GALVANICALLY ISOLATED HIGH POWER CONVERTERS FOR MVDC APPLICATIONS

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Switzerland

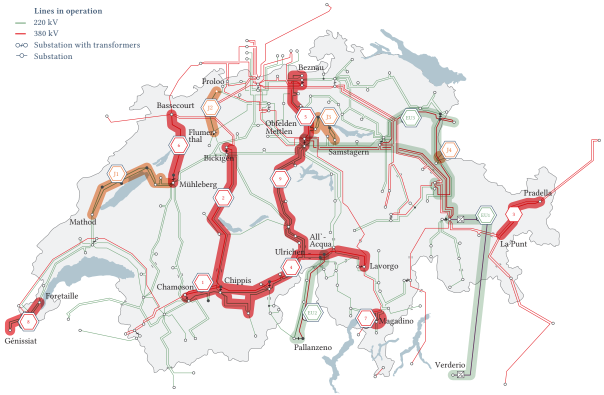
INTRODUCTION

Why more modular converters are needed?

SCCER – FURIES
Shaping the FUtuRe SwIss Electrical InfraStructure

SwissGrid infrastructure

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

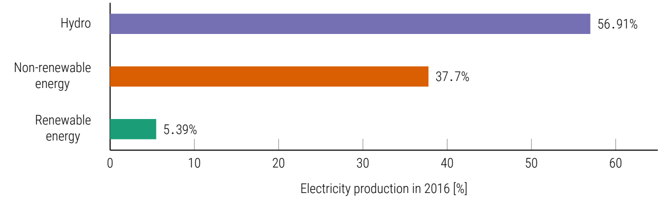


MVDC grids

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

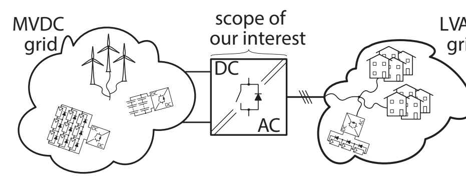
Swiss energy landscape

- Annual consumption 60 TWh
- Nuclear phase out by 2050



Swiss Competence Centers for Energy Research (SCCERs)

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



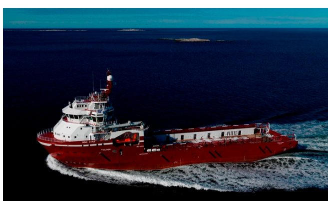
TREND TOWARDS DC

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


LVDC ships

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




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

Open challenges

- DC breaker
- Conversion blocks missing
- Protection coordination

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⇒ dc beneficial for medium / high power applications

Open challenges

- DC breaker
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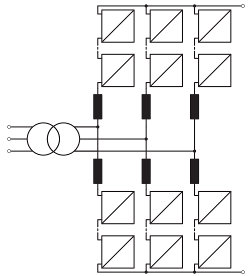
- Protection coordination

TREND TOWARDS HIGHLY MODULAR CONVERTER TOPOLOGIES

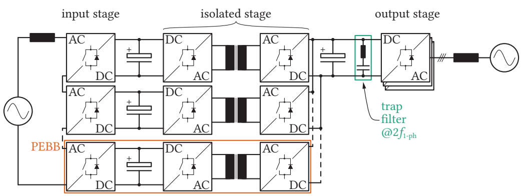
HVDC

- 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



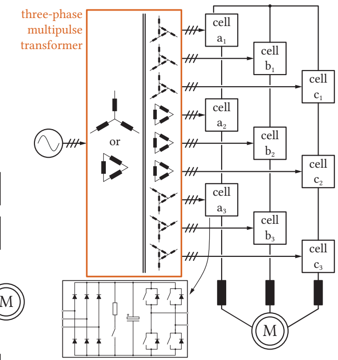
Solid-state transformers (SSTs)

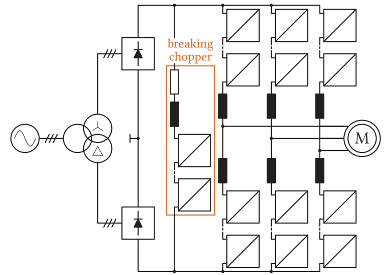
- Power density increase w/ conversion & isolation at higher frequency
- Grid applications / traction transformer w/ different optimization objectives
- MFT design / isolation are the bottlenecks



MV drives

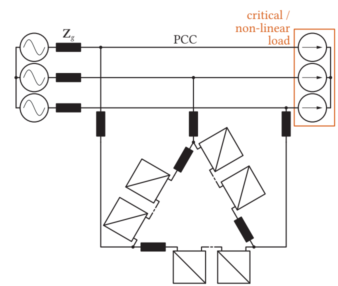
- Monolithic ML topologies (NPC, NPP, FC, ANPC) are not scalable
- Robicon drive → everyone offers it
- Siemens & Benshaw: MMC drive
- Low dv/dt ⇒ motor friendly





FACTS

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



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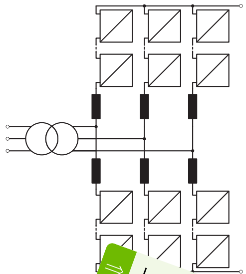

⇒ benefits in high power applications

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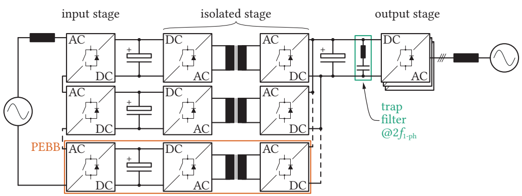

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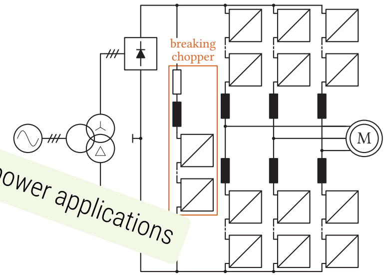

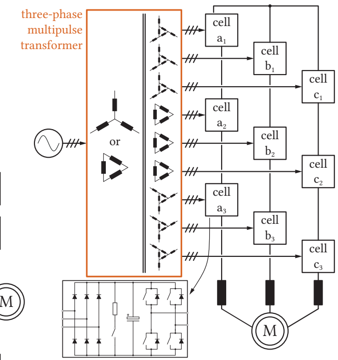

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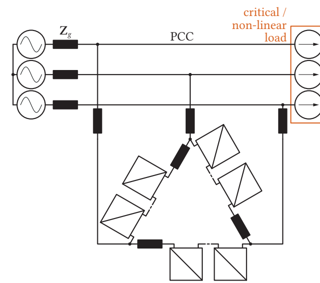


EMERGING MVDC APPLICATIONS

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

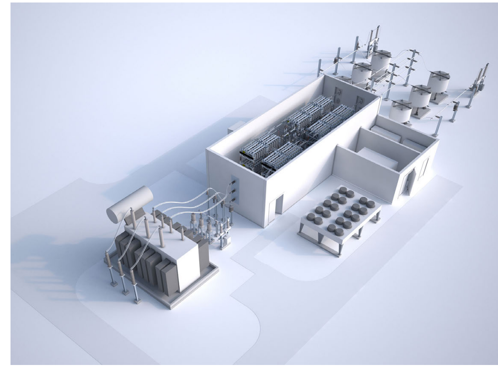
- Angle DC: conversion of 33 kV MVac line to ±27 kV MVdc [4]

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

[1] ABB. *Tjæreborg*. http://new.abb.com/systems/hvdc/references/tjaereborg

[2] Charles Bodel. *Paimpol-Bréhat tidal demonstrator project*. http://eusew.eu/sites/default/files/programme-additional-docs/EUSEW1606160PresentationtoEUSEWbyEDF.pdf. EDF

[3] G. Bathurst, G. Hwang, and L. Tejwani. "MVDC - The New Technology for Distribution Networks." *11th IET International Conference on AC and DC Power Transmission*. Feb. 2015, pp. 1–5

[4] SP Energy Networks. *Angle dc*. https://www.spenergynetworks.co.uk/pages/angle_dc.aspx

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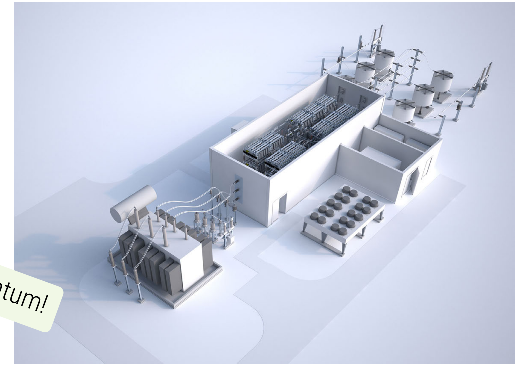

⇒ MVDC is gaining momentum!

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[1] ABB. *Tjæreborg*. http://new.abb.com/systems/hvdc/references/tjaereborg

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[4] SP Energy Networks. *Angle dc*. https://www.spenergynetworks.co.uk/pages/angle_dc.aspx

MEDIUM OR LOW FREQUENCY CONVERSION?

Focus

- MVDC-LVAC galvanically isolated conversion system

Features

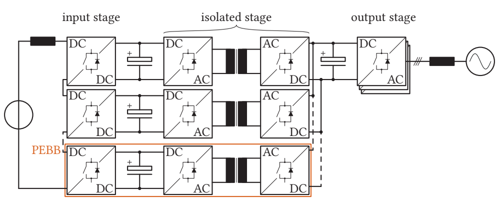
- High efficiency
- Galvanic isolation
- Modularity
- Scalability
- Reliability
- Availability

Prototype ratings

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

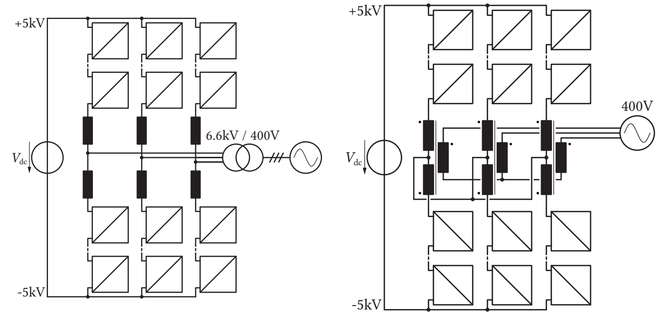
SST

- VSI on LVAC side of SST reduces efficiency by ≈ 2 % (!) [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]

[5] J. E. Huber and J. W. Kolar. "Volume/weight/cost comparison of a 1MVA 10 kV/400 V solid-state against a conventional low-frequency distribution transformer." *2014 IEEE Energy Conversion Congress and Exposition (ECCE)*. Sept. 2014, pp. 4545–4552
[6] A. Christe and D. Dujic. "Virtual Submodule Concept for Fast Semi-Numerical Modular Multilevel Converter Loss Estimation." *IEEE Transactions on Industrial Electronics* 64.7 (July 2017), pp. 5286–5294
[7] A. Christe, E. Coulinge, and D. Dujic. "Insulation coordination for a modular multilevel converter prototype." *2016 18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe)*. Sept. 2016, pp. 1–9

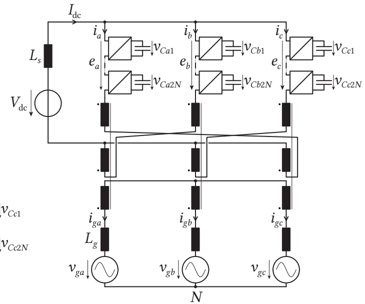
GALVANICALLY ISOLATED MODULAR CONVERTER

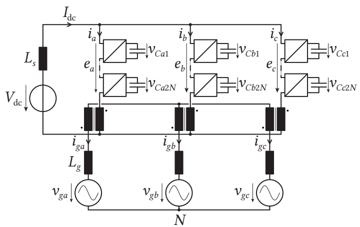
Integrating line frequency transformer into the MMC...

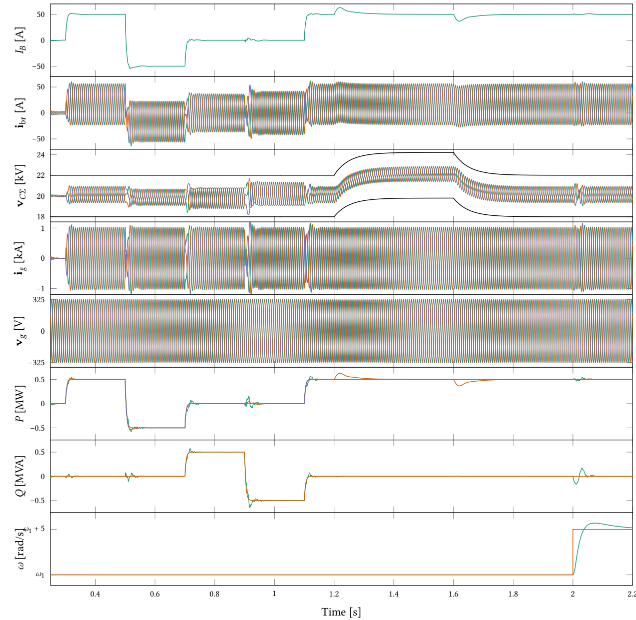
TRANSFORMER INTEGRATION PROPOSALS

OEWMMC [8]

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

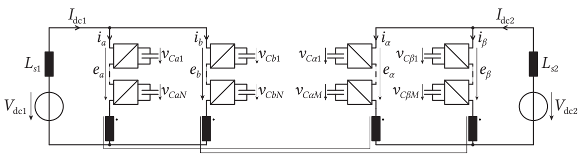






Isolated dc/dc converter [10]

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



[8] *Multilevel converter*. WO Patent App. PCT/EP2012/072,757. Jan. 2014. URL: https://www.google.com/patents/WO2013110371A3?cl=en

[9] N. Serbia, P. Ladoux, and P. Marino. “Half Wave Bridge AC/DC Converters - From diode rectifiers to PWM multilevel converters.” *PCIM Europe 2014; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*. May 2014, pp. 1–8

[10] *High voltage dc/dc converter with transformer driven by modular multilevel converters (mmc)*. WO Patent App. PCT/EP2011/070,629. May 2013. URL: https://www.google.com/patents/WO2013075735A1?cl=fr

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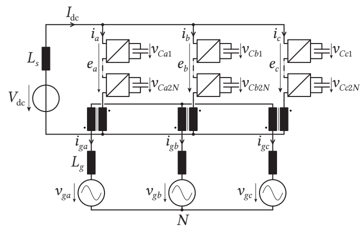
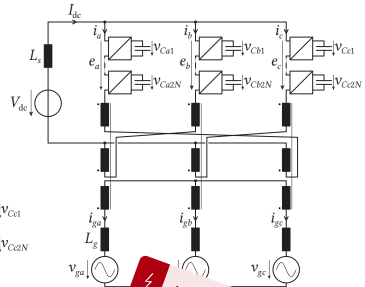
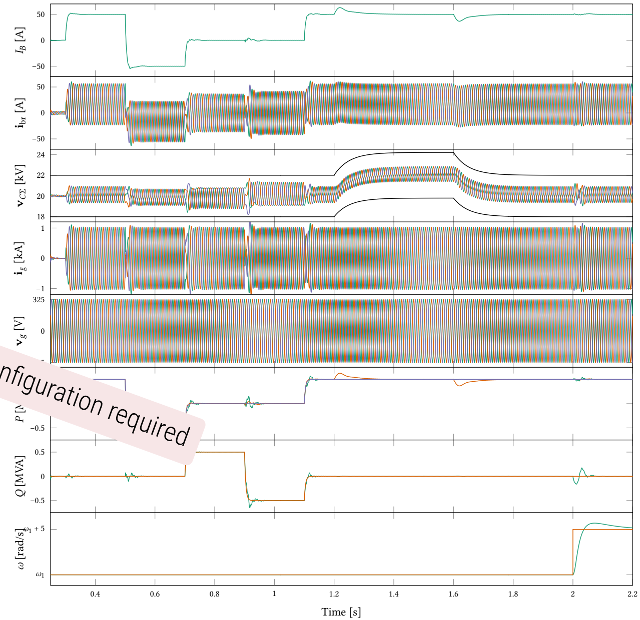


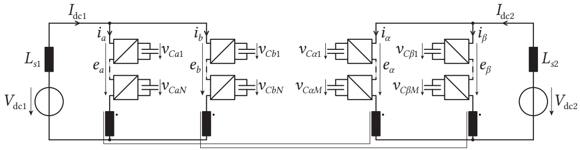




proper transformer configuration required

Isolated dc/dc converter [10]

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



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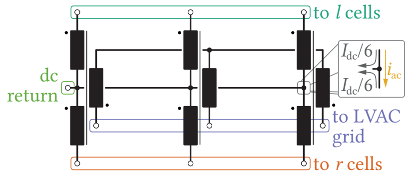
THE GALVANICALLY ISOLATED MODULAR CONVERTER - GIMC

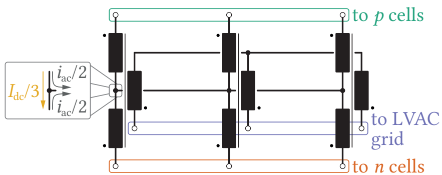
Integration opportunities

- Multi-windings trafo
- Unification of proposals [11] & [12]
- Dc bias cancellation is effective for any operating point
- Different dc voltage levels can be accommodated with the same branch design

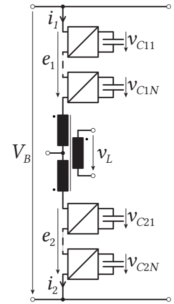


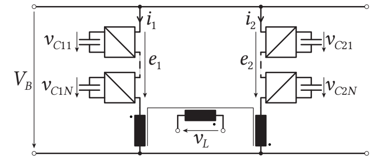
▲ iGIMC trafo

▼ sGIMC trafo



GIMC [13]





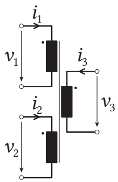
▲ Interleaved GIMC (iGIMC)

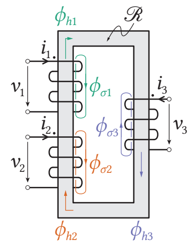
◀ Stacked GIMC (sGIMC)

[11] S. Tamada, Y. Nakazawa, and S. Irokawa. "A proposal of Modular Multilevel Converter applying three winding transformer." *2014 International Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE ASIA)*. May 2014, pp. 1357–1364
[12] M. Hagiwara and H. Akagi. "Experiment and Simulation of a Modular Push-Pull PWM Converter for a Battery Energy Storage System." *IEEE Transactions on Industry Applications* 50.2 (Mar. 2014), pp. 1131–1140
[13] A. Christe and D. Dujic. "Galvanically isolated modular converter." *IET Power Electronics* 9.12 (2016), pp. 2318–2328

Method

- Carried out once via terminal mapping [14]
- $\mathbf{v} = \mathbb{L}\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{i} + \mathbb{R}\mathbf{i}$





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

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

iGIMC

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

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:

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

[14] A. Christe and D. Dujić. "State-space modeling of modular multilevel converters including line frequency transformer." *2015 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe)*. Sept. 2015, pp. 1–10

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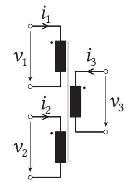

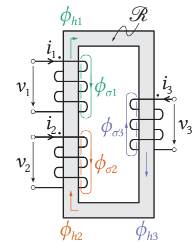

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$$\mathbb{R} = \begin{bmatrix} R_{\mathrm{HV}} & 0 & 0 \\ 0 & R_{\mathrm{HV}} & 0 \\ 0 & 0 & R_{\mathrm{LV}} \end{bmatrix}$$

⇒ same as for conventional MMC

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$$v_3 = v_L \qquad i_3 = -i_g$$

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:

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

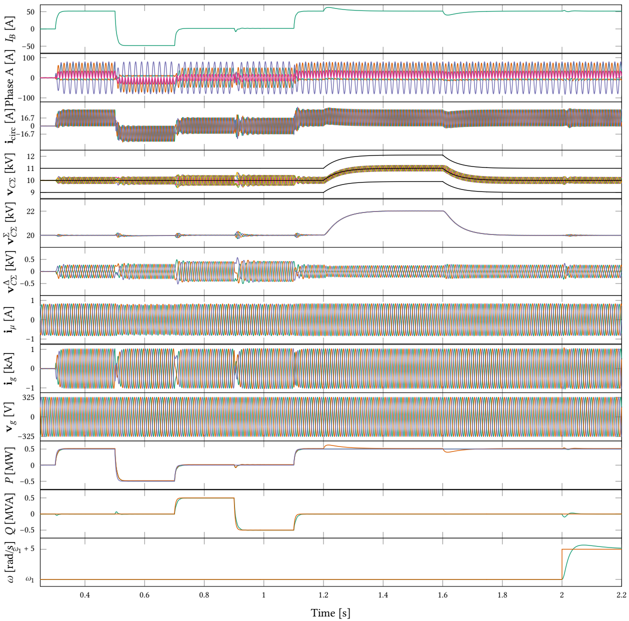
$$0 = -e_p + e_n + R_{\mathrm{HV}}(-i_p + i_n) + (L_{\sigma,\mathrm{HV}} + 2L_{\mathrm{HV}})\left(-\frac{\mathrm{d}}{\mathrm{d}t}i_p + \frac{\mathrm{d}}{\mathrm{d}t}i_n\right) + 2M_{\mathrm{LV}}\frac{\mathrm{d}}{\mathrm{d}t}i_g - 2v_{MO}$$

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

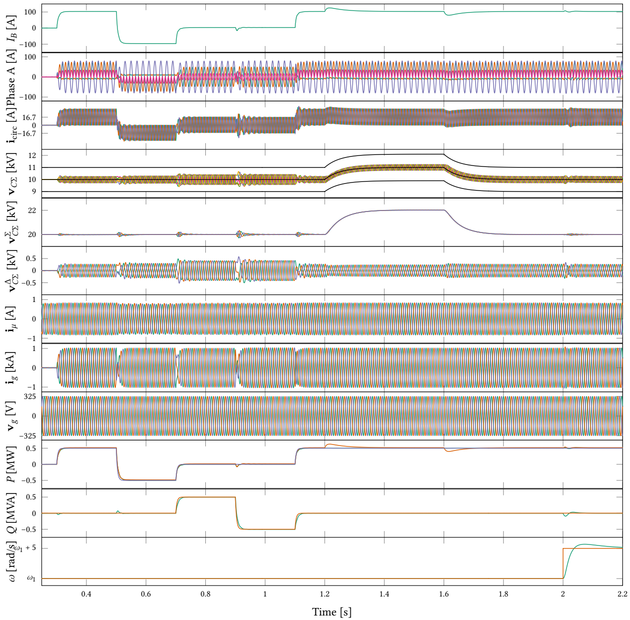
[14] A. Christe and D. Dujić. "State-space modeling of modular multilevel converters including line frequency transformer." *2015 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe)*. Sept. 2015, pp. 1–10

GIMC - OPERATION

- Inverter mode operation
  - sGIMC



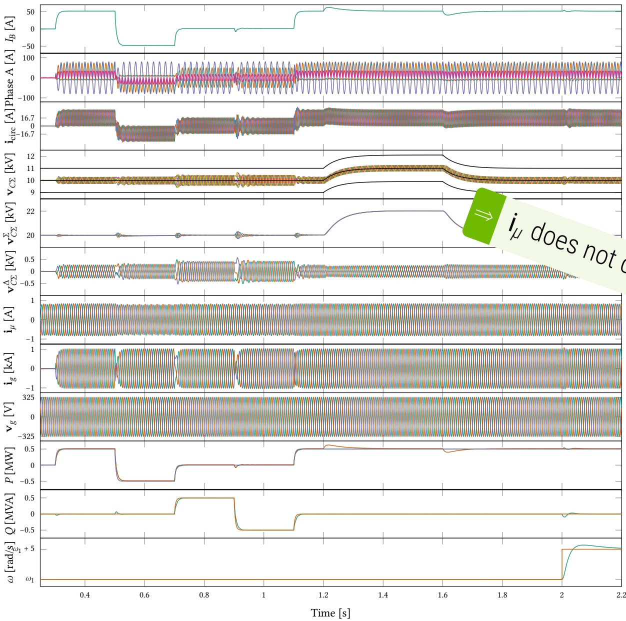
  - iGIMC



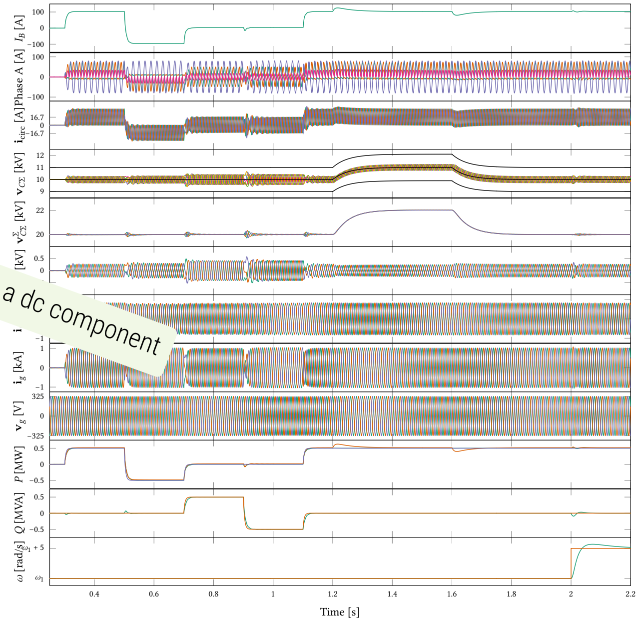
GIMC - OPERATION

- Inverter mode operation

- sGIMC



- iGIMC



⇒ i_μ does not contain a dc component

MAGNETIC COMPONENTS DESIGN

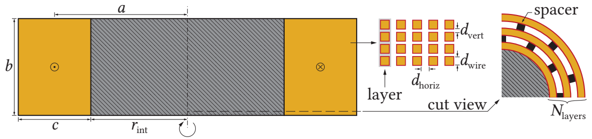
How much gain with the integrated magnetic component?

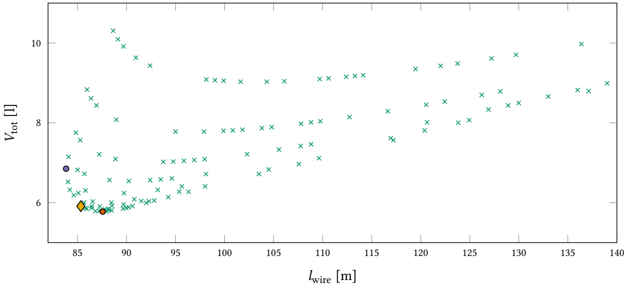
Design space (PEL target values)

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

Analytical designs

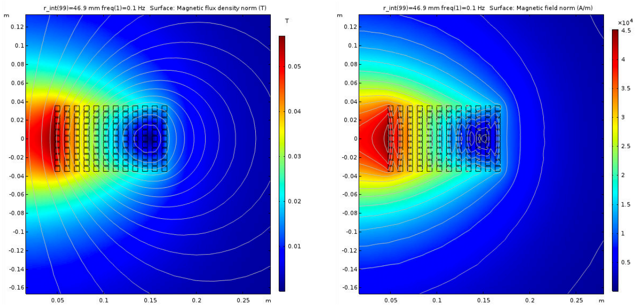
- $L_{Welsby} = \frac{\mu_0 N^2 \pi a^2}{b} \frac{1}{1 + 0.9\frac{a}{b} + 0.32\frac{c}{a} + 0.84\frac{c}{b}}$ [H]
- Cost function: $J_{cost} = \sqrt{\left(\frac{l_{wire}}{10}\right)^2 + V_{tot}^2}$





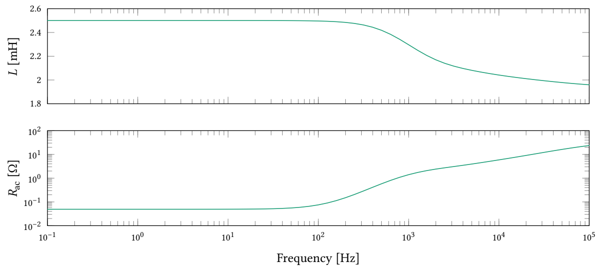
Optimal design

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



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

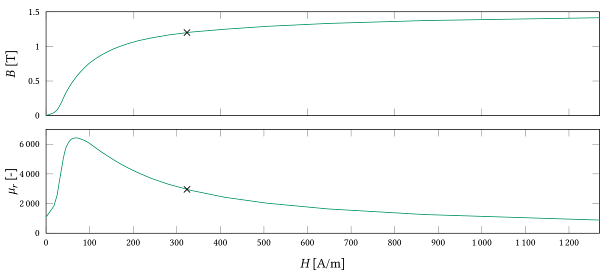
▼ Impedance between 0.1 Hz and 100 kHz

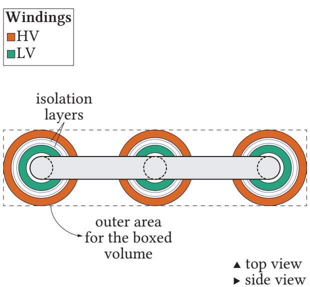


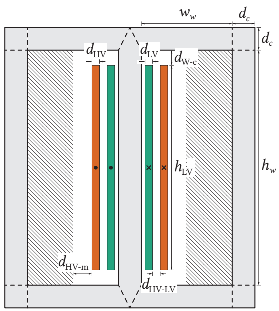
LFT DESIGN

Design

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





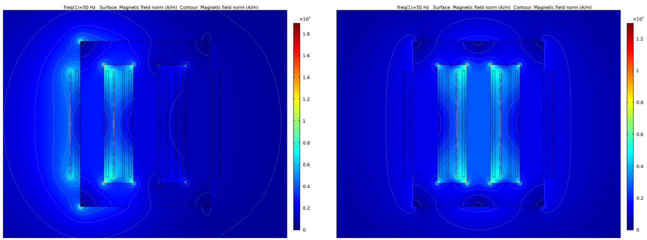


Core's permeance model

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

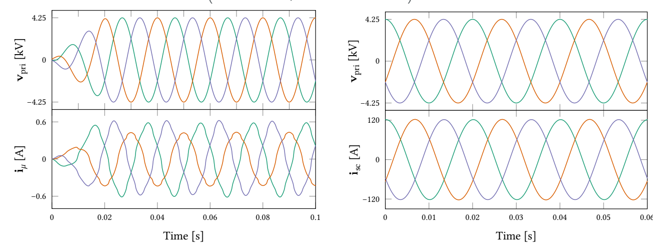
Best design

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



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

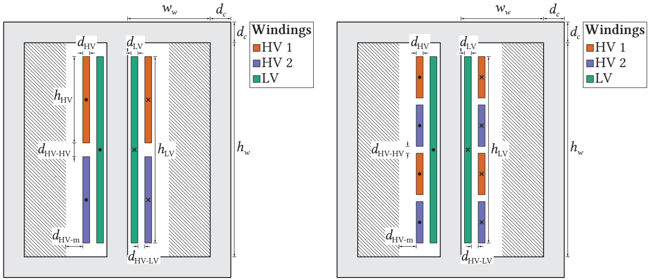
▼ Time domain simulations (← no-load / → short-circuit)



GIMC TRANSFORMER DESIGN

Degree of freedom

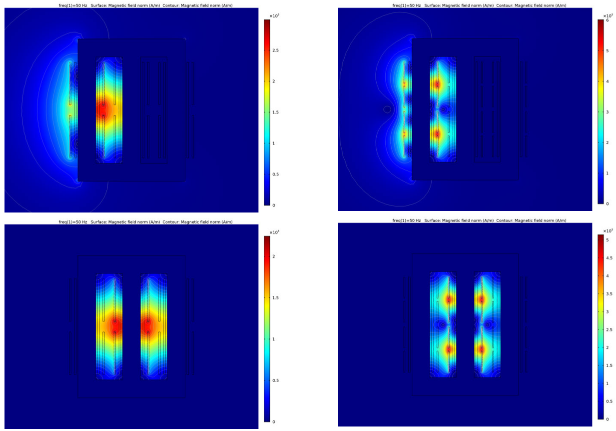
- HV windings interleaving
- Leakage inductance (i.e., branch inductance) tuning



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]



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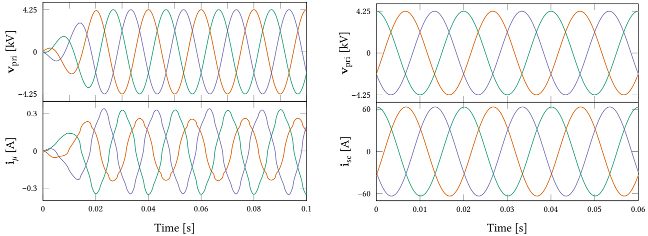

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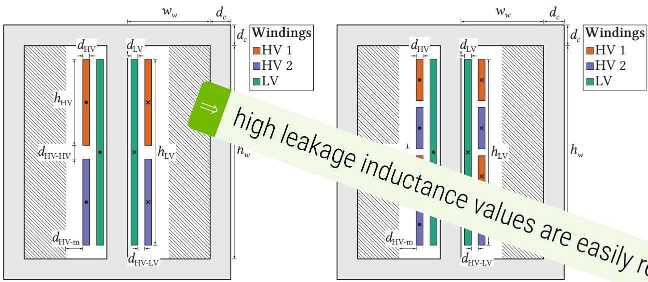
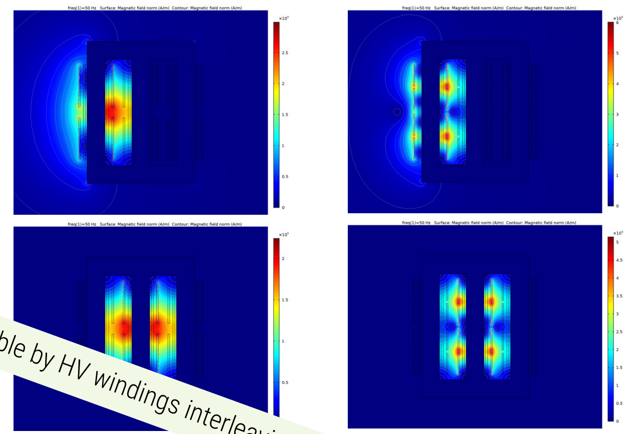


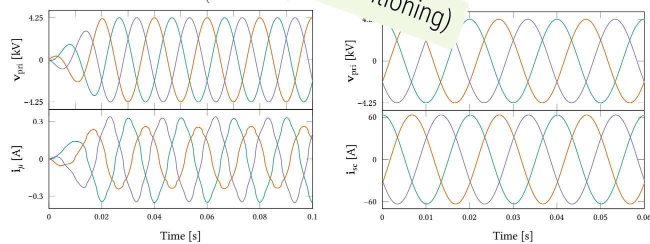
⇒ high leakage inductance values are easily reachable by HV windings interleaving (+ positioning)

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



▲ Leakage H-fields

▼ Time domain simulations (← no-load /



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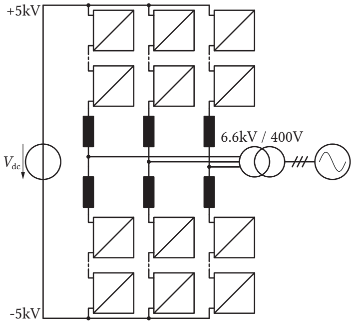
MAGNETIC COMPONENTS COMPARISON

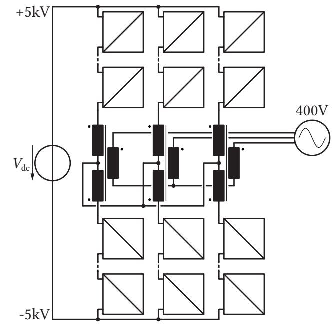
Case 1 MMC

- 6 branch inductors + conventional LFT



Case 2 GIMC [15]

- 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 %)

[15] Design values are related to ongoing prototype design at Power Electronics Laboratory

MAGNETIC COMPONENTS COMPARISON

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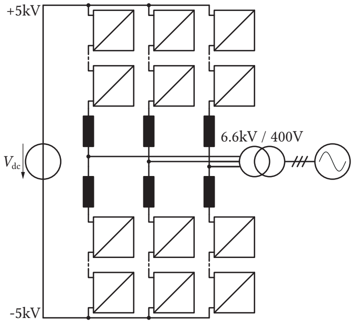

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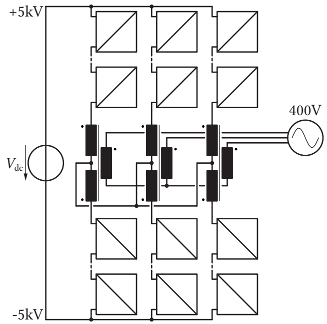

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DC/3-AC MMC	6× 6 l	780 W (0.156 %)	481.7 l	660 W (0.132 %)
GIMC	-	-	573.1 l	945 W (0.19 %)

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

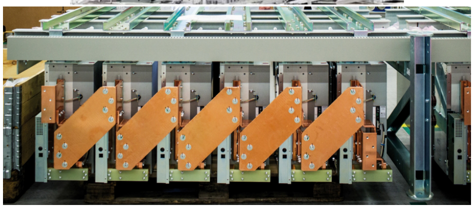
[15] Design values are related to ongoing prototype design at Power Electronics Laboratory

MV MMC CONVERTER PLATFORM

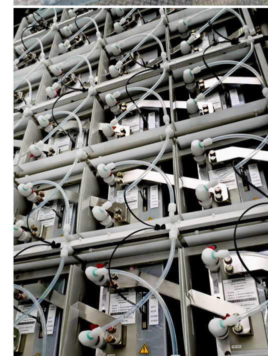
University laboratory environment...

INDUSTRIAL MMC CELL DESIGNS

- HVDC designs



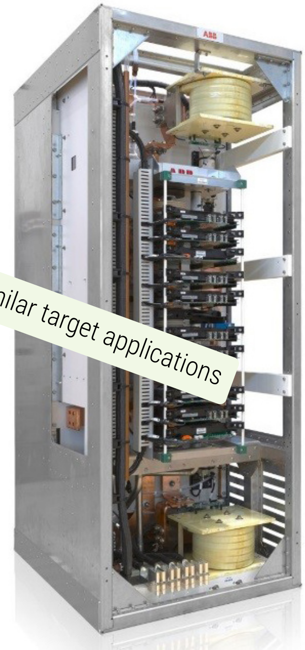
- MV designs

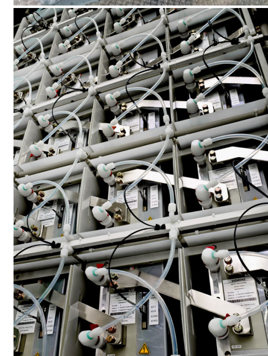


INDUSTRIAL MMC CELL DESIGNS

- HVDC designs

- MV designs





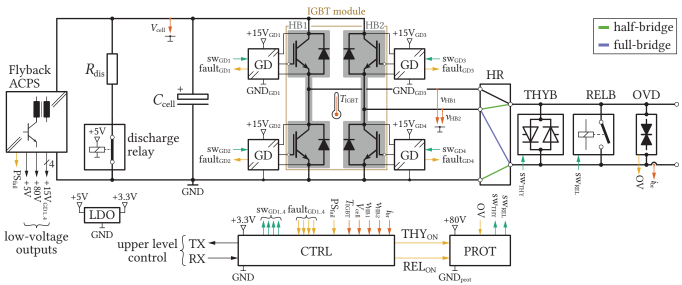
⇒ numerous designs for similar target applications

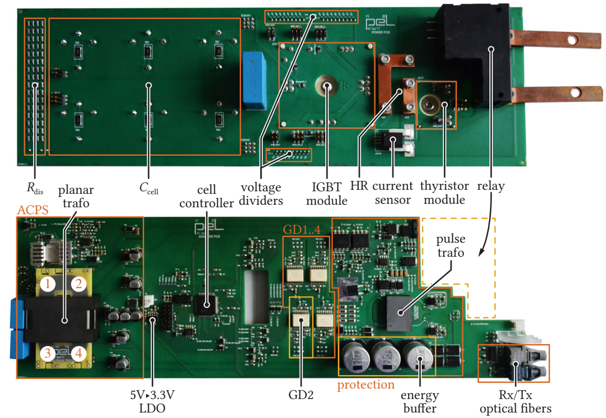
MMC CELL @ PEL

Ratings

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

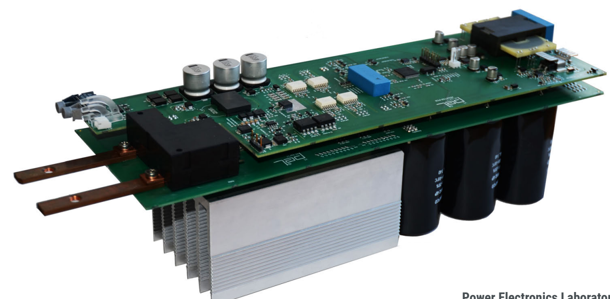
Cell concept





▲ Circuit partitioning

▼ Assembled cell

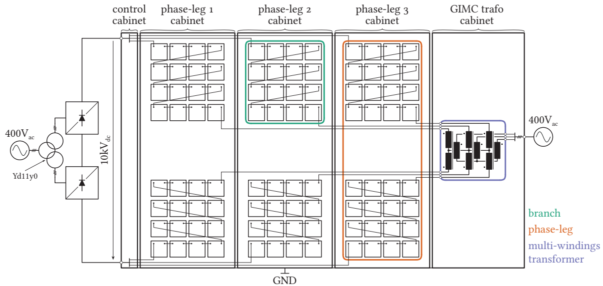


Design

- 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

INSULATION COORDINATION OF A MV CONVERTER PROTOTYPE

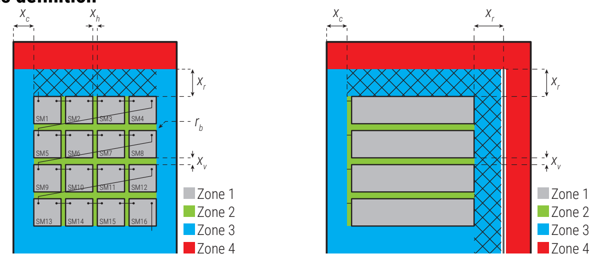
System partitioning



Standards

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

Zones definition



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

Zone 2 (ins. coord. branch)

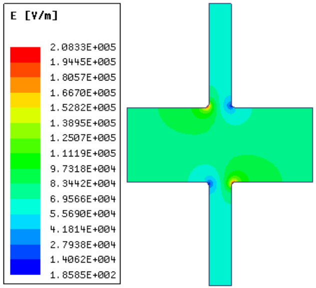
- Horizontal system voltage: 1 kV$_{ac}$
- Vertical system voltage: 3.6 kV$_{ac}$

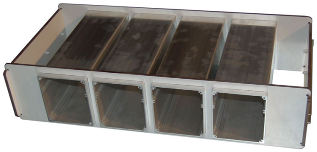
Zone 3 (ins. coord. branch - cabinet (at GND)) system voltage: 6.6 kV$_{ac}$

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

Zone 2

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

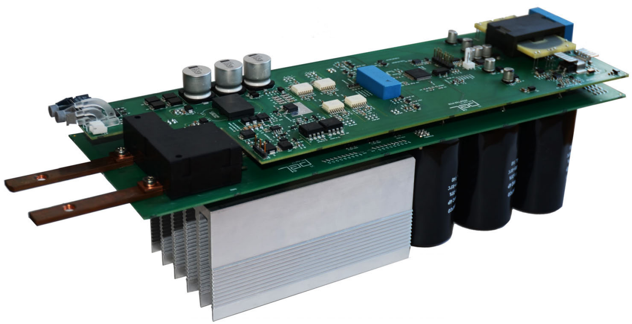




SUMMARY

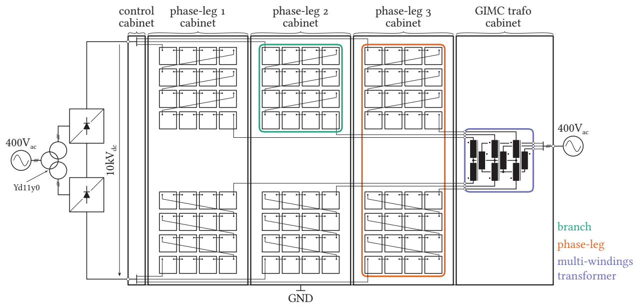
GIMC

- 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



ADCGS
Aachen DC Grid Summit

GALVANICALLY ISOLATED HIGH POWER CONVERTERS FOR MVDC APPLICATIONS

Prof. Drazen Dujic, Dr. Alexandre Christe

École Polytechnique Fédérale de Lausanne (EPFL)
Power Electronics Laboratory
Switzerland

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE