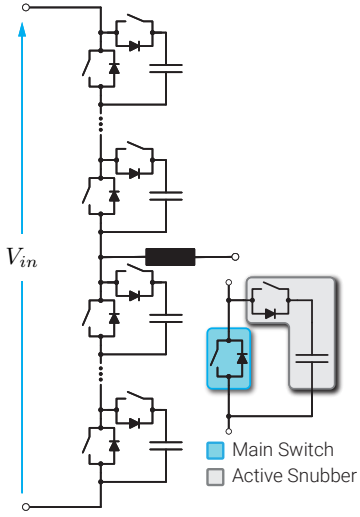
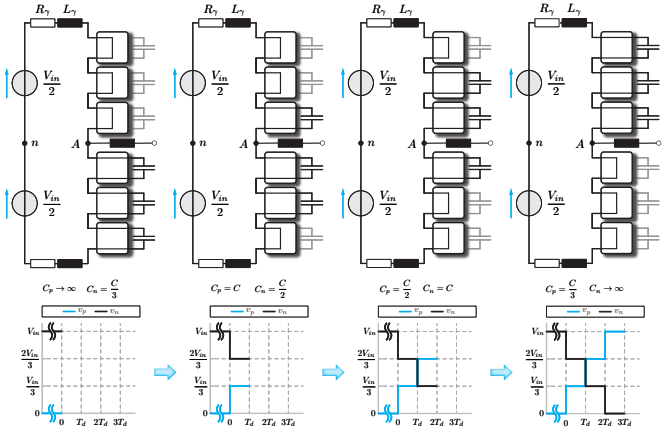
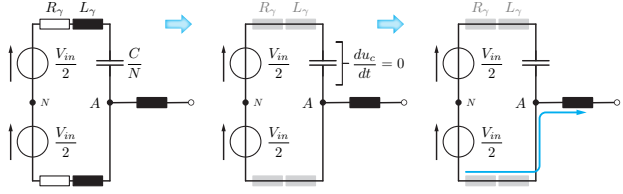


▲ Quasi Two-Level Converter



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



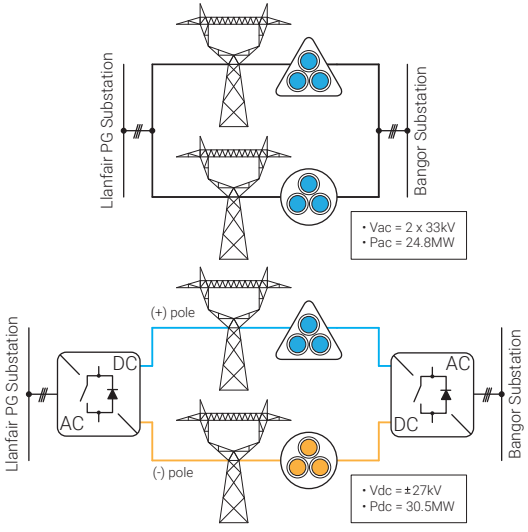
⇒ Output current drifts to a single branch. Common mode current does not exist!

MMC-BASED DC-DC CONVERTERS UTILIZING SCOTT TRANSFORMER CONNECTION

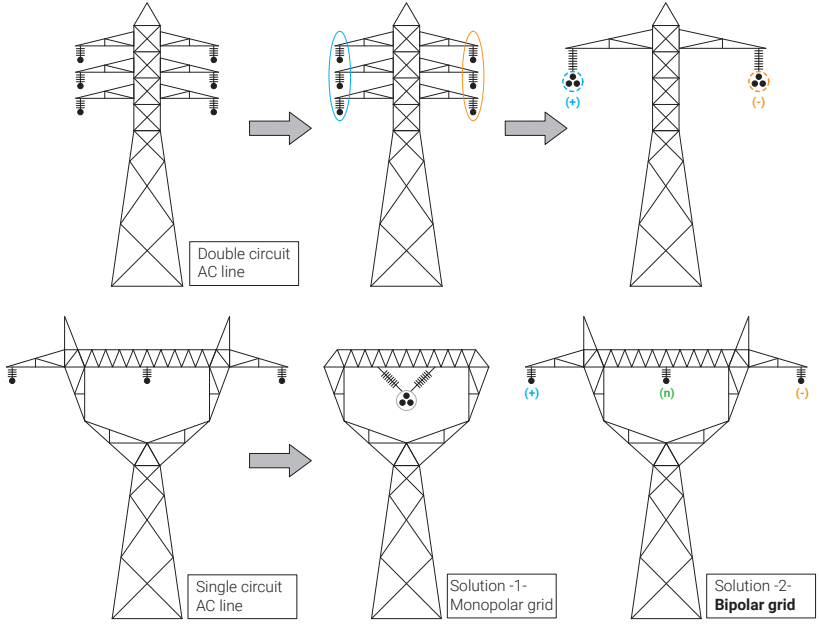
Medium Frequency Conversion, High Power, Redundancy ...

MOTIVATION - 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



▲ Angle DC Project - UK



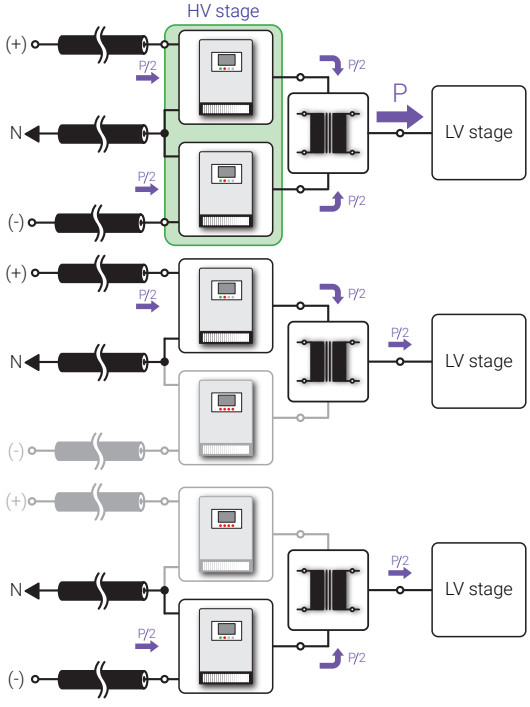
▲ Conversion of two typical AC lines into DC [31], [32], [33], [34]

MVDC BIPOLAR POWER DISTRIBUTION NETWORKS

- Provided ratings

Parameter	Value
Input voltage (V_{in})	±20kV
Output voltage (V_o)	1.5kV
Rated power (P_{nom})	10MW
Operating frequency (f)	1kHz

- **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

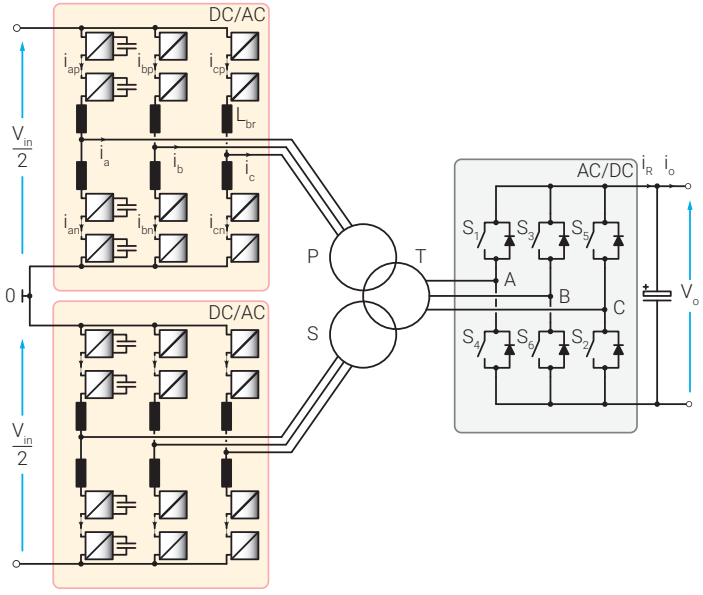
SIX-STEP MMC-BASED HIGH POWER DC-DC CONVERTER

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

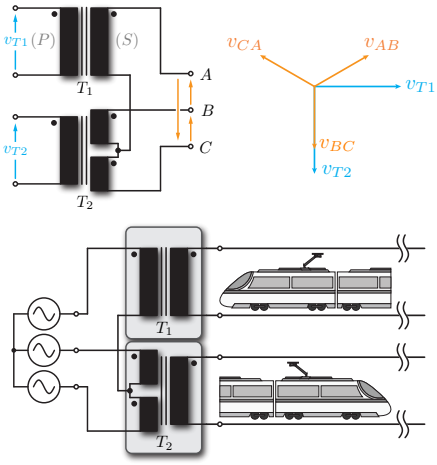
Drawbacks?

- Twelve arm inductors (or six coupled inductors)
- Magnetic coupling (circulating currents)



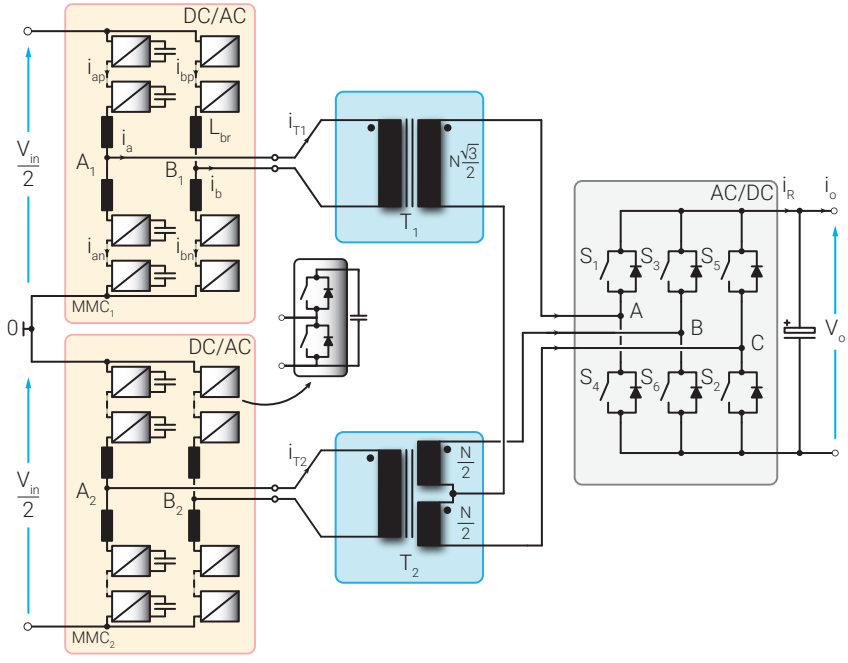
▲ Six-Step MMC-Based High Power DC-DC Converter [35]

MMC-BASED BIDIRECTIONAL DC-DC CONVERTER EMPLOYING STC[2]



▲ Scott Transformer Connection

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



▲ MMC-Based High Power DC-DC Converter Employing Scott Transformer Connection [36]

[2] S. Milovanović, D. Dujić, "MMC-Based High Power DC-DC Converter Employing Scott Transformer." PCIM Europe 2018

OPERATING PRINCIPLES

- MMCs independent operation

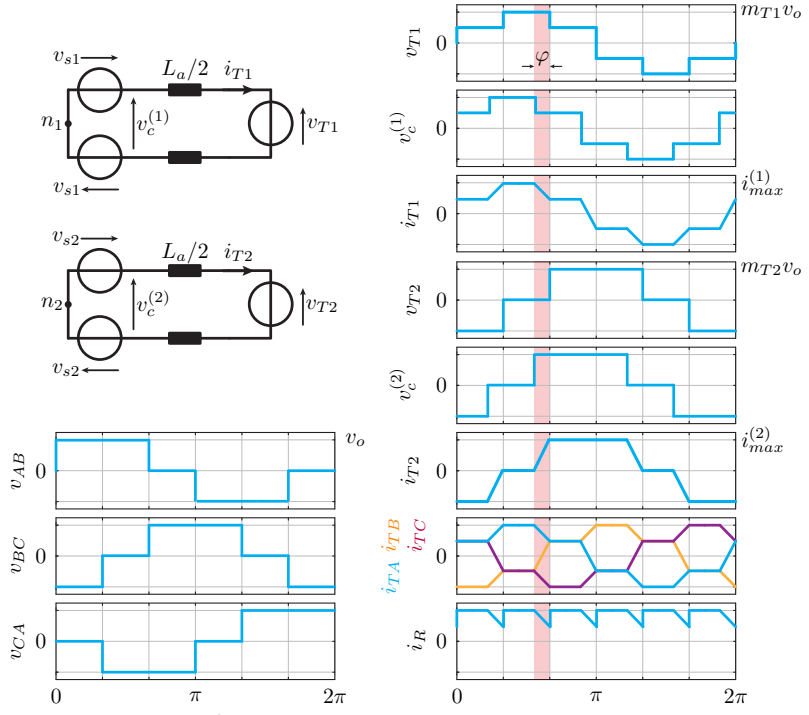
$$V_{T1} = m_{T1}\frac{V_{AB} - V_{CA}}{2}$$
$$V_{T2} = m_{T2}V_{BC}$$

- Suitable HV side voltages (V_{c1}, V_{c2})?
- DAB behavior (phase modulated converter)

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

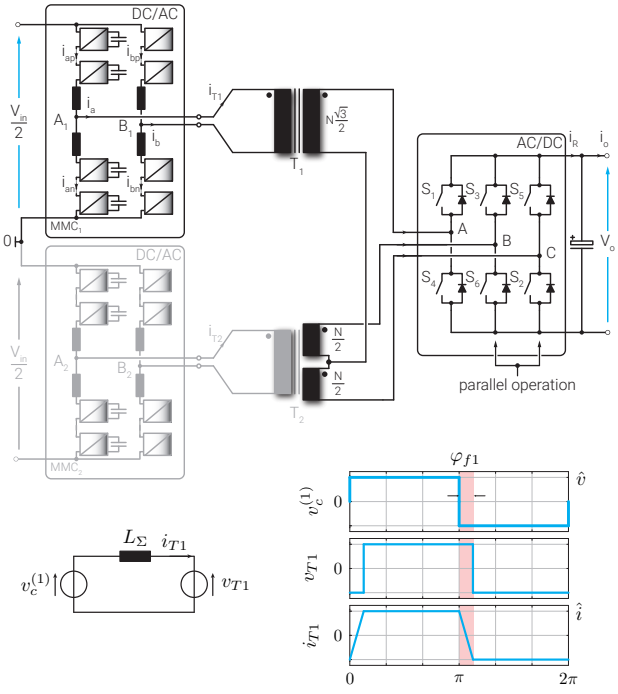
$$\left(m_{T1} == \frac{2}{\sqrt{3}}m_{T2}\right) \wedge \left(\varphi_1 == \varphi_2\right)$$
$$\Rightarrow P_1 = P_2$$

- Bidirectional topology
- Fundamental frequency switching
- Redundant under faults

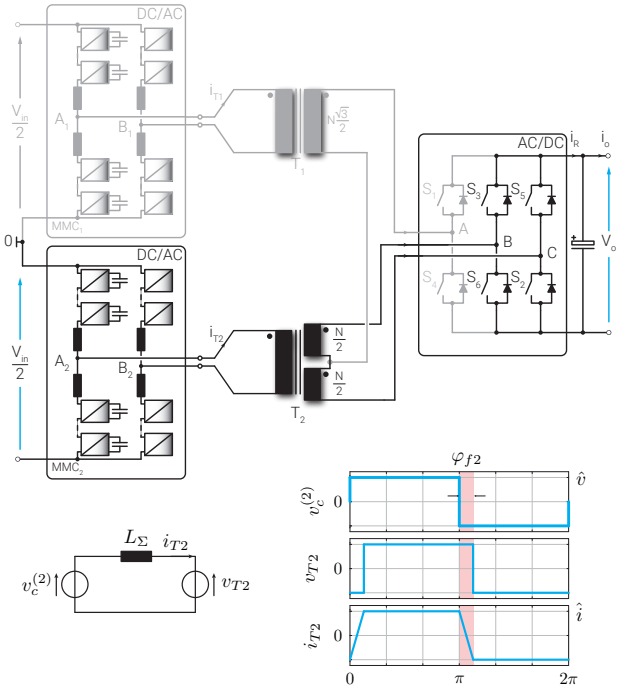


▲ Converter idealized operating waveforms

OPERATION UNDER FAULTS

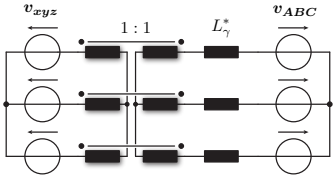


▲ Converter operation in the case of "Minus" DC pole malfunction



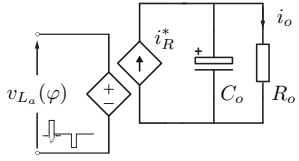
▲ Converter operation in the case of "Plus" DC pole malfunction

- 3PH-DAB equivalent model



$$\boldsymbol{v_{xyz}} = \boldsymbol{v_{ABC}} e^{j\varphi}$$
$$L_\gamma^* = \frac{L_a}{2m_{T2}^2}$$

- Linearization

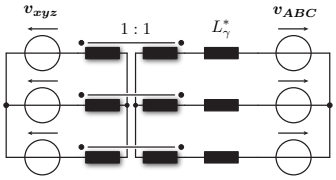


▲ SSC equivalent circuit seen from the LV side

$$V_o \overline{i_R} = 2\frac{m_{T1}^2 V_o^2}{\omega L_a} \underbrace{\varphi\left(\frac{1}{2} - \frac{3\varphi}{8\pi}\right)}_{\textit{Linearized!}}$$

$$\Rightarrow \overline{i_R} \approx \frac{7m_{T1}^2 V_o^*}{8\omega L_a}\varphi$$

- 3PH-DAB equivalent model



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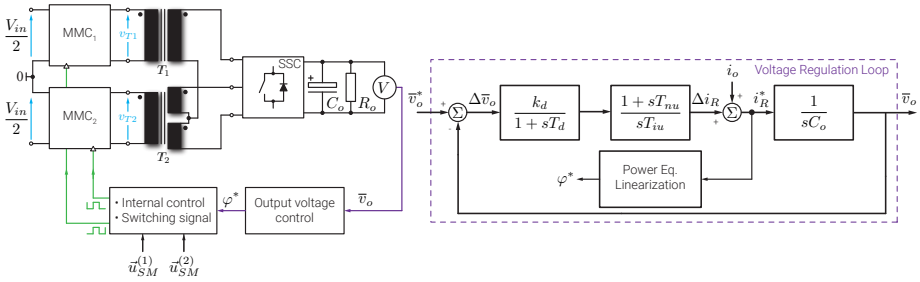
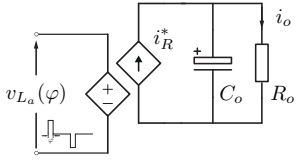


▲ STC-based SST Control block scheme

- Linearization



▲ SSC equivalent circuit seen from the LV side

$$V_o \overline{i_R} = 2\frac{m_{T1}^2 V_o^2}{\omega L_a} \underbrace{\varphi\left(\frac{1}{2} - \frac{3\varphi}{8\pi}\right)}_{\textit{Linearized!}}$$

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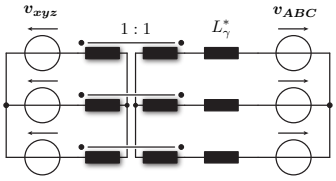

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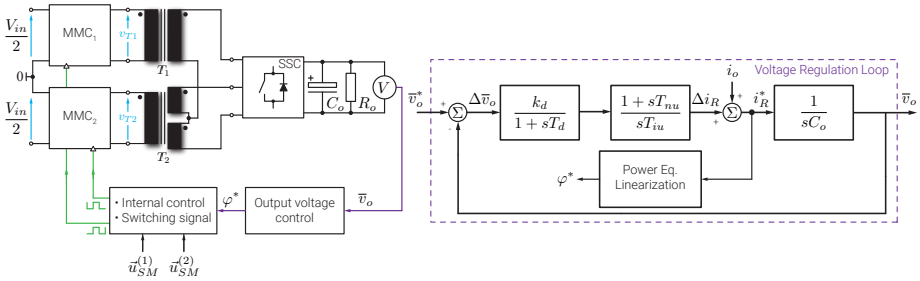
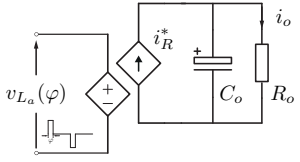
$$L_\gamma^* = \frac{L_a}{2m_{T2}^2}$$



▲ STC-based SST Control block scheme

- Linearization



▲ SSC equivalent circuit seen from the LV side

? What if $P_1 \neq P_2$ for any reason?

$$V_o \overline{i_R} = 2\frac{m_{T1}^2 V_o^2}{\omega L_a} \underbrace{\varphi\left(\frac{1}{2} - \frac{3\varphi}{8\pi}\right)}_{\text{Linearized!}}$$

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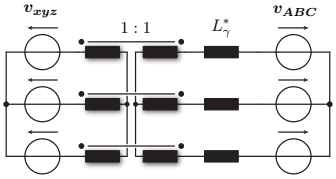
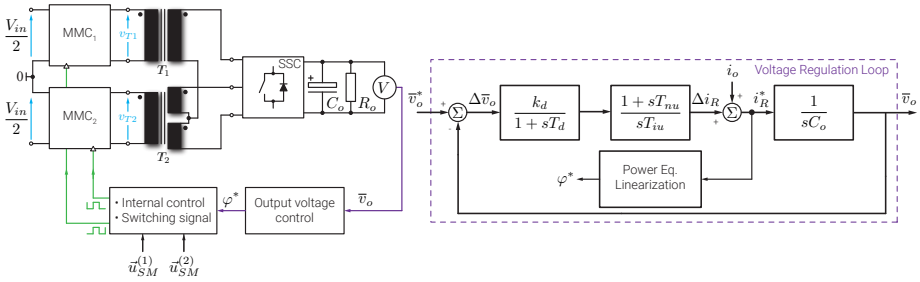


$$v_{xyz} = v_{ABC} e^{j\varphi}$$
$$L_\gamma^* = \frac{L_a}{2m_{T2}^2}$$



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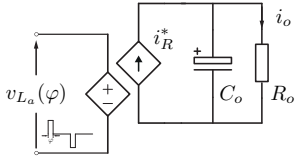

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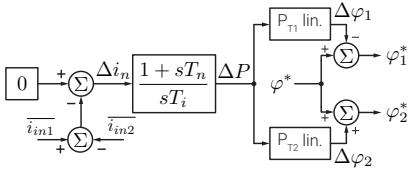
$$\Rightarrow \overline{i_R} \approx \frac{7m_{T1}^2 V_o^*}{8\omega L_a}\varphi$$

$$\Delta P_{T1}^{lin} = \frac{7V_o^2 m_{T1}^2}{16\omega L_a}\Delta\varphi_1$$

$$\Delta P_{T2}^{lin} = \frac{7V_o^2 m_{T2}^2}{12\omega L_a}\Delta\varphi_2$$

? What if $P_1 \neq P_2$ for any reason?



▲ Power balance loop

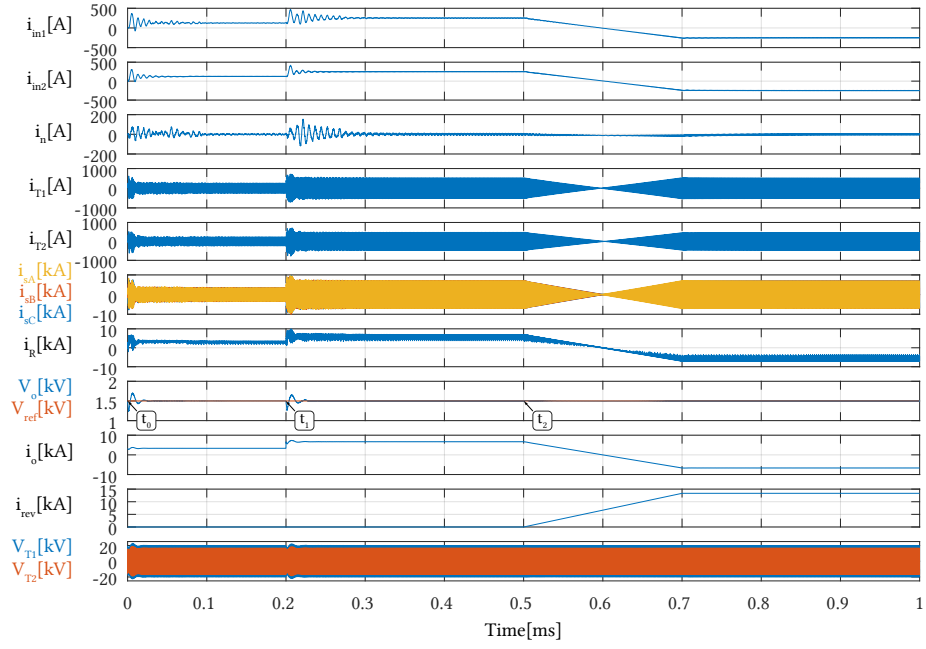
⇒ Additional control compensates small power mismatches!

SIMULATION RESULTS (I)

Table 1 Simulated system ratings

Parameter	Value
Input voltage (V_{in})	±20kV
Output voltage (V_o)	1.5kV
Rated power (P_{nom})	10MW
Operating frequency (f)	1kHz

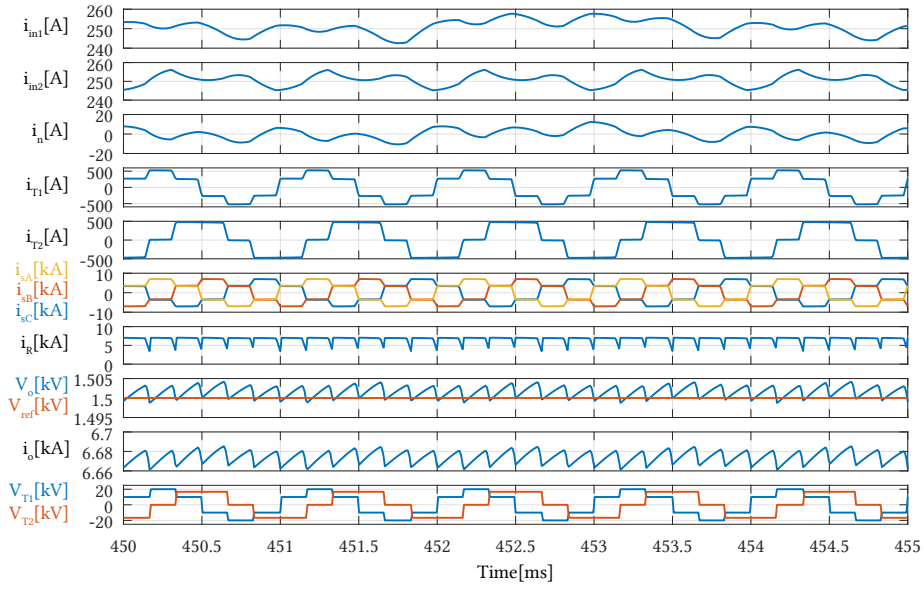
- i_{in1} → MMC_1 input current
- i_{in2} → MMC_2 input current
- i_{in} → neutral conductor current
- i_{T1} → T_1 P-winding current
- i_{T2} → T_2 P-winding current
- i_S → LV stage 3PH-currents
- i_R → SSC output current
- V_o → load voltage
- i_o → load current
- i_{rev} → LV side current injection
- V_{T1} → T_1 P-winding voltage
- V_{T2} → T_2 P-winding voltage



▲ Converter operating waveforms

SIMULATION RESULTS (II)

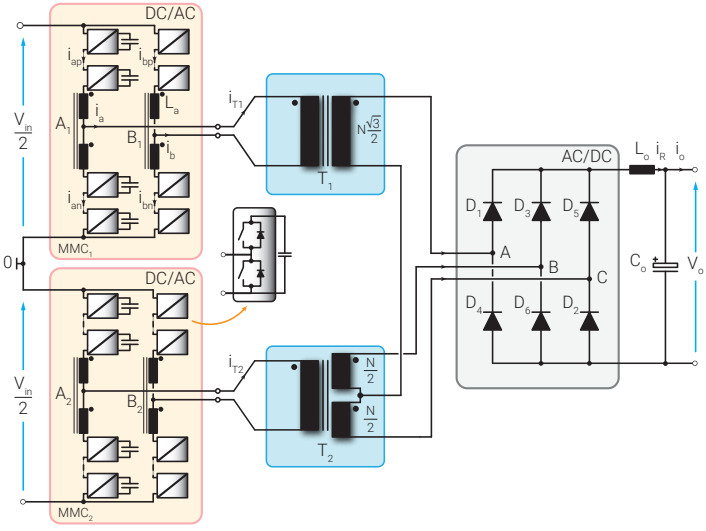
- i_{in1} → MMC_1 input current
- i_{in2} → MMC_2 input current
- i_{in} → neutral conductor current
- i_{T1} → T_1 P-winding current
- i_{T2} → T_2 P-winding current
- i_S → LV stage 3PH-currents
- i_R → SSC output current
- V_o → load voltage
- i_o → load current
- i_{rev} → LV side current injection
- V_{T1} → T_1 P-winding voltage
- V_{T2} → T_2 P-winding voltage



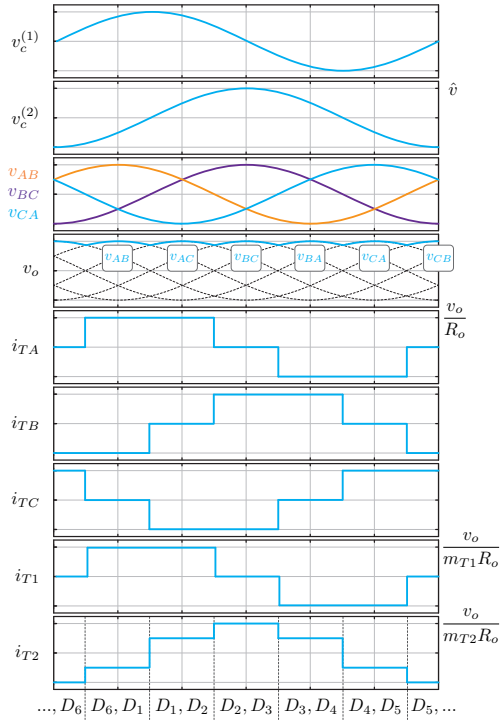
▲ Converter operating waveforms during five fundamental cycles

MMC-BASED HIGH POWER UNIDIRECTIONAL DC-DC CONVERTER

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

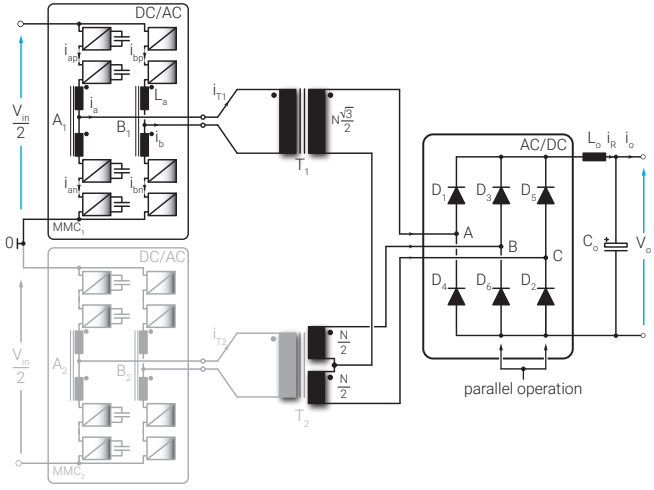


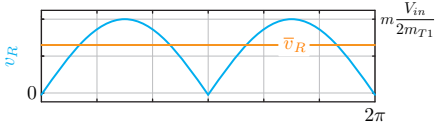
▲ MMC-based High-Power Unidirectional DC-DC Converter



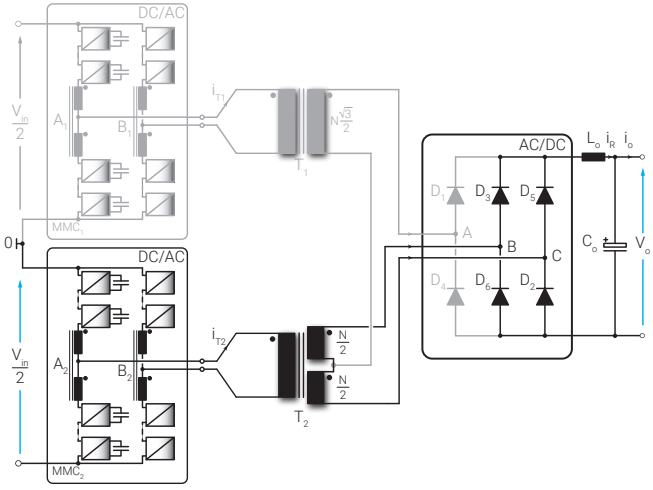
▲ Converter idealized operating waveforms

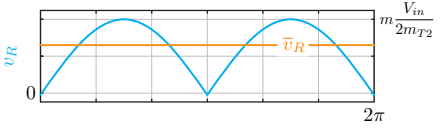
OPERATION UNDER FAULTS





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





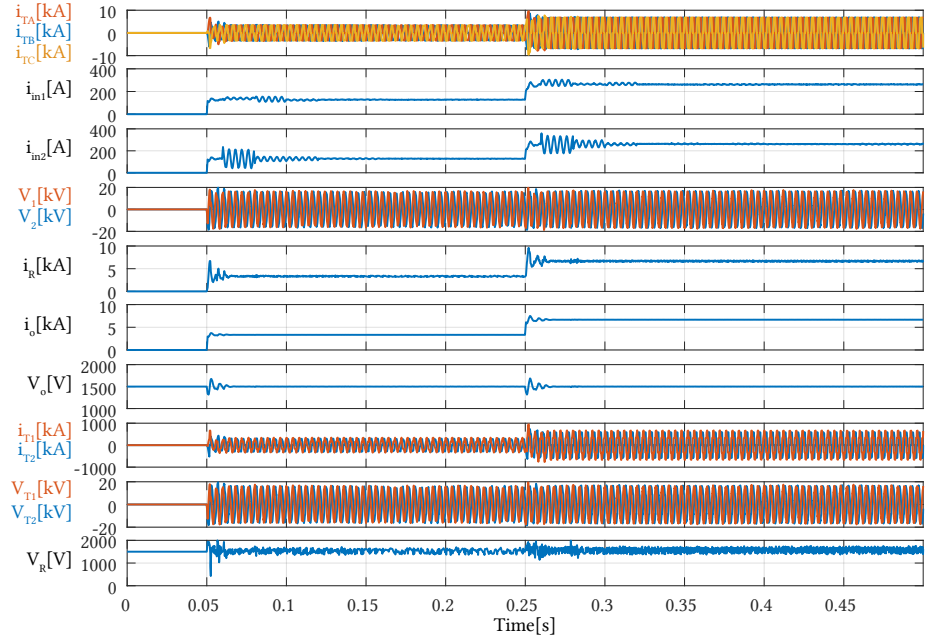
▲ Converter operation in the case of "Plus" DC pole malfunction

SIMULATION RESULTS (I)

Table 2 Simulated system ratings

Parameter	Value
Input voltage (V_{in})	±20kV
Output voltage (V_o)	1.5kV
Rated power (P_{nom})	10MW
Operating frequency (f)	250Hz

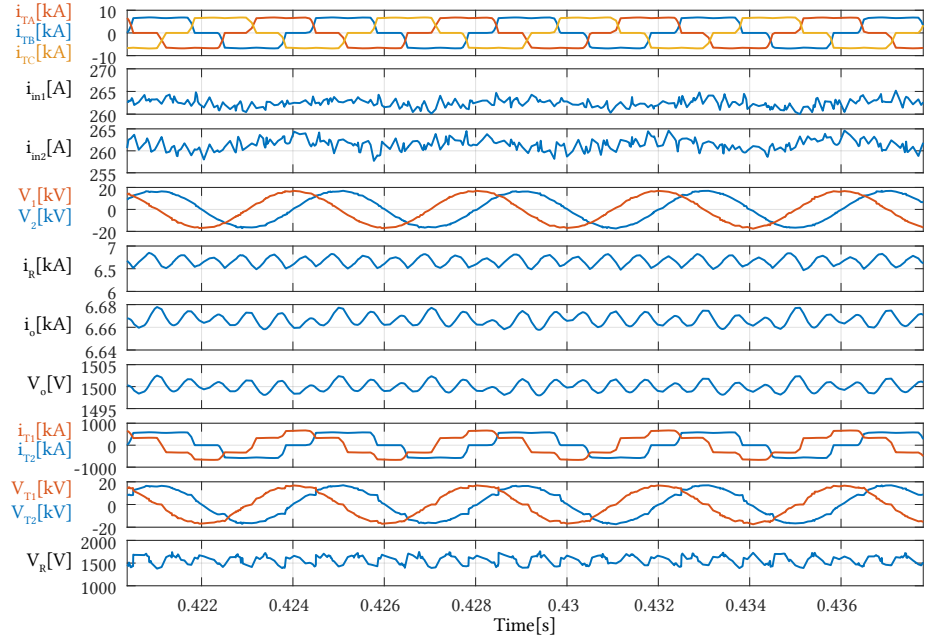
- i_T → LV-stage 3PH - currents
- i_{in1} → MMC_1 input current
- i_{in2} → MMC_2 input current
- V_1 → MMC_1 AC voltage
- V_2 → MMC_2 AC voltage
- i_R → DR output current
- i_o → load current
- V_o → load voltage
- i_{T1} → T_1 P-winding current
- i_{T2} → T_2 P-winding current
- V_{T1} → T_1 P-winding voltage
- V_{T2} → T_2 P-winding voltage
- V_R → DR output voltage



▲ Converter operating waveforms

SIMULATION RESULTS (II)

- $i_T \rightarrow$ 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

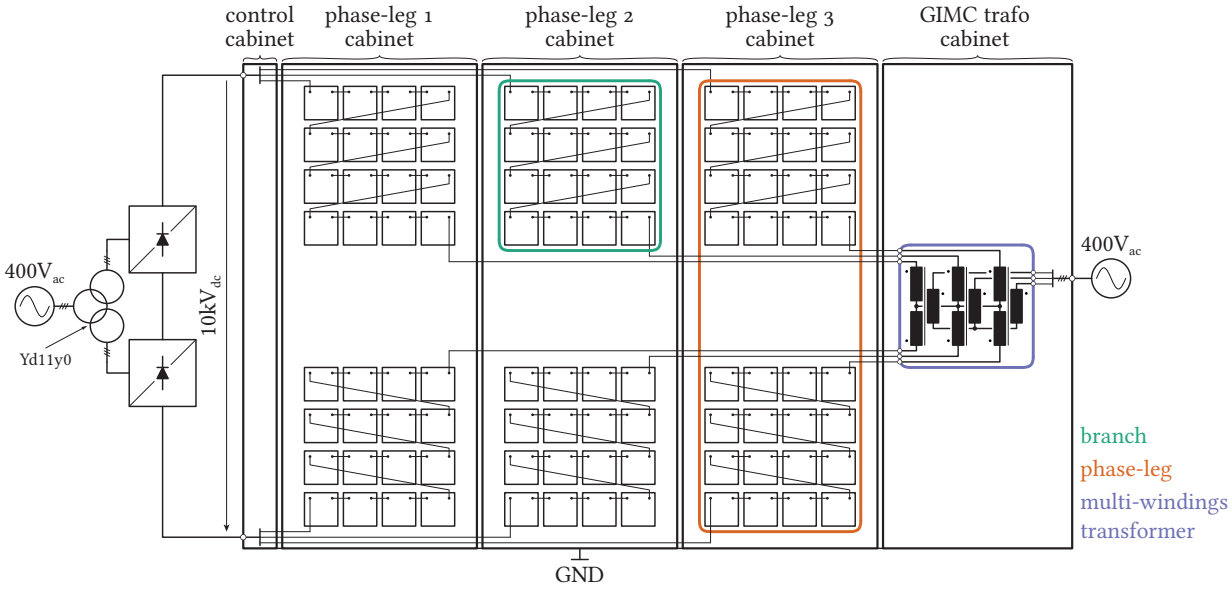
MV MMC CONVERTER PLATFORM

University lab prototype

GIMC – CONVERTER LAYOUT

MMC demonstrator ratings are:

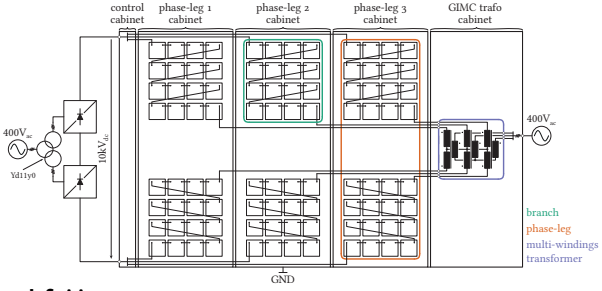
- 500 kVA
- 10 kV_{dc} ↔ 400 V_{ac} or 6.6 kV_{ac}
- 16 low voltage cells per branch ⇒ 32 cells per phase (cabinet) ⇒ 96 cells in total
- Industrial central controller and communication (ABB AC PEC 800)



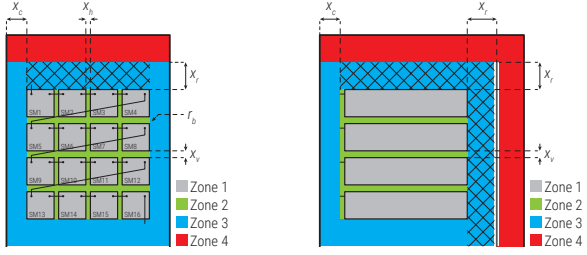
▲ DC/3-AC MMC Converter Layout

INSULATION COORDINATION OF A MV CONVERTER PROTOTYPE (I)

System partitioning



Zones definition



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

Zone 2 (ins. coord. branch)

- Horizontal system voltage: 1 kV_{ac}
- Vertical system voltage: 3.6 kV_{ac}

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

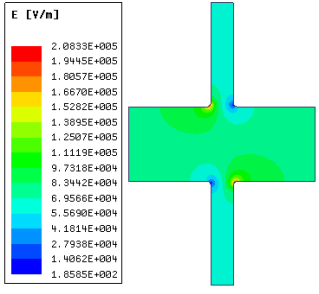
Zone 4 (ins. coord. for LV circuits) system voltage: 0.4 kV_{ac}

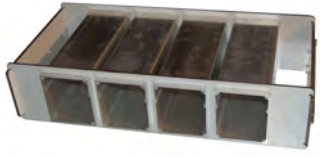
Standards

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

Zone 2

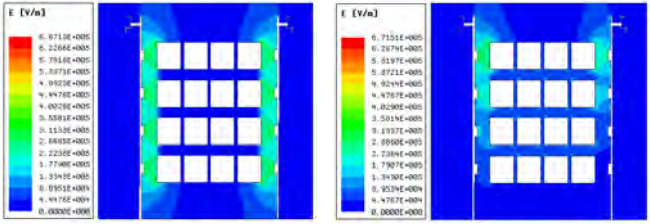
- Box at dc- cell's potential (floating)
- Box corner radius: 3 mm
- MKHP (high CTI material) drawer holding 4 cells



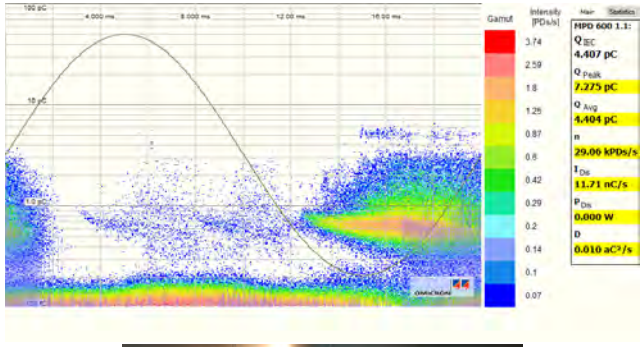


INSULATION COORDINATION OF A MV CONVERTER PROTOTYPE (II)

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



Ac dielectric withstand test



Design recap

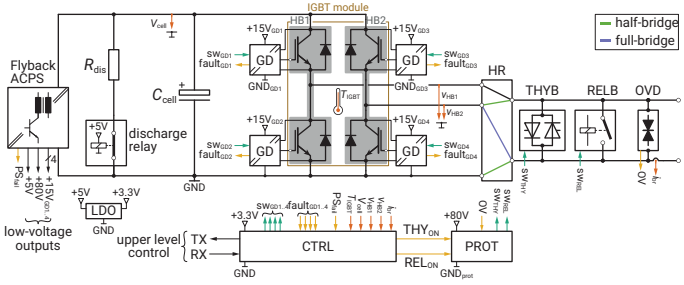
Variable	Minimal value [mm]	Actual design value [mm]
r_b		3
$d_{L,h}$	6.8	15
$d_{C,h}$	3.2	15
$d_{L,v}$	30	50
$d_{C,v}$	12.5	275
$d_{L,c}$	60	81.5
$d_{C,c}$	60	93
$d_{L,r}$	102	120

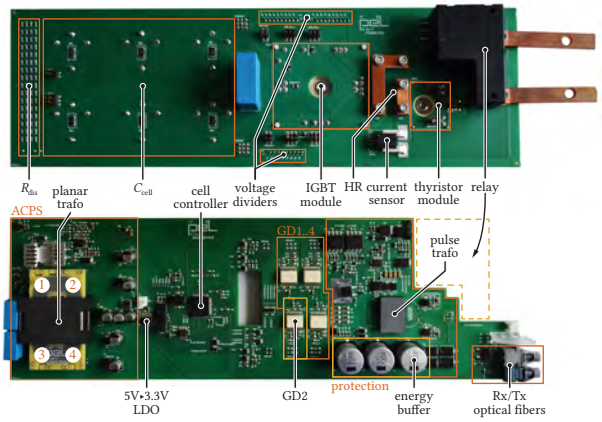
MMC CELL

Ratings

- 0.5 MVA apparent power
- 10 kV MVdc connection
- 400 V / 6 kV ac output
- 96 cells (16 per branch)

Cell concept





▲ Circuit partitioning

▼ Assembled cell

Design

- 1.2 kV / 50 A IGBT module (Semikron SK50GH12T4T)
- 1.2 kV / 70 A Thyristor module (Semikron SK70KQ)
- C_{sm} = 2.25 mF (6x Exxalia SnapSiC 4P 1500 µF, 400 V)
- Current sensor (Allegro ACS759 100 A)
- Bypass relay (KG K100 B-D012 X P)
- TI TMS320F28069 DSP
- Integrated Flyback auxiliary cell power supply from DC link with planar trafo

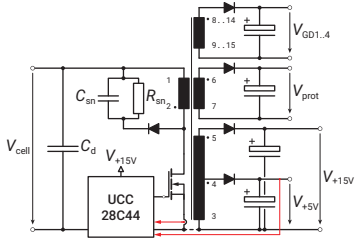
AUXILIARY CELL POWER SUPPLY (I)

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})

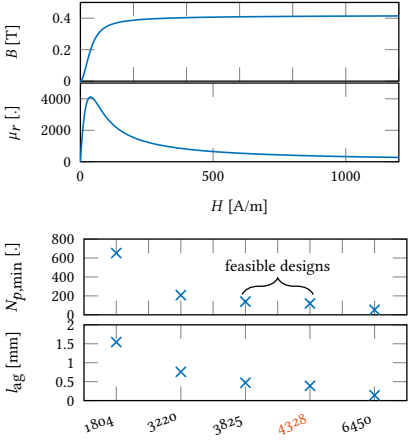


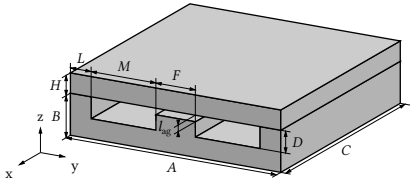
Planar trafo design

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

Matlab design tool

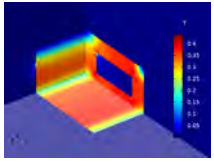
- Account for flux fringing [37]
- BH curve for CF297
- Jiles-Atherton parametrization

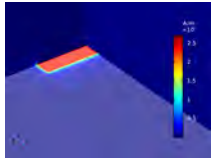


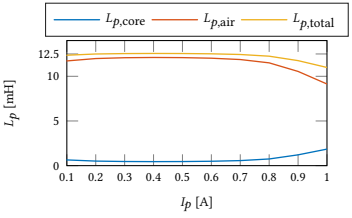


FEM

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



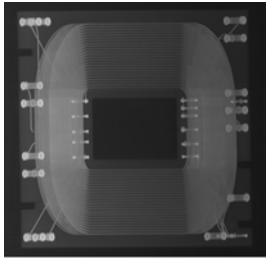


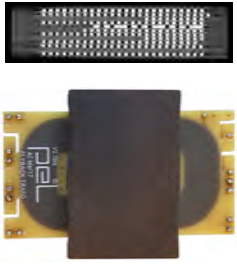


AUXILIARY CELL POWER SUPPLY (II)

Transformer assembly

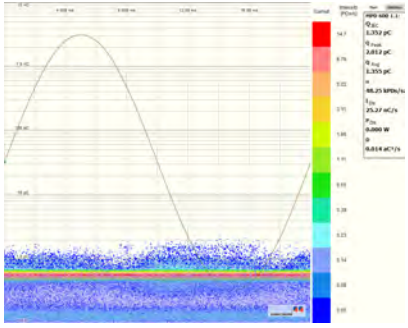
- 14 copper layers PCB
- Custom gapped ferrite E+I core



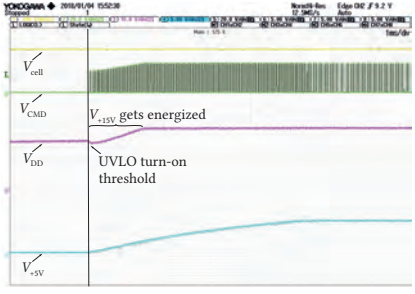


AC dielectric withstand test

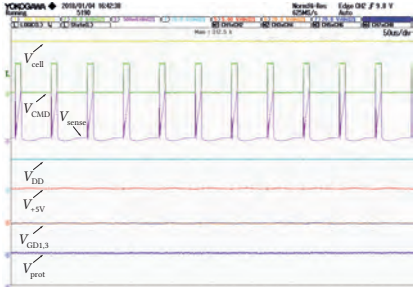
- Way below threshold level of 10pC



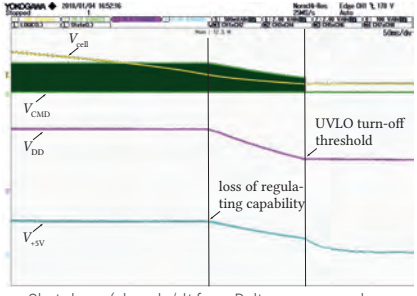
Tests



▲ Start-up



▲ Steady-state operation



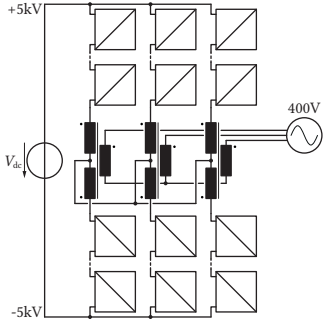
▲ Shut-down (slow dv/dt from Delta power-supply used to emulate the cell)

SUMMARY

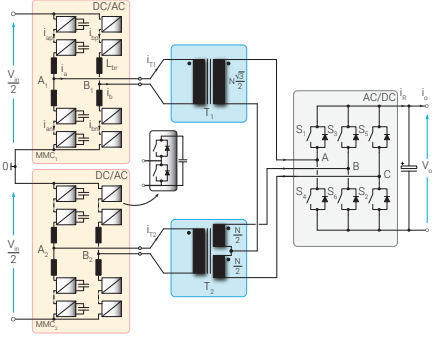
Modular Multilevel Converter

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

▲ HVDC Light valve hall from ABB.



▲ Galvanically Isolated Modular Converter



▲ High Power DC-DC Converter Employing Scott Transformer Connection

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