GALVANICALLY ISOLATED HIGH POWER CONVERTERS FOR MVDC APPLICATIONS

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INTRODUCTION

Why more modular converters are needed?
SwissGrid infrastructure

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

Swiss energy landscape

- Annual consumption 60 TWh
- Nuclear phase out by 2050

<table>
<thead>
<tr>
<th>Energy Type</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>Hydro</td>
<td>56.91%</td>
</tr>
<tr>
<td>Non-renewable</td>
<td>37.7%</td>
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<tr>
<td>Renewable</td>
<td>5.39%</td>
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Swiss Competence Centers for Energy Research (SCCERs)

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

MVDC grids

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

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

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

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

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

Open challenges
- DC breaker
- Conversion blocks missing
- Protection coordination
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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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EMERGING MVDC APPLICATIONS

Installations

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

Projects

▶ Angle DC: conversion of 33 kV MVac line to ±27 kV MVdc [4]

Universities

▶ Increased number of laboratories active in high power domain
▶ China, Europe, USA,…

Products

▶ Siemens MVDC Plus
  ▶ 30 - 150 MW
  ▶ < 200 km
  ▶ < ±50 kVdc

▶ RXPE Smart VSC-MVDC
  ▶ 1 - 10 MVar
  ▶ ±5 - ±50 kVdc
  ▶ 40 - 200 km

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MVDC is gaining momentum!


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MEDIUM OR LOW FREQUENCY CONVERSION?

Focus
▶ MVDC-LVAC galvanically isolated conversion system

Features
▶ High efficiency
▶ Galvanic isolation
▶ Modularity
▶ Scalability
▶ Reliability
▶ Availability

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

SST
▶ VSI on LVAC side of SST reduces efficiency by $\approx 2 \%$ (I) \[^{[5]}\]
▶ Drawn solution is not the unique possibility

MMC
▶ Solution with MMC + LFT has higher efficiency

Investigations
1. Comparative assessment of the control methods for a dc/3-ac MMC
2. Critical assessment of the modulation and branch balancing methods
3. Merging of the branch inductances and LFT leakage inductances: the GIMC
4. Virtual Submodule Concept for fast cell loss estimation method \[^{[6]}\]
5. Design of a MMC cell (under certain academic constraints) \[^{[7]}\]


GALVANICALLY ISOLATED MODULAR CONVERTER

Integrating line frequency transformer into the MMC...
TRANSFORMER INTEGRATION PROPOSALS

**OEWMMC [8]**

- Only one branch per phase-leg
- No CM voltage injection
- No current decoupling
- DC bias in trafo → zig-zag trafo [9]

**Isolated dc/dc converter [10]**

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

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Integration opportunities

- Multi-windings trafo
- Dc bias cancellation is effective for any operating point
- Different dc voltage levels can be accommodated with the same branch design

**Method**

- Carried out once via terminal mapping \[14\]
- \( v = L \frac{di}{dt} + Ri \)

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

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

\[i\text{GIMC}\]

\[
\begin{align*}
v_1 &= v_i \\
v_2 &= -v_r \\
v_3 &= v_L
\end{align*}
\]

\[
\begin{align*}
i_1 &= i_j \\
i_2 &= -i_r \\
i_3 &= -i_g
\end{align*}
\]

Result:

\[
\begin{align*}
v_B &= e_i + e_r + R_{HV}(i_j + i_r) + L_{\sigma,HV}\left(\frac{di_j}{dt} + \frac{di_r}{dt}\right) \\
0 &= -e_i + e_r + R_{HV}(-i_j + i_r) + (L_{\sigma,HV} + 2L_{HV})\left(\frac{di_j}{dt} + \frac{di_r}{dt}\right) \\
&\quad + 2M_{LV} \frac{di_j}{dt} - 2v_{CM} \\
v_L &= M_{LV}\left(\frac{di_j}{dt} - \frac{di_r}{dt}\right) - (L_{\sigma,LV} + L_{LV}) \frac{di_j}{dt} - R_{LV} i_g
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\[s\text{GIMC}\]

\[
\begin{align*}
v_1 &= v_p \\
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GIMC - MODELING

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\text{iGIMC} & : & v_1 &= v_i \\
& & v_2 &= -v_r \\
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v_B &= e_i + e_r + L_{HV} (i_j + i_r) + L_{\sigma,HV} \left( \frac{d}{dt} i_j + \frac{d}{dt} i_r \right) \\
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\end{align*}\]
Inverter mode operation

GIMC - OPERATION

sGIMC

iGIMC

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Inverter mode operation

\[ i_\mu \text{ does not contain a dc component} \]
MAGNETIC COMPONENTS DESIGN

How much gain with the integrated magnetic component?
AIR-CORE BRANCH INDUCTOR DESIGN

Design space (PEL target values)

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

Analytical designs

- $L_{\text{Welsby}} = \frac{\mu_0 N^2 n a^2}{b} \left( \frac{1}{1 + 0.9 \frac{b}{D} + 0.32 \frac{c}{a} + 0.84 \frac{c}{D}} \right) \, \text{[H]}$

- Cost function: $J_{\text{cost}} = \sqrt{\left( \frac{l_{\text{wire}}}{10} \right)^2 + V_\text{tot}^2}$

Optimal design

- $N_{\text{turns}} = 132, \, N_{\text{layers}} = 12, \, r_{\text{int}} = 42.4\, \text{mm} \rightarrow 42.6\, \text{mm}$
- $V_{\text{tot}} \approx 61$
- $P_{\text{losses}} = 130\, \text{W}$

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

- Impedance between 0.1 Hz and 100 kHz
Design

- Three-limb dry-type transformer
- Short-circuit impedance > 5%
- Silicon steel (M19 from AK Steel): $B_{\text{max}} = 1.2 \text{T} \Rightarrow \mu = 1.37\%$
- $V_{21t} = 10\text{V}$
- $J_{\text{HV}} = 2.5 \text{A/mm}^2$, $J_{\text{LV}} = 2 \text{A/mm}^2$

Core's permeance model

- Single unknown: $w_w = \frac{4\mu_0\mu_rA_c - \mathcal{P}_c^*(6 + \pi)d_c}{(4 + 6\alpha\mathcal{P}_c^*)}$

Best design

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

Leakage H-field in COMSOL @ 50 Hz ($\leftarrow$ phase a / $\rightarrow$ phase b)

Time domain simulations ($\leftarrow$ no-load / $\rightarrow$ short-circuit)
Degree of freedom

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

Best design

- $w_w = 259.8$ mm and $a = 4$
- $V_{tot} = 573.11$
- $P_{w,HV} = 63.29$ 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]
GIMC TRANSFORMER DESIGN

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

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MAGNETIC COMPONENTS COMPARISON

Case 1 MMC
- 6 branch inductors + conventional LFT

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<tr>
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Case 2 GIMC [15]
- no branch inductors + multi-windings transformer

[15] Design values are related to ongoing prototype design at Power Electronics Laboratory.
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⇒ volume + cost reduction & efficiency increase with the integrated magnetic component

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MV MMC CONVERTER PLATFORM

University laboratory environment...
INDUSTRIAL MMC CELL DESIGNS

- HVDC designs
- MV designs
INDUSTRIAL MMC CELL DESIGNS

▸ HVDC designs

▸ MV designs

numerous designs for similar target applications
MMC CELL @ PEL

**Ratings**
- 0.5 MVA apparent power
- 10 kV MVDC connection
- 400 V / 6 kV AC output
- 96 cells (16 per branch)

**Cell concept**
- Half-bridge
- Full-bridge
- GD
- GD
- HR
- THYB
- RELB
- OVD
- Flyback
- ACPS
- 4
- Low-voltage outputs
- +15V GD1
- GND GD1
- +15V GD2
- sw GD1
- fault GD1
- sw GD2
- fault GD2
- CTRL
- TX
- Rx
- Optical fibers
- +5V
- +80V
- +15V GD3
- GND GD3
- +15V GD4
- sw GD3
- fault GD3
- sw GD4
- fault GD4
- HB2

**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

**Circuit partitioning**
- Assembled cell
INSULATION COORDINATION OF A MV CONVERTER PROTOTYPE

System partitioning:

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

Branch phase-leg
10kVdc
400Vac
400Vac
Multi-windings transformer

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
SUMMARY

**GIMC**
- DC bias free magnetic structure (no penalty on magnetic material utilization)
- iGIMC & sGIMC suitable for Boost or Buck between the DC and AC voltages
- The integrated magnetics offer efficiency and power density increase
- Cost savings

**MV MMC converter platform**
- Realistically sized MV converter prototype
- LV IGBT based MMC cell
- Flyback-based ACPS, local cell controlled
- Complete dielectric design - insulation coordination
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