SCCER - FURIES
Shaping the FUtuRe SwIss Electrical InfraStructure

GALVANICALLY ISOLATED MODULAR CONVERTERS

A. Christe, Prof. D. Dujic
École Polytechnique Fédérale de Lausanne
Power Electronics Laboratory
Switzerland

PEL RESEARCH ACTIVITIES

Ongoing research projects related to MVDC

- *MVDC Energy Conversion Technologies and Systems*, SFOE funding
- *Multiport Energy Gateway*, SNSF NRP 70 funding
- *Solid State Resonant Conversion*, SNSF funding
- *Medium Frequency Transformer Design and Optimization*, internal funding
- *Galvanically Isolated Modular Converter*, SCCER-FURIES funding
- *High Power Multi Drive Systems operated from a MVDC Bus*, ind. funding
- *MVDC Protection Coordination*, ind. funding
- ...

Research focus

- System design optimization
- Source-load interactions and stability studies
- Power electronic conversion technologies
- Energy storage integration
- Medium frequency transformers for galvanic isolation

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Bundesamt für Energie BFE
Office fédéral de l'énergie OFEN

Energy Turnaround
National Research Programme NRP 70

FNSNF

SCCER – FURIES
Shaping the FUtuRe SwIss Electrical InfraStructure

In cooperation with the CTI

Energy funding programme
Swiss Competence Centers for Energy Research

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Commission for Technology and Innovation CTI

Objectives

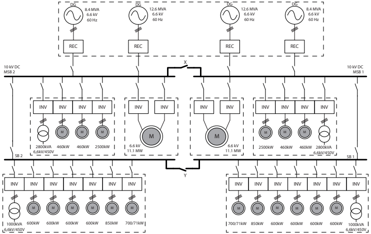
- Quantify potential and impact of MVDC systems (w.r.t. MVAC)
- Develop dynamic models and stability assessment tools
- Develop enabling power electronics technologies

Demonstration in PEL's MV laboratory

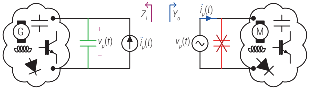
- Efficient electrical energy conversion (less losses)
- Compact electrical energy conversion (less raw materials)
- Energy storage integration (improved energy management)

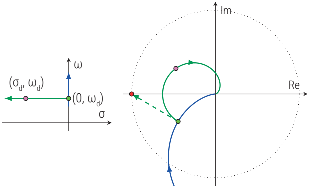
WG SC C6.31 *MVDC Grids - Feasibility Study* - next meeting to be held in Lausanne, January 17th - 18th, 2017

MVDC
ENERGY CONVERSION TECHNOLOGIES AND SYSTEMS



▲ MVDC for marine distribution [1]





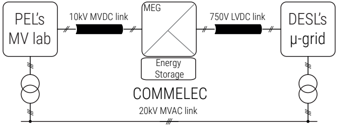
▲ Stability studies

[1] U. Javaid, D. Dujić, and W. van der Merwe. "MVDC marine electrical distribution: Are we ready?" *IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society*. Nov. 2015, pp. 823–828

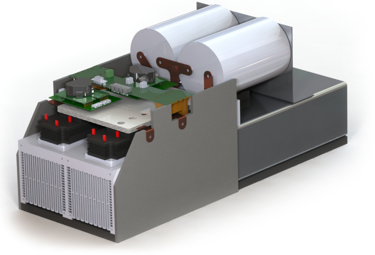
MULTIPORT ENERGY GATEWAY (MEG)

Focus

- MVDC-LVDC conversion system with integrated energy storage

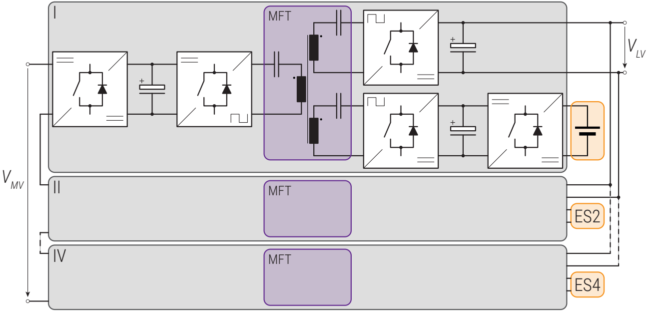


HV PEBB



Converter Topology

- SST with multiport resonant stage [2]



Features

- DC transformer
- Soft switching
- Hybrid ES
- Three windings MFT
- LLC resonant circuit
- Efficiency

Prototype ratings

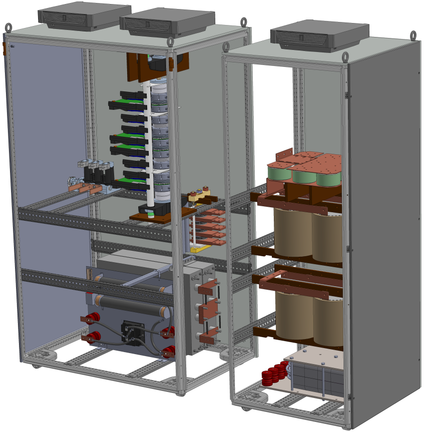
- $P = 0.5$ MW
- $V_{MV} = 10$ kV
- $V_{LV} = 750$ V

[2] Y.-K. Tran and D. Dujic. "A Multiport Medium Voltage Isolated DC-DC Converter." *The 42nd Annual Conference of IEEE Industrial Electronics Society-IECON*. EPFL-CONF-222799. 2016

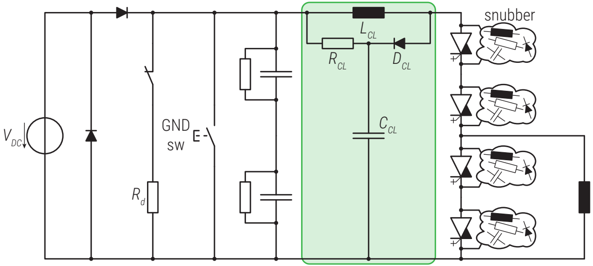
Focus

- Bulk power conversion
- IGCT characterization & optimization
- High power magnetics design

Test setup

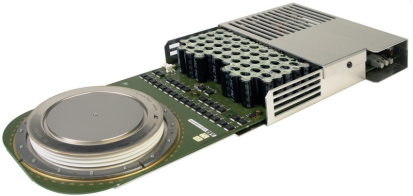


Characterization setup



Prototype

- $V_{DC} = 5\,\mathrm{kV}$
- $I_{max} = 2.25\,\mathrm{kA}$

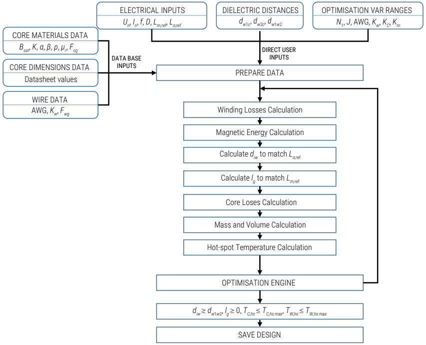


MFT DESIGN & OPTIMIZATION

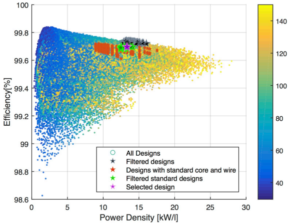
Focus

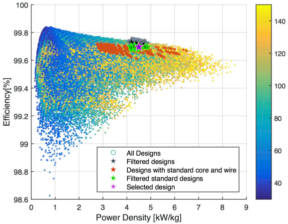
- High voltage MFT design [3] - insulation coordination
- Precise parameter control - resonant operation
- High power conversion - thermal design
- Characterization of magnetic materials

Design algorithm



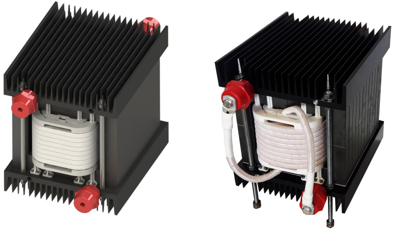
Optimization





Prototype

- $P = 100$ kW
- $V_p = V_s = 750$ V
- $f_{sw} = 10$ kHz

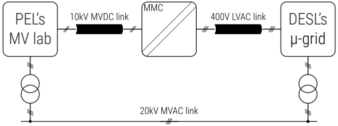


[3] M. Mogorovic and D. Dujic. "Medium Frequency Transformer Design and Optimization." *PCIM Europe 2017; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*. (submitted), May 2017

GALVANICALLY ISOLATED MODULAR CONVERTER (GIMC)

Focus

- MVDC-LVAC galvanically isolated conversion system



Features

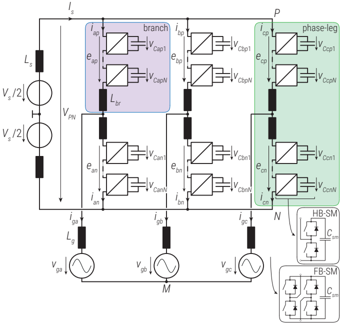
- High efficiency
- Galvanic isolation
- Modularity
- Scalability
- Reliability
- Availability

Prototype ratings

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

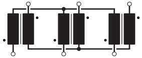
Considerations

- VSI on LVAC side of SST reduces efficiency by ≈ 2 % (!) [4]
- Solution with MMC + LFT preferred to overcome that issue



◀ Double-star Modular Multilevel Converter [5] for power flow and voltage control

▼ Line Frequency Transformer for voltage adaptation



Research challenge

- Transformer integration into the MMC

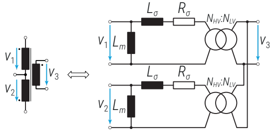
[4] J.E. Huber and J.W. Kolar. "Volume/weight/cost comparison of a 1MVA 10 kV/400 V solid-state against a conventional low-frequency distribution transformer." *Energy Conversion Congress and Exposition (ECCE), 2014 IEEE*. Sept. 2014, pp. 4545–4552

[5] R. Marquardt, A. Lesnicar, and J. Hildinger. "Modulares Stromrichterkonzept für Netzkupplungsanwendungen bei hohen Spannungen." *ETG-Fachtagung*. 2002

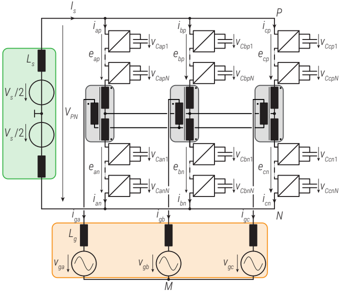
GIMC – TOPOLOGY AND OPERATING PRINCIPLES

- Transformer integration must achieve DC bias cancellation in magnetic core
- Two new structures are obtained
  1. Stacked GIMC [6]
  2. Interleaved GIMC [7]

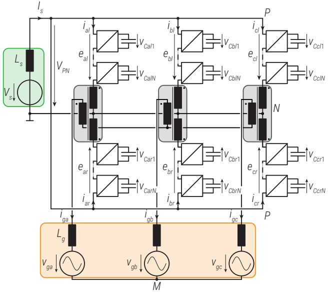
  } flexible configuration
- State-space models are identical ⇒ same control algorithm [8]



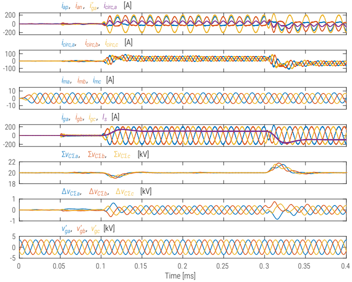
▲ Three-windings transformer



▲ Stacked GIMC



▲ Interleaved GIMC



▲ Full switched model simulation

[6] S. Tamada, Y. Nakazawa, and S. Irokawa. "A proposal of Modular Multilevel Converter applying three winding transformer." *Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE-ASIA), 2014 International*. May 2014, pp. 1357–1364

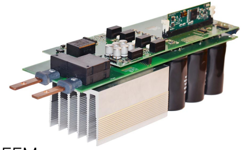
[7] M. Hagiwara and H. Akagi. "Experiment and Simulation of a Modular Push-Pull PWM Converter for a Battery Energy Storage System." *Industry Applications, IEEE Transactions on* 50.2 (Mar. 2014), pp. 1131–1140

[8] A. Christe and D. Dujic. "Galvanically isolated modular converter." *IET Power Electronics* 9.12 (2016), pp. 2318–2328

GIMC – CELL DESIGN

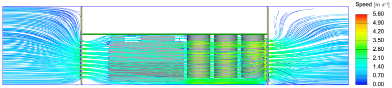
Cell

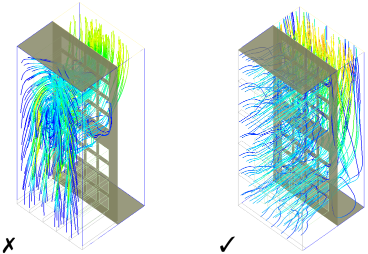
- 1.2 kV / 50 A full-bridge IGBT module
- $C_{cell} = 1.9$ mF



Thermal design [9]

- Cell level: detailed FEM
- Cabinet level: simplified FEM

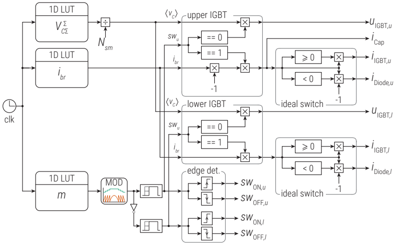


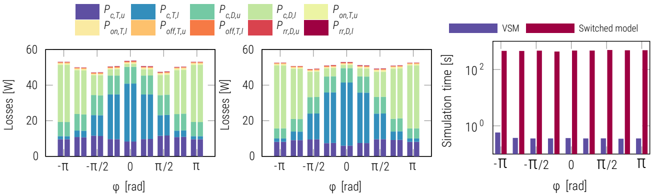


✗ ✓

Semiconductor losses

- Virtual Submodule concept has been utilized
- Closed-loop waveforms are approached by analytical waveforms





▲ PS-PWM, DC circ ▲ PS-PWM, DC+2nd circ ▲ Time benchmark

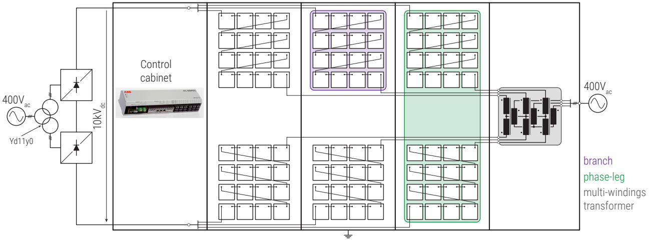
[9] E. Coulinge, A. Christe, and D. Dujic. "Electro-Thermal Design of a Modular Multilevel Converter Prototype." *PCIM Europe 2016; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*. May 2016, pp. 1–8

GIMC – CONVERTER LAYOUT

Dielectric design

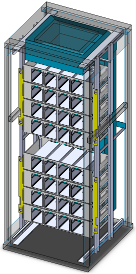
- Cell compliant to UL840 (< 1 kV_{ac} circuit)
- Converter compliant to IEC 61800-5-1 (6.6 kV_{ac} system, PD 1 & OV cat. I) [10]
- Design phase supported by FEM simulations
- Measurement in PD test setup (≤ 10 pC ✓)

Converter layout



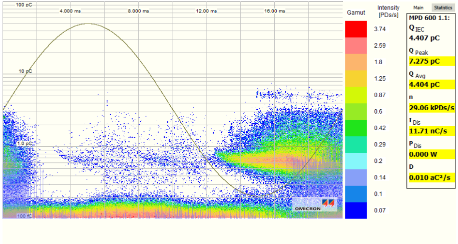
Design constraints to CAD

Var	Min [mm]
r_b	3
$d_{L,h}$	6.8
$d_{C,h}$	3.2
$d_{L,v}$	30
$d_{C,v}$	12.5
$d_{L,c}$	60
$d_{C,c}$	60
$d_{L,r}$	102



PD test setup

AC dielectric test



[10] A. Christe, E. Coulinge, and D. Dujic. "Insulation Coordination for a Modular Multilevel Converter Prototype." *Power Electronics and Applications (EPE 2016), Proceedings of the 2016-18th European Conference on.* 2016, pp. 1–10

ENABLING TECHNOLOGIES AT PEL

High power medium voltage conversion

- Offers efficient and controllable bulk power processing [MW]
- Requires careful insulation coordination - safety
- Leads to modular designs
- Implies advanced control / communication strategies
- Reliability and availability must be ensured

Research path

- System studies
- Modeling and simulations
- Control system design
- Medium voltage high power prototyping
- Performance verification
- Publishing

It is possible in an academic research laboratory...

SCCER - FURIES

Shaping the FUtuRe SwIss Electrical InfraStructure

GALVANICALLY ISOLATED MODULAR CONVERTERS

A. Christe, Prof. D. Dujic

École Polytechnique Fédérale de Lausanne

Power Electronics Laboratory

Switzerland

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE