MVDC
TECHNOLOGIES AND SYSTEMS

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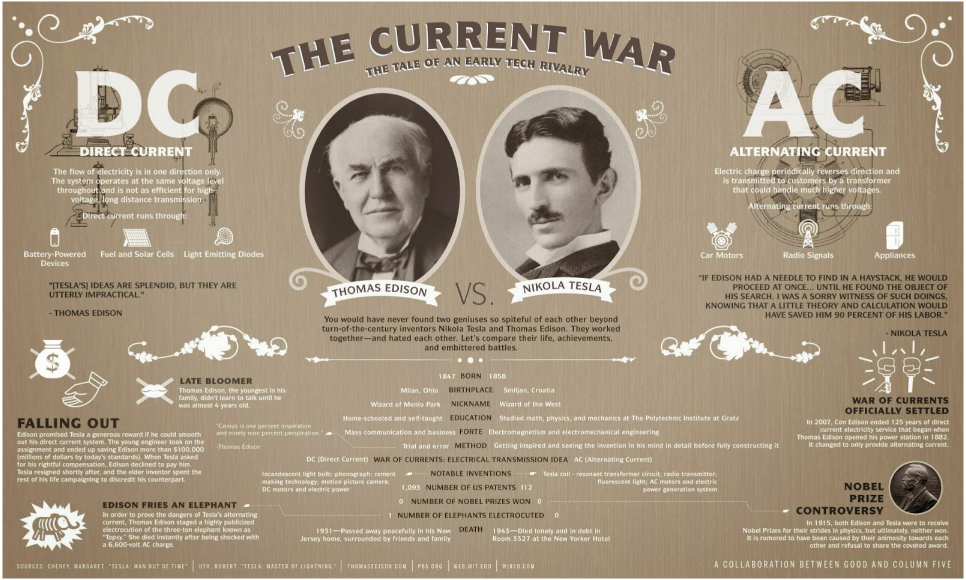
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

WAR OF CURRENTS



THE CURRENT WAR

THE TALE OF AN EARLY TECH RIVALRY

DC

DIRECT CURRENT

The flow of electricity is in one direction only. The system operates at the same voltage level throughout and is not as efficient for high-voltage, long distance transmission.

Direct current runs through:

- Battery-Powered Devices
- Fuel and Solar Cells
- Light Emitting Diodes

"[TESLA'S] IDEAS ARE SPLENDID, BUT THEY ARE UTTERLY IMPRACTICAL."

- THOMAS EDISON

AC

ALTERNATING CURRENT

Electric charge periodically reverses direction and is transmitted to customers by a transformer that could handle much higher voltages.

Alternating current runs through:

- Car Motors
- Radio Signals
- Appliances

"IF EDISON HAD A NEEDLE TO FIND IN A HAYSTACK, HE WOULD PROCEED AT ONCE... UNTIL HE FOUND THE OBJECT OF HIS SEARCH. I WAS A SORRY WITNESS OF SUCH DOINGS, KNOWING THAT A LITTLE THEORY AND CALCULATION WOULD HAVE SAVED HIM 90 PERCENT OF HIS LABOR."

- NIKOLA TESLA

THOMAS EDISON VS. NIKOLA TESLA

You would have never found two geniuses so spiteful of each other beyond turn-of-the-century inventors Nikola Tesla and Thomas Edison. They worked together—and hated each other. Let's compare their life, achievements, and embittered battles.

THOMAS EDISON		NIKOLA TESLA
1847	BORN	1858
Milan, Ohio	BIRTHPLACE	Smiljan, Croatia
Wizard of Menlo Park	NICKNAME	Wizard of the West
Home-schooled and self-taught	EDUCATION	Studied math, physics, and mechanics at The Polytechnic Institute at Gratz
Mass communication and business	FORTE	Electromagnetism and electromechanical engineering
Trial and error	METHOD	Getting inspired and seeing the invention in his mind in detail before fully constructing it
DC (Direct Current)	WAR OF CURRENTS: ELECTRICAL TRANSMISSION IDEA	AC (Alternating Current)
Incandescent light bulb; phonograph; cement making technology; motion picture camera; DC motors and electric power	NOTABLE INVENTIONS	Tesla coil - resonant transformer circuit; radio transmitter; fluorescent light; AC motors and electric power generation system
1,093	NUMBER OF US PATENTS	112
0	NUMBER OF NOBEL PRIZES WON	0
1	NUMBER OF ELEPHANTS ELECTROCUTED	0
1931—Passed away peacefully in his New Jersey home, surrounded by friends and family	DEATH	1943—Died lonely and in debt in Room 3327 at the New Yorker Hotel

LATE BLOOMER

Thomas Edison, the youngest in his family, didn't learn to talk until he was almost 4 years old.

"Genius is one percent inspiration and ninety nine percent perspiration."

-Thomas Edison

FALLING OUT

Edison promised Tesla a generous reward if he could smooth out his direct current system. The young engineer took on the assignment and ended up saving Edison more than $100,000 (millions of dollars by today's standards). When Tesla asked for his rightful compensation, Edison declined to pay him. Tesla resigned shortly after, and the elder inventor spent the rest of his life campaigning to discredit his counterpart.

EDISON FRIES AN ELEPHANT

In order to prove the dangers of Tesla's alternating current, Thomas Edison staged a highly publicized electrocution of the three-ton elephant known as "Topsy." She died instantly after being shocked with a 6,600-volt AC charge.

WAR OF CURRENTS OFFICIALLY SETTLED

In 2007, Con Edison ended 125 years of direct current electricity service that began when Thomas Edison opened his power station in 1882. It changed to only provide alternating current.

NOBEL PRIZE CONTROVERSY

In 1915, both Edison and Tesla were to receive Nobel Prizes for their strides in physics, but ultimately, neither won. It is rumored to have been caused by their animosity towards each other and refusal to share the coveted award.

SOURCES: CHENEY, MARGARET. "TESLA: MAN OUT OF TIME" | UTH, ROBERT. "TESLA: MASTER OF LIGHTNING." | THOMASEDISON.COM | PBS.ORG | WEB.MIT.EDU | WIRED.COM

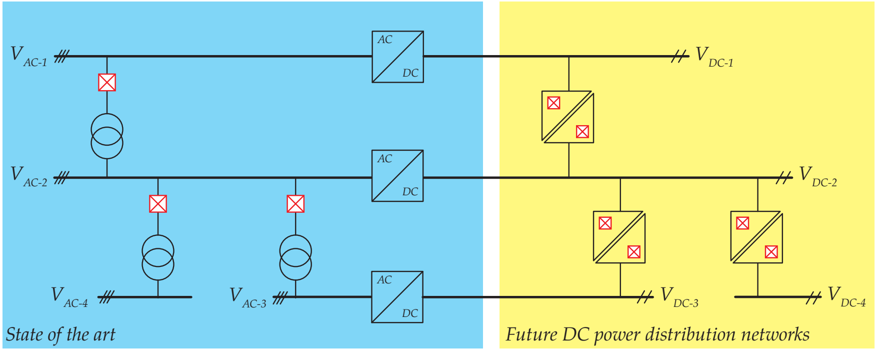
A COLLABORATION BETWEEN GOOD AND COLUMN FIVE

▲ War of Currents - History is repeating, but in a somewhat different way

MVDC POWER DISTRIBUTION NETWORKS

DC is already a reality

- LVDC - Telecom, Transportation, DER, ES
- HVDC - Bulk power transmission
- **MVDC** - Neither developed nor fully explored?
- Lack of **Conversion** and **Protection** technologies



▲ Today's AC and tomorrow's DC power distribution networks

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)

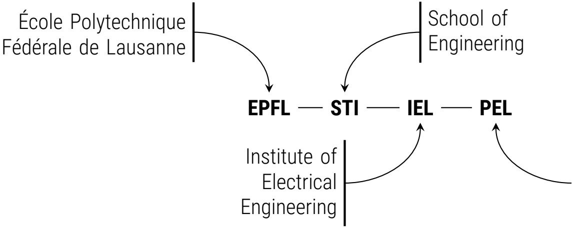
ABB Medium Voltage Drives

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



École Polytechnique
Fédérale de Lausanne

School of
Engineering

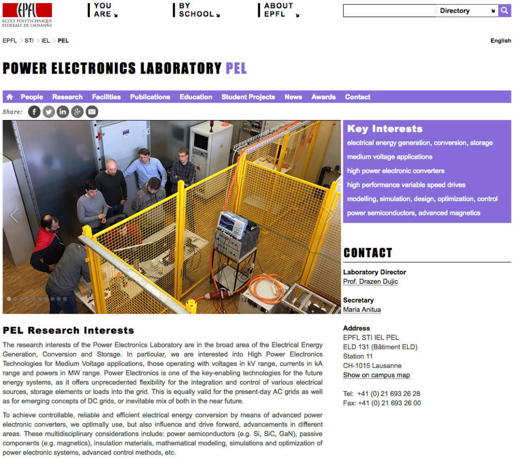
EPFL — STI — IEL — PEL

Institute of
Electrical
Engineering

- Online since February 2014
- `http://pel.epfl.ch`

ECPE

Competence Centre



POWER ELECTRONICS LABORATORY PEL

Key Interests

- electrical energy generation, conversion, storage
- medium voltage applications
- high power electronic converters
- high performance variable speed drives
- modelling, simulation, design, optimization, control
- power semiconductors, advanced magnetics

PEL Research Interests

The research interests of the Power Electronics Laboratory are in the broad area of the Electrical Energy Generation, Conversion and Storage. In particular, we are interested into High Power Electronics Technologies for Medium Voltage applications, those operating with voltages in kV range, currents in kA range and powers in MW range. Power Electronics is one of the key-enabling technologies for the future energy systems, as it offers unprecedented flexibility for the integration and control of various electrical sources, storage elements or loads into the grid. This is equally valid for the present-day AC grids as well as for emerging concepts of DC grids, or inevitable mix of both in the near future.

To achieve controllable, reliable and efficient electrical energy conversion by means of advanced power electronic converters, we optimally use, but also influence and drive forward, advancements in different areas. These multidisciplinary considerations include: power semiconductors (e.g. Si, SiC, GaN), passive components (e.g. magnetics), insulation materials, mathematical modeling, simulations and optimization of power electronic systems, advanced control methods, etc.

CONTACT

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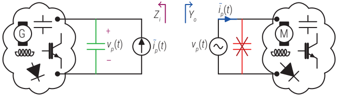
MVDC RESEARCH FOCUS

Technologies and Systems

- System Stability
- Protection Coordination
- Power Electronic Conversion

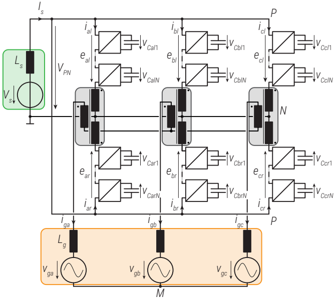
MVDC

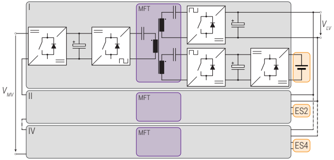
ENERGY CONVERSION TECHNOLOGIES AND SYSTEMS



High Power Converters

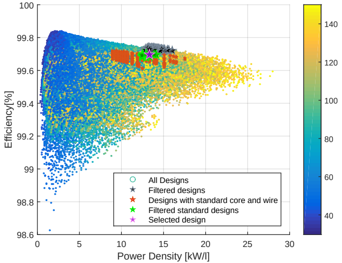
- Modular Multilevel Converters
- Solid State Transformers
- Medium Frequency Conversion

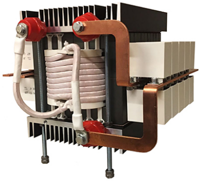




Components

- Semiconductor devices
- Magnetic components
- Optimization





MVDC POWER DISTRIBUTION NETWORKS

MVDC Power Distribution Networks

- Feasibility (Applications)
- System Level Gains
- Dynamic Stability

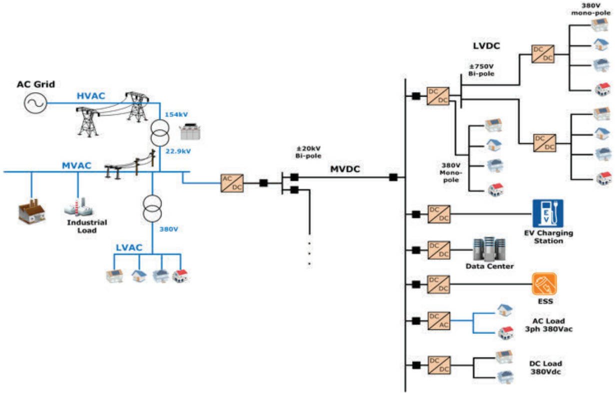
Conversion

- Passive, Efficient and Stable
- Flexible, Modular and Scalable
- Efficient

Protection

- DC Breaker?
- Fault Current Limiting by Converters
- Protection Coordination

▲ Power electronics constituents



▲ Possible future MVDC grids and its links with existing grids

MVDC RESEARCH PROJECTS

MVDC

Power Electronic Systems

- ***MVDC*** *Energy Conversion Technologies and Systems*
- *High Power Multi Drive Systems Operated from a* ***MVDC*** *Bus*
- ***MVDC*** *Protection Coordination*

Power Electronic Conversion

- *Multiport Energy Gateway -* ***MVDC*** *DC-DC-DC*
- *Galvanically Isolated Modular Converter -* ***MVDC****-LVAC*
- *SST for* ***MVDC*** *Applications -* ***MVDC****-LVDC*

Power Electronic Components

- *Solid State Resonant Conversion*
- *Medium Frequency Transformer Design and Optimization*

MVDC ENERGY CONVERSION – TECHNOLOGIES AND SYSTEMS

Objectives

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

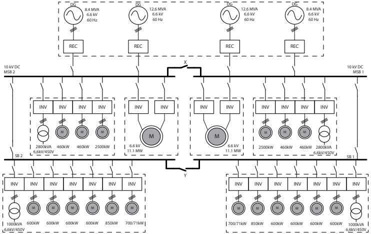
Demonstration in PEL's MV laboratory

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

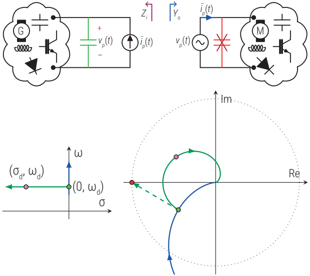
WG SC C6.31 *MVDC Grids - Feasibility Study*

MVDC

ENERGY CONVERSION TECHNOLOGIES AND SYSTEMS



▲ MVDC for marine distribution [1]



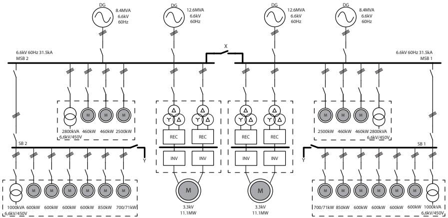
▲ MVDC stability studies [2]

MARINE MVDC ELECTRICAL DISTRIBUTION

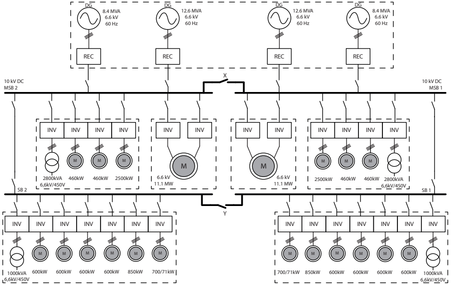
MVDC Benefits:

- Increased fuel efficiency
- Removal of need to synchronize multiple generators
- Removal of bulky line frequency transformers
- Flexibility in design of ship electrical system
- Easier energy storage integration
- Less losses in MVDC cables (less resistive and no reactance effects)
- Better MVDC cable utilization (no skin effect)

▲ Electrical ship layout



▲ MVAC marine distribution - real case



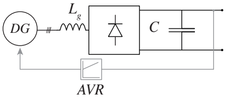
▲ MVDC marine distribution - possible evolution [1]

MARINE MVDC ELECTRICAL DISTRIBUTION

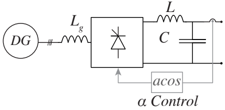
MVDC Challenges:

- Lack of conversion technologies for MVDC
- Lack of protection technologies (DC breaker)
- Multiple possible layouts for MVDC electrical distribution
- Various options are possible for MVDC supplies
- Need for stability studies during design
- Understanding degrees of freedom in the design of enabling technologies
- Design of advance control algorithms for MVDC load/sources

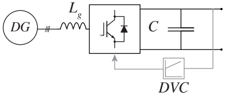
▲ Electrical ship layout



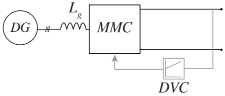
▲ Diode rectifier



▲ SCR Rectifier



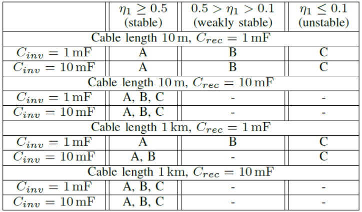
▲ Active Rectifier - Multilevel



▲ Active Rectifier - MMC

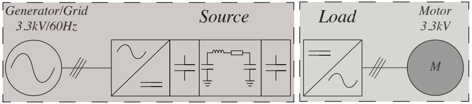
MVDC LOAD-SOURCE INTERACTIONS

- MVDC power supplies:
  - 6-pulse diode rectifier
  - 6-pulse thyristor rectifier
  - 3-L NPC active rectifier
- VSD at full and partial load
- Realistic control bandwidth assumptions
- Passive components are swept (cable length, capacitances, etc.)
- Active rectifier shows high interactions with VSD controller

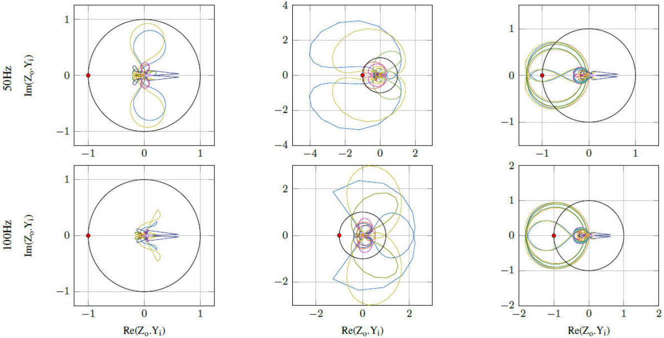


	$\eta_1 \geq 0.5$ (stable)	$0.5 > \eta_1 > 0.1$ (weakly stable)	$\eta_1 \leq 0.1$ (unstable)
Cable length 10 m, $C_{rec} = 1\,\mathrm{mF}$			
$C_{inv} = 1\,\mathrm{mF}$	A	B	C
$C_{inv} = 10\,\mathrm{mF}$	A	B	C
Cable length 10 m, $C_{rec} = 10\,\mathrm{mF}$			
$C_{inv} = 1\,\mathrm{mF}$	A, B, C	-	-
$C_{inv} = 10\,\mathrm{mF}$	A, B, C	-	-
Cable length 1 km, $C_{rec} = 1\,\mathrm{mF}$			
$C_{inv} = 1\,\mathrm{mF}$	A	B	C
$C_{inv} = 10\,\mathrm{mF}$	A, B	-	C
Cable length 1 km, $C_{rec} = 10\,\mathrm{mF}$			
$C_{inv} = 1\,\mathrm{mF}$	A, B, C	-	-
$C_{inv} = 10\,\mathrm{mF}$	A, B, C	-	-

▲ Stability results



▲ Two port MVDC model used for the study



(a) Diode Rectifier (b) Thyristor Controlled Rectifier (c) Active Rectifier

▲ Nyquist plots for stability assessments (from $Z_i(\omega)Y_o(\omega)$ data) [2]

DC PROTECTION COORDINATION

Fault Detection

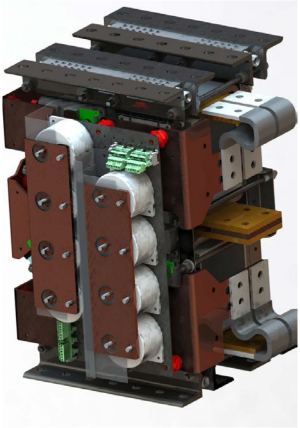
- Different Z_{SC} at different voltage levels
- Obscured by fast control actions
- Fast and Reliable detection is needed

Fault Localization

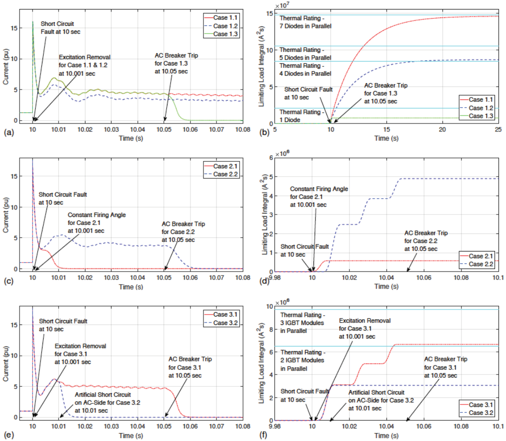
- System Architecture
- Zonal Power Distribution
- Quick localization is needed

Fault Isolation

- DC Breaker or Fault Current Limiting?
- Short-Circuit Proof Bus-Ties
- Fast Action is needed (Semiconductors)

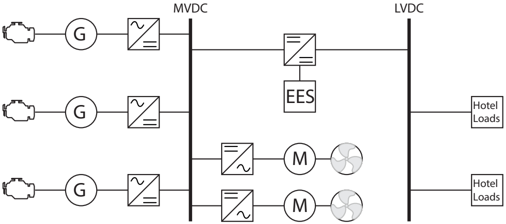


▲ Short-Circuit Proof DC Bus-Tie (Source: Siemens)

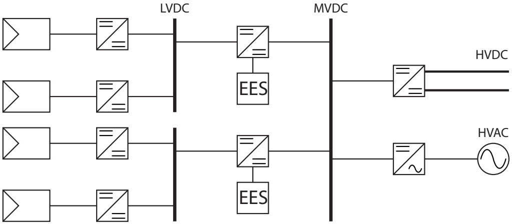


▲ DC short circuit analysis simulations, 4MW, LVDC: (a-b) DRU, (c-d) SCR, (e-f) ARU

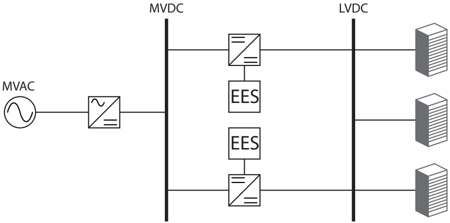
MVDC ENERGY STORAGE - MULTIPORT ENERGY GATEWAY



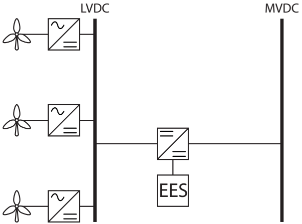
▲ MEG for marine applications



▲ MEG for renewable PV applications



▲ MEG for data-center applications

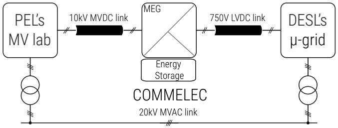


▲ MEG for renewable wind applications

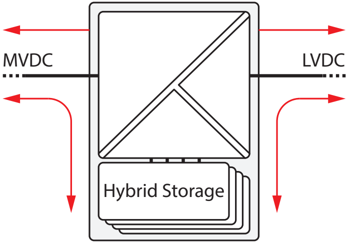
MULTIPORT ENERGY GATEWAY (MEG)

Focus

- MVDC-LVDC conversion system with integrated energy storage

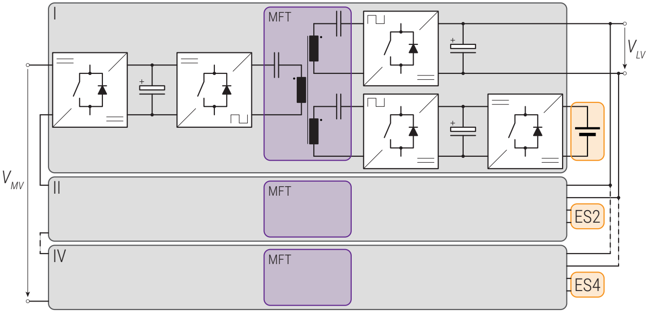


Idea



Converter Topology

- SST with multiport resonant stage [3]



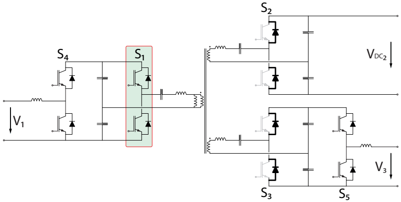
Features

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

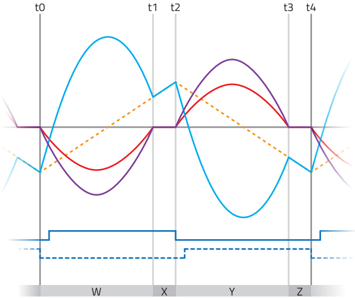
Prototype ratings

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

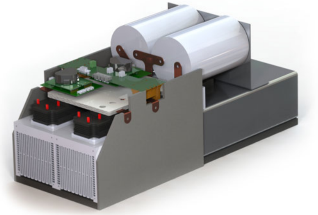
MEG DEMONSTRATOR



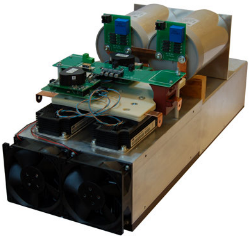
▲ MEG mode of operation



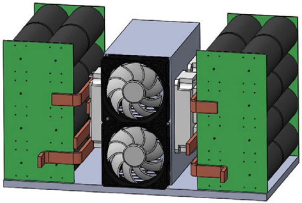
▲ MEG resonant current waveforms



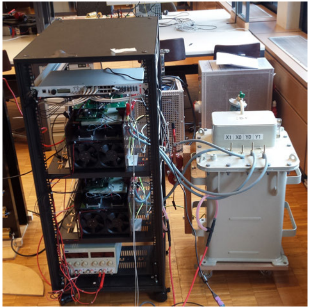
▲ MEG HV PEBB - design



▲ MEG HV PEBB - prototype



▲ MEG LV PEBB - design

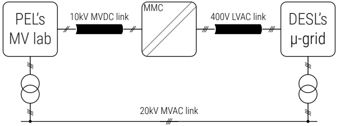


▲ MEG test setup

GALVANICALLY ISOLATED MODULAR CONVERTER (GIMC)

Focus

- MVDC-LVAC galvanically isolated conversion system



Features

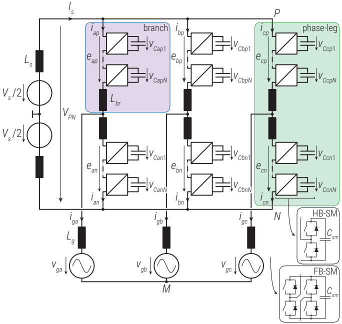
- High efficiency
- Galvanic isolation
- Modularity
- Scalability
- Reliability
- Availability

Prototype ratings

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

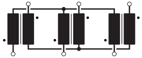
Considerations

- VSI on LVAC side of SST reduces efficiency by $\approx 2\,\%$ (!)
- Solution with MMC + LFT preferred to overcome that issue



◂ Double-star Modular Multilevel Converter for power flow and voltage control [4]

▾ Line Frequency Transformer for voltage adaptation



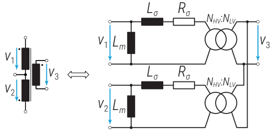
Research challenge

- Transformer integration into the MMC
- Control system implications
- Overall system optimization

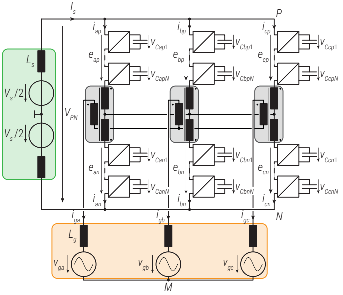
GIMC – TOPOLOGY AND OPERATING PRINCIPLES

- Transformer integration must achieve DC bias cancellation in magnetic core [5]
- Two new structures are obtained
  1. Stacked GIMC [4],[6]
  2. Interleaved GIMC [7]

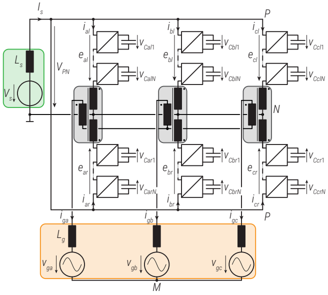
  } flexible configuration
- State-space models are identical ⇒ the same control algorithm [8]



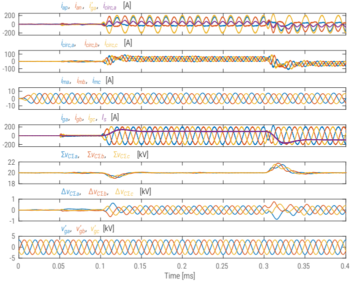
▲ Three-windings transformer



▲ Stacked GIMC



▲ Interleaved GIMC

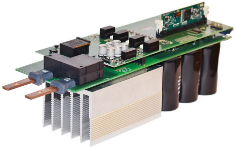


▲ Full switched model simulation

GIMC – CELL OPTIMIZATION

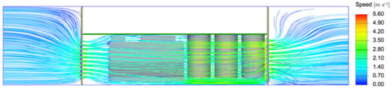
Cell

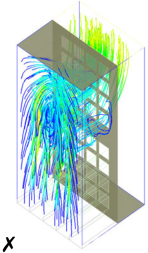
- 1.2 kV / 50 A full-bridge IGBT module
- $C_{cell} = 2.25\,\text{mF}$



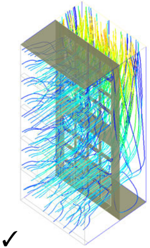
Thermal design [9]

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





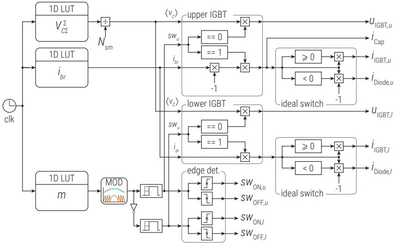
✗

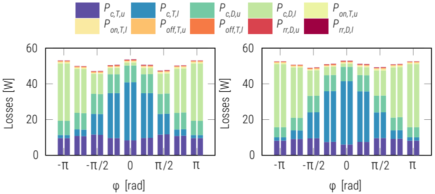


✓

Semiconductor losses

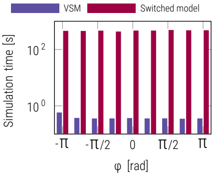
- Virtual Submodule concept has been utilized [10]
- Closed-loop waveforms are approached by analytical waveforms





▲ PS-PWM, DC circ

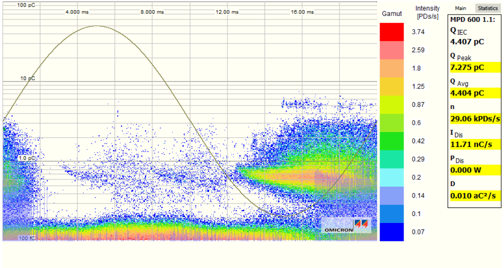
▲ PS-PWM, DC+2nd circ



▲ Time benchmark

GIMC – CONVERTER DESIGN

- ✓ MV MMC converter laboratory prototype layout compliant with:
  - UL840 (for cell)
  - IEC 61800-5-1
- ✓ Complete AC dielectric withstand tests on real prototype [11]

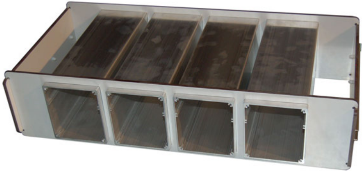


MPD 600 1.1:
Q_{IEC}
4.407 pC
Q_{Peak}
7.275 pC
Q_{Avg}
4.404 pC
n
29.06 kPDs/s
I_{Dis}
11.71 nC/s
P_{Dis}
0.000 W
D
0.010 aC²/s

▲ AC dielectric withstand test result

◄ Cabinet of one phase-leg (32 cells) in Faraday cage during insulation coordination testing

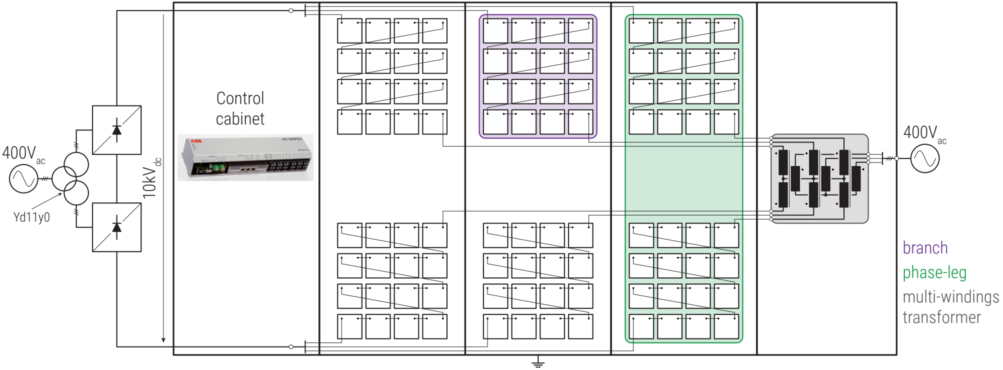
▼ Drawer holding 4 cell (MKHP material)



GIMC – CONVERTER LAYOUT

MMC demonstrator ratings are:

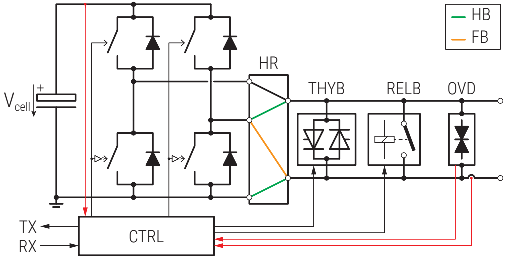
- 500 kVA
- 10 $kV_{dc} \leftrightarrow 400\ V_{ac}$ or 6.6 kV_{ac}
- 16 low voltage cells per branch $\Rightarrow$ 32 cells per phase (cabinet) $\Rightarrow$ 96 cells in total
- Industrial central controller and communication (ABB AC PEC 800)



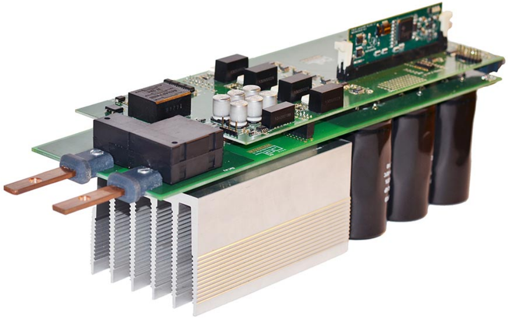
▲ DC/3-AC MMC Converter Layout

GIMC – CELL RATINGS

- 1.2 kV / 50 A IGBT module (Semikron SK50GH12T4T)
- 1.2 kV / 70 A Thyristor module (Semikron SK70KQ12)
- 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)
- DSP TI TMS320F28069
- Integrated Flyback auxiliary cell power supply from DC link
- Fiber Optical communication with the central controller



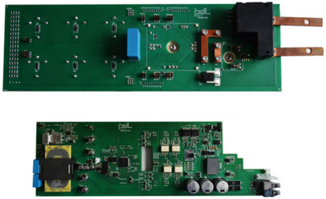
▲ Simplified MMC cell: HR block allow for reconfiguration



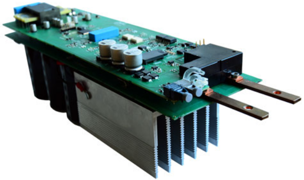
▲ MMC cell - early design

GIMC – CELL DESIGN

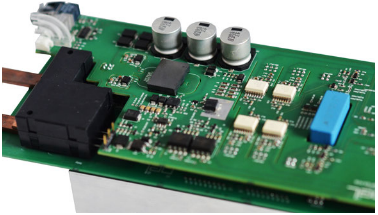
▲ MMC Cell - metal enclosure



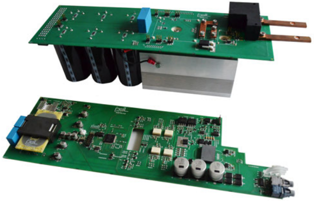
▲ MMC Cell PCBs - top view



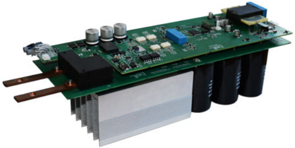
▲ MMC Cell - angled view



▲ MMC Cell - zoom in



▲ MMC Cell PCBs - side view



▲ MMC Cell - angle view

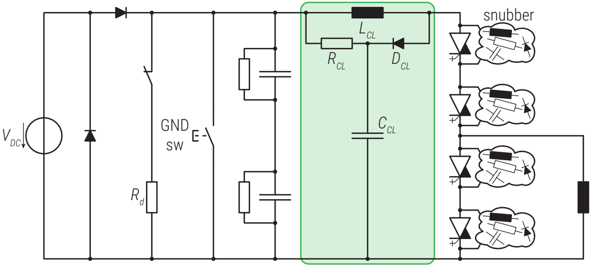
SOLID STATE RESONANT CONVERSION

Focus

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

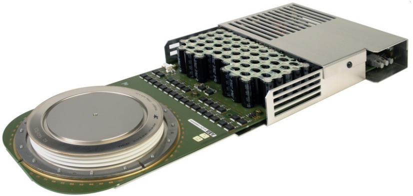
Test setup

Characterization setup



Prototype

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



LINE FREQUENCY TRANSFORMERS

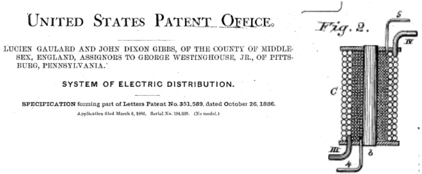
IEC 60076-1 definition - Power Transformer: *A static piece of apparatus with two or more windings which, by electromagnetic induction, transforms a system of alternating voltage and current into another system of voltage and current usually of different values and at the same frequency for the purpose of transmitting electrical power.*

Line Frequency Transformers

- Around for more than 100 of years
- Operated at low (grid) frequencies: 16.7Hz, 25Hz, 50/60Hz
- Standardized shapes and materials
- Cheap: ≈ 10kUSD / MW
- Efficient: above 99 % for utility applications
- Simple and reliable device

What are the problems?

- Bulky - for certain applications
- Inefficient - for certain applications
- Uncontrollable power flow
- Fixed transformation (power, voltage, current, frequency)



UNITED STATES PATENT OFFICE.

LUCIEN GAULARD AND JOHN DIXON GIBBS, OF THE COUNTY OF MIDDLESEX, ENGLAND, ASSIGNORS TO GEORGE WESTINGHOUSE, JR., OF PITTSBURG, PENNSYLVANIA.

SYSTEM OF ELECTRIC DISTRIBUTION.

SPECIFICATION forming part of Letters Patent No. 351,589, dated October 26, 1886.

Application filed March 6, 1886. Serial No. 194,229. (No model.)

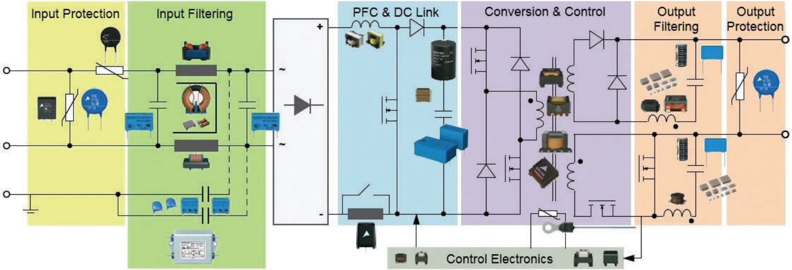
▲ Source: www.abb.com

MEDIUM-HIGH FREQUENCY CONVERSION

Switched Mode Power Supply (SMPS) Technologies

- Medium or High frequency conversion is not a new thing!
- Widely deployed in low voltage/power applications
- High efficiency
- Galvanic isolation at high frequency (standardized core sizes and shapes)
- Compact size (e.g. laptop chargers)
- Increased power density
- Cost savings

Could a Solid State Transformer provide that for a High Power Medium Voltage Applications?



▲ SMPS Technologies; Source: www.mouser.ch/new/tdk/epcos-smps/

SOLID STATE TRANSFORMERS

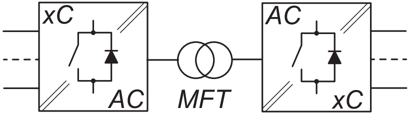
What is a Solid State Transformers?

- Not a transformer replacement?
- Should not be compared against 50/60 Hz transformer!

What is it?

- A converter
- A converter with galvanic isolation
- Can be designed for DC and AC (1-ph, 3-ph) grid
- Can be used in LV, MV and HV applications
- Can be made for AC-AC, DC-DC, AC-DC, DC-AC conversion
- Has power electronics on each terminal
- Transformer frequency higher than 50/60 Hz

Excellent tutorials are available at: https://www.pes.ee.ethz.ch



▲ Simplified SST concept

ETH zürich

IEEE PEMC

Tutorial No. 1

Solid-State Transformers
Key Design Challenges, Applicability,
and Future Concepts

Johann W. Kolar, Jonas E. Huber
Power Electronic Systems Laboratory
ETH Zurich, Switzerland

J. W. Kolar, **J. Huber**	Fundamentals and Application-Oriented Evaluation of Solid-State Transformer Concepts	Tutorial at the Southern Power Electronics Conference (SPEC 2016), Auckland, New Zealand, December 5-8, 2016
J. W. Kolar, **J. E. Huber**	Solid-State Transformers - Key Design Challenges, Applicability, and Future Concepts	Tutorial at the Internal Conference on Power Electronics and Motion Control (PEMC 2016), Varna, Bulgaria, September 25-30, 2016
J. W. Kolar, **J. Huber**	Solid-State Transformers - Key Design Challenges, Applicability, and Future Concepts	Tutorial at the 8th International Power Electronics and Motion Control Conference (IPEMC 2016-ECCE Asia), Hefei, China, May 22-25, 2016
J. W. Kolar, **J. Huber**	Solid-State Transformers: Key Design Challenges, Applicability, and Future Concepts	Tutorial at the Applied Power Electronics Conference (APEC), Long Beach, CA, USA, Mar. 20-24, 2016
R. Burkart, **J. W. Kolar**	Advanced Modeling and Multi-Objective Optimization / Evaluation of SiC Converter Systems,	Tutorial at the 3rd IEEE Workshop on Wide Bandgap Power Devices and Applications (WiPDA 2015), Blacksburg, USA, Nov. 2-5, 2015
R. Bosshard, **J. W. Kolar**	Fundamentals and Multi-Objective Design of Inductive Power Transfer Systems	Tutorial at the the 17th European Conference on Power Electronics and Applications (ECCE Europe 2015), Geneva, Switzerland, September 8-10, 2015
R. Bosshard, **J. W. Kolar**	Fundamentals and Multi-Objective Design of Inductive Power Transfer Systems	Tutorial at the 9th International Conference on Power Electronics (ICPE 2015-ECCE Asia), Seoul, Korea, June 1-5, 2015
R. Bosshard, **J. W. Kolar**	Fundamentals and Multi-Objective Design of Inductive Power Transfer Systems	Tutorial at the Conference for Power Conversion and Intelligent Motion (PCIM Europe 2015), Nuremberg, Germany, May 19-21, 2015
J. W. Kolar, **J. Huber**	Solid-State Transformers in Future Traction and Smart Grids	Tutorial at the Conference for Power Conversion and Intelligent Motion (PCIM Europe 2015), Nuremberg, Germany, May 19-21, 2015
G. Ortiz, **J. W. Kolar**	Solid State Transformer Concepts in Traction and Smart Grid Applications	Seminar at the Conference for Power Electronics, Intelligent Motion, Power Quality (PCIM South America 2014), Saõ Paulo, Brazil, October 14-15, 2014.

SST APPLICATIONS

Railway

- 1-phase AC grids [12]
- Few voltage levels: 15kV (16.7Hz) or 25kV (50Hz)
- Low frequency (historically): (15kV) 16.7Hz or (25kV) 50Hz
- On-board installations - serious space constraints
- Volume and Weight reduction - system savings
- Reliability - high number of devices?
- Efficiency - easy to beat traction LFT
- Control - similar to existing solutions
- Cost?

▲ ABB's PETT (Source: www.abb.com) [13], [14]

Utility

- 3-phase AC grids
- Many voltage levels: 3.3, 4.16, 6, 11, 15, 20kV, ...
- Grid frequency: 50Hz or 60Hz
- Sub-station installations - relatively low space constraints
- Volume and Weight reduction - not that relevant
- Reliability - even more complex due to 3-phases
- Efficiency - hard to beat distribution LFT
- Control - improved compared to existing solutions
- Cost?

▲ GE's SST [15] (Source: www.ge.com)

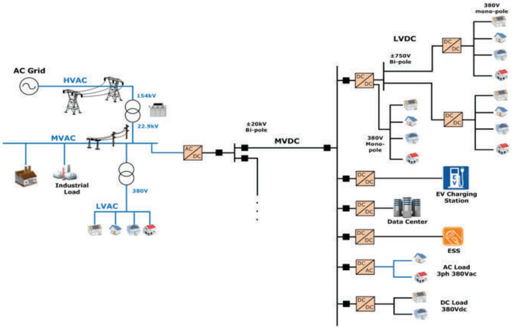
SST APPLICATIONS (CONT.)

MVDC Grids

- DC grids as a missing link
- Galvanic isolation seen as necessary
- Bidirectional power flow
- High efficiency
- Need for high power DC-DC converters

Marine LVDC / MVDC Distribution

- System level benefits
- Improved partial load efficiency
- Integration of storage technologies
- Protection coordination
- Need for high power DC-DC converters



▲ MVDC grids (Source: www.english.hhi.co.kr)

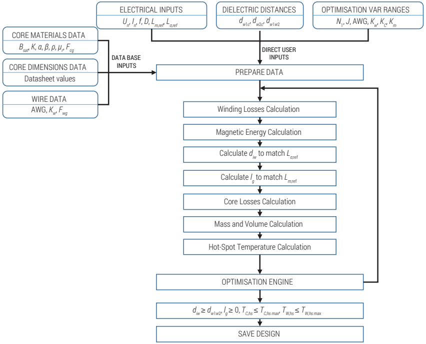
▲ MVDC marine distribution (Source: www.abb.com)

MFT DESIGN & OPTIMIZATION

Focus

- High voltage MFT design [1] - insulation coordination
- Precise parameter control - resonant operation
- High power conversion - thermal design
- Characterization of magnetic materials

Design algorithm



ELECTRICAL INPUTS
$U_n, I_n, f, D, L_{m,ref}, L_{\sigma,ref}$

DIELECTRIC DISTANCES
$d_{w1c}, d_{w2c}, d_{w1w2}$

OPTIMISATION VAR RANGES
N_1, J, AWG, K_w, K_C, K_m

CORE MATERIALS DATA
$B_{sat}, K, \alpha, \beta, \rho, \mu_r, F_{cg}$

CORE DIMENSIONS DATA
Datasheet values

WIRE DATA
AWG, K_w, F_{wg}

DATA BASE INPUTS

DIRECT USER INPUTS

PREPARE DATA

Winding Losses Calculation

Magnetic Energy Calculation

Calculate d_{iw} to match $L_{\sigma,ref}$

Calculate l_g to match $L_{m,ref}$

Core Losses Calculation

Mass and Volume Calculation

Hot-Spot Temperature Calculation

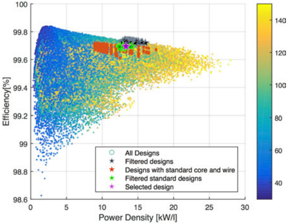
OPTIMISATION ENGINE

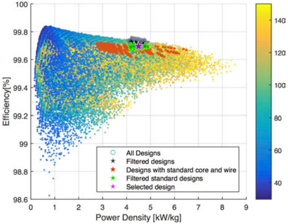
$d_{iw} \geq d_{w1w2}, l_g \geq 0, T_{C,hs} \leq T_{C,hs\,max}, T_{W,hs} \leq T_{W,hs\,max}$

SAVE DESIGN

▲ MFT design optimization algorithm [16], [17], [18]

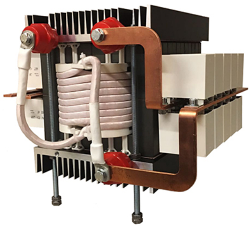
Optimization





Prototype

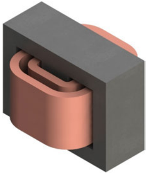
- $P = 100$ kW
- $V_p = V_s = 750$ V
- $f_{sw} = 10$ kHz

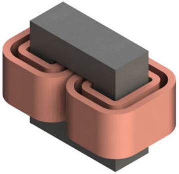


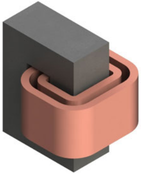
MFT TECHNOLOGIES AND MATERIALS

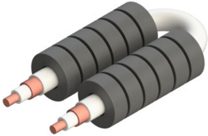
Construction Choices:

- MFT Types


Shell Type


Core Type

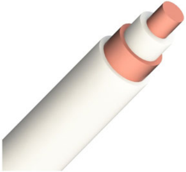

C-Type

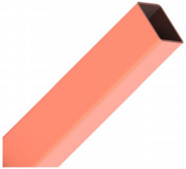

Coaxial Type

- Winding Types


Litz Wire


Foil


Coaxial


Hollow

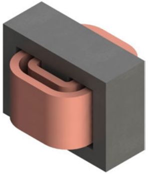
Materials:

- Magnetic Materials
  - Silicon Steel
  - Amorphous
  - Nanocrystalline
  - Ferrites
- Windings
  - Copper
  - Aluminum
- Insulation
  - Air
  - Solid
  - Oil
- Cooling
  - Air natural/forced
  - Oil natural/forced
  - Water

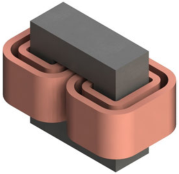
MFT TECHNOLOGIES AND MATERIALS

Construction Choices:

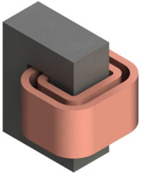
- MFT Types



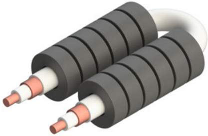
Shell Type



Core Type



C-Type

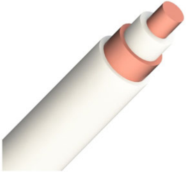


Coaxial Type

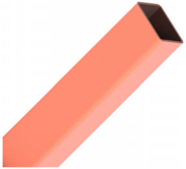
- Winding Types

Litz Wire

Foil



Coaxial

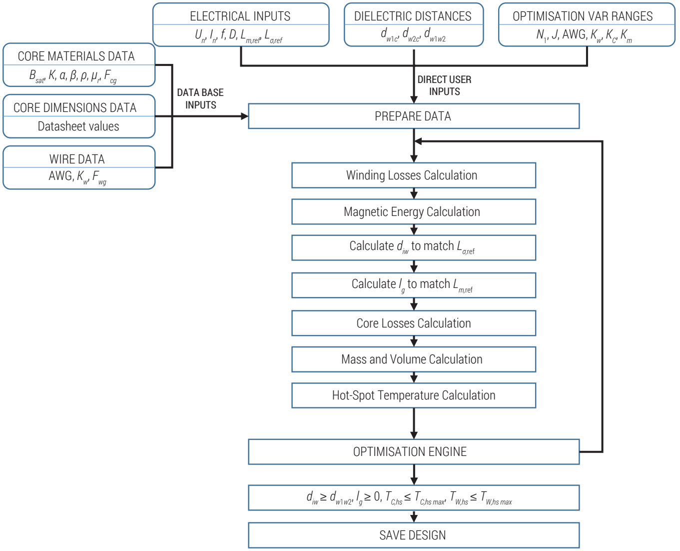


Hollow

Materials:

- Magnetic Materials
  - Silicon Steel
  - Amorphous
  - Nanocrystalline
  - **Ferrites**
- Windings
  - **Copper**
  - Aluminum
- Insulation
  - **Air**
  - Solid
  - Oil
- Cooling
  - **Air natural**/forced
  - Oil natural/forced
  - Water

MFT DESIGN OPTIMIZATION: ALGORITHM



ELECTRICAL INPUTS
$U_n, I_n, f, D, L_{m,ref}, L_{\sigma,ref}$

DIELECTRIC DISTANCES
$d_{w1c}, d_{w2c}, d_{w1w2}$

OPTIMISATION VAR RANGES
$N_1, J, AWG, K_w, K_c, K_m$

CORE MATERIALS DATA
$B_{sat}, K, \alpha, \beta, \rho, \mu_r, F_{cg}$

CORE DIMENSIONS DATA
Datasheet values

WIRE DATA
AWG, K_w, F_{wg}

DATA BASE INPUTS

DIRECT USER INPUTS

PREPARE DATA

Winding Losses Calculation

Magnetic Energy Calculation

Calculate d_{iw} to match $L_{\sigma,ref}$

Calculate l_g to match $L_{m,ref}$

Core Losses Calculation

Mass and Volume Calculation

Hot-Spot Temperature Calculation

OPTIMISATION ENGINE

$d_{iw} \geq d_{w1w2}, l_g \geq 0, T_{C,hs} \leq T_{C,hs\,max}, T_{W,hs} \leq T_{W,hs\,max}$

SAVE DESIGN

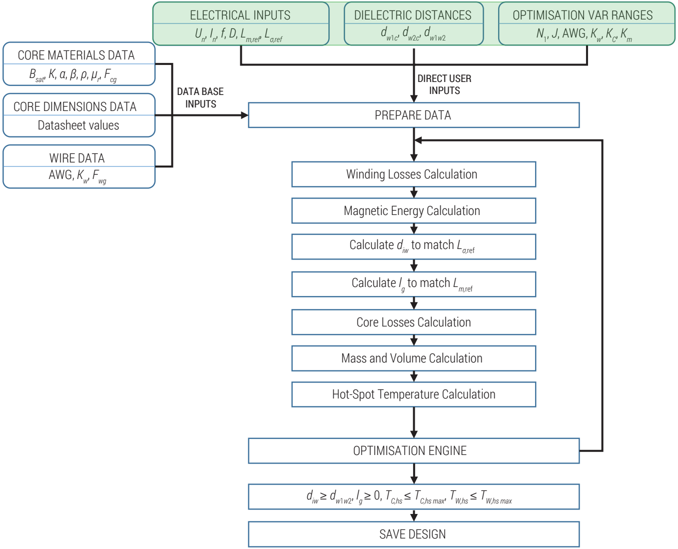
▲ MFT design optimization algorithm

Algorithm Specifications:

- Used Software Platform:
  - MathWorks MATLAB
- Used Hardware Platform:
  - Laptop PC (i7-2.1GHz, 8GB RAM)
- Performance Measure:
  - 59000 designs are generated in less than 190 seconds
- Electrical Specifications:

P_n	$100kW$	f_{sw}	$10kHz$
V_1	$750V$	V_2	$750V$
$L_{\sigma1,2}$	$3.27\mu H$	L_m	$1.8mH$

MFT DESIGN OPTIMIZATION: ALGORITHM



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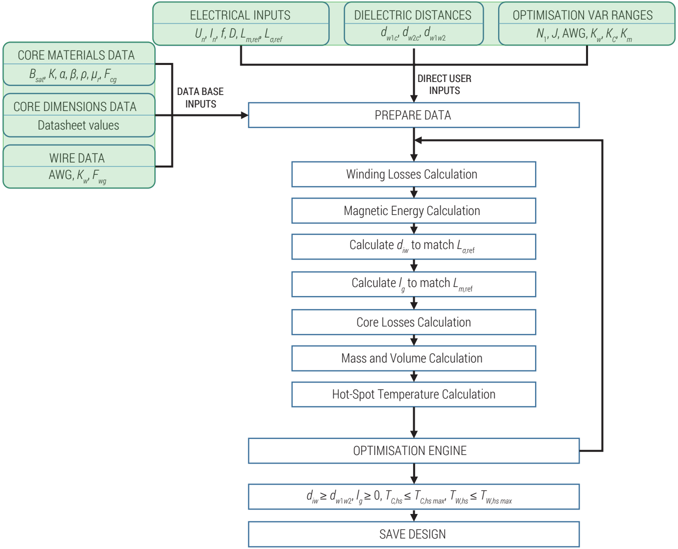

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OPTIMISATION VAR RANGES

N_1, J, AWG, K_w, K_c, K_m

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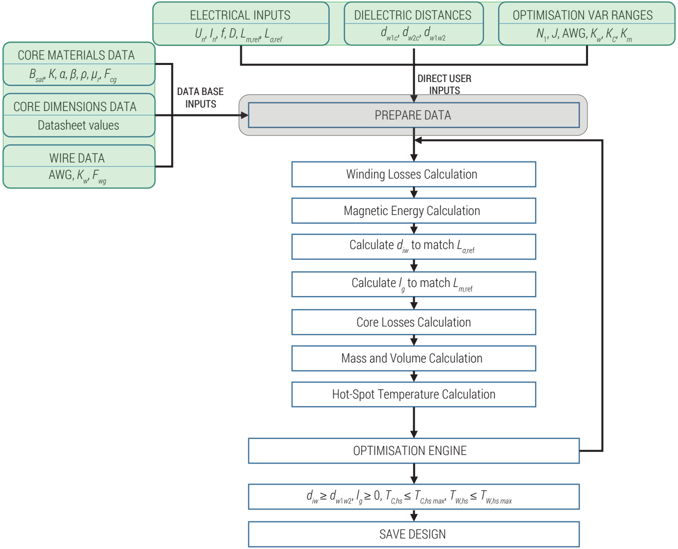

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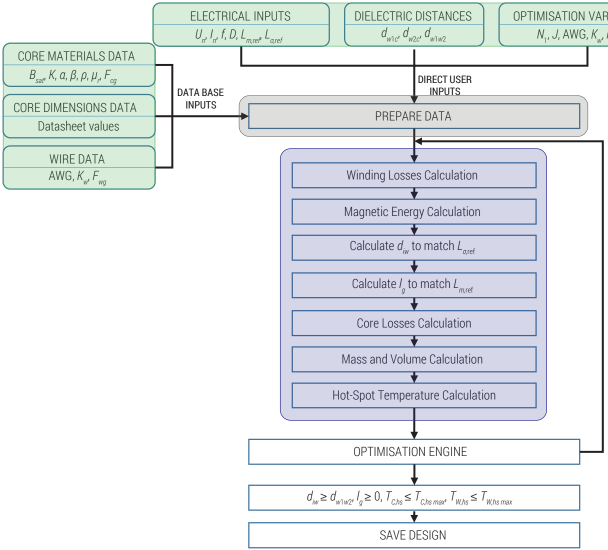

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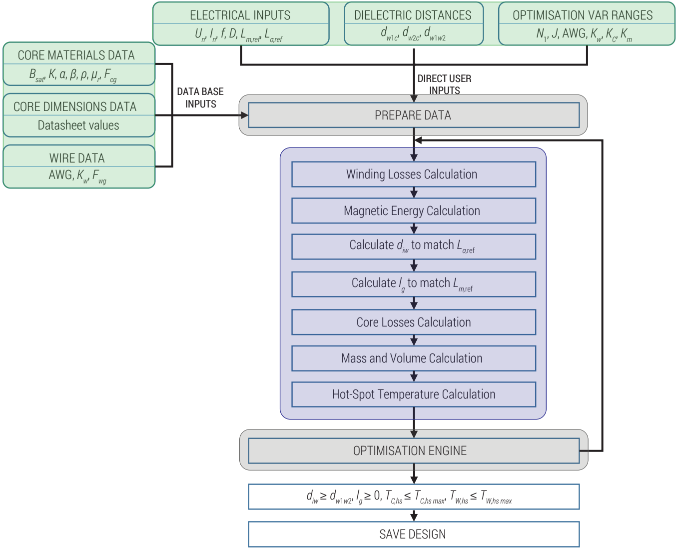

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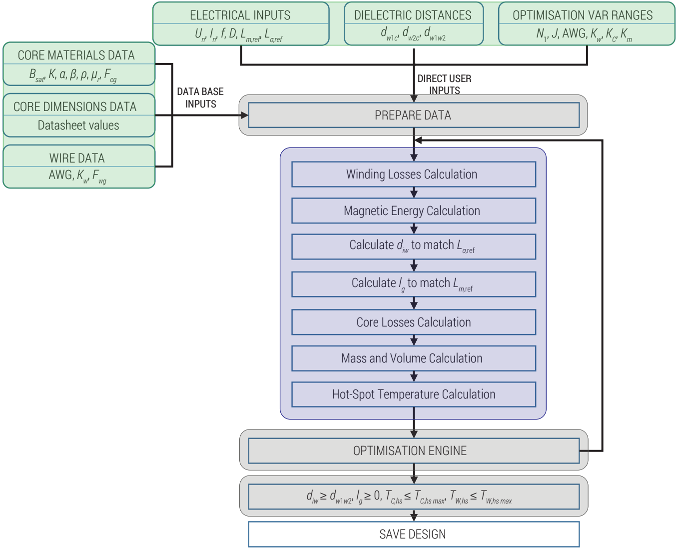

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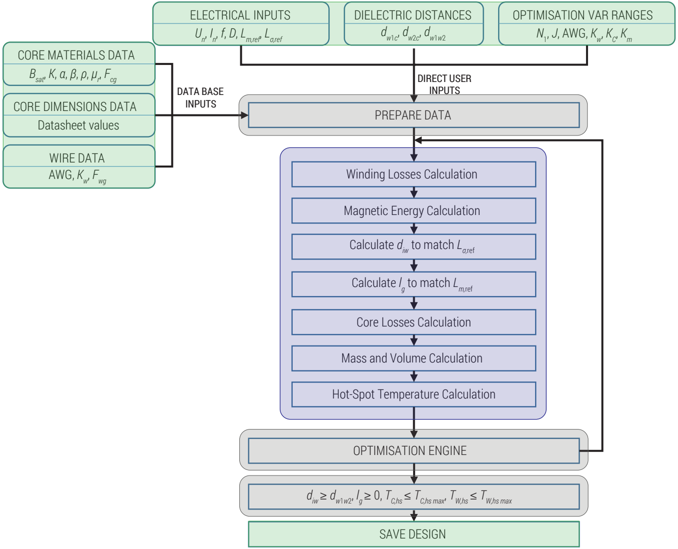
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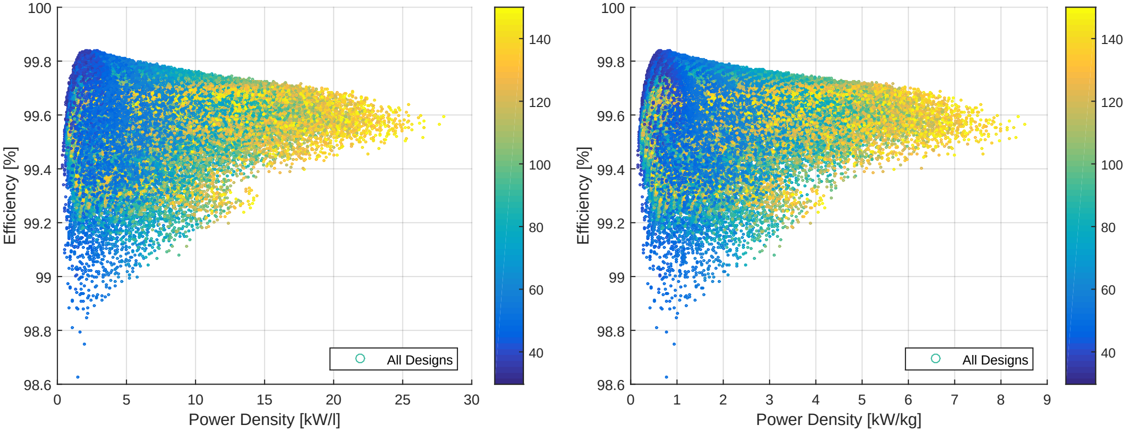
MFT DESIGN OPTIMIZATION: RESULTS

Applied Filters:

T_{Wmax} $[^oC]$	T_{Cmax} $[^oC]$	V_{max} $[l]$	M_{max} $[kg]$	η_{min} $[\%]$
150	100	/	/	/

Number of Designs:

- More than 1.8 Million



▲ Generated designs: left: Efficiency vs V-density; right: Efficiency vs W-density. Color code indicates hot-spot temperature

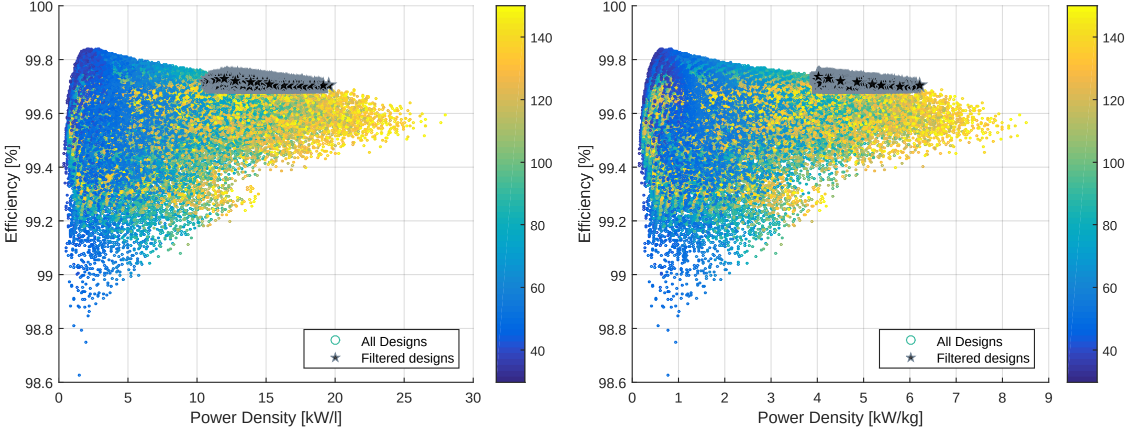
MFT DESIGN OPTIMIZATION: RESULTS

Applied Filters:

$T_{Wmax}\ [^oC]$	$T_{Cmax}\ [^oC]$	$V_{max}\ [l]$	$M_{max}\ [kg]$	$\eta_{min}\ [\%]$
150	100	12	25	99.7

Number of Designs:

- More than 1.8 Million



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MFT DESIGN OPTIMIZATION: RESULTS

Applied Filters:

T_{Wmax} [^oC]	T_{Cmax} [^oC]	V_{max} [l]	M_{max} [kg]	η_{min} [%]
130	80	9	24	99.72

Number of Designs:

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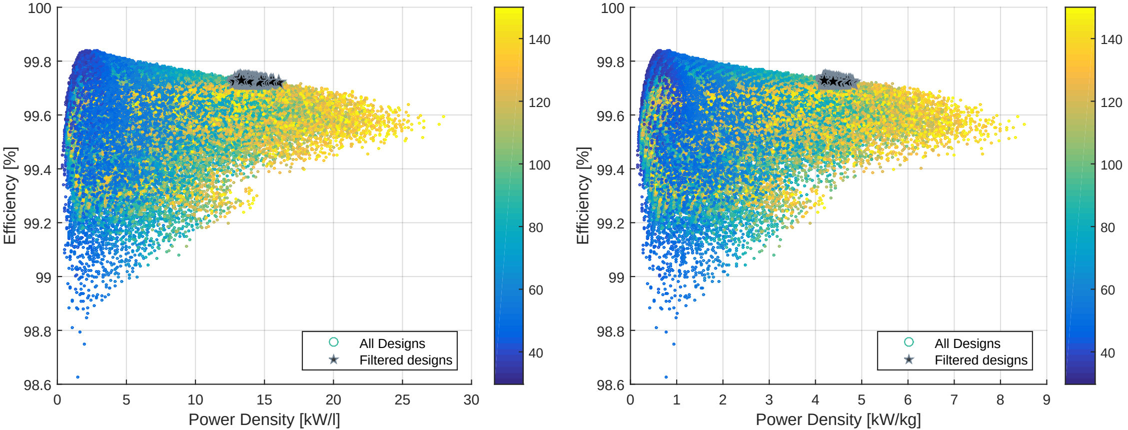

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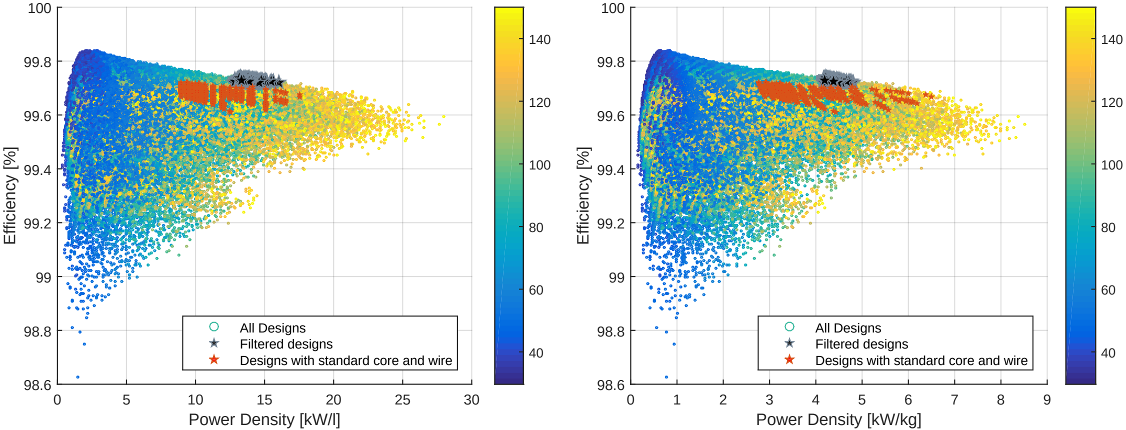

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MFT DESIGN OPTIMIZATION: RESULTS

Applied Filters:

$T_{Wmax}\ [^{o}C]$	$T_{Cmax}\ [^{o}C]$	$V_{max}\ [l]$	$M_{max}\ [kg]$	$\eta_{min}\ [\%]$
135	80	10	24	99.6

Number of Designs:

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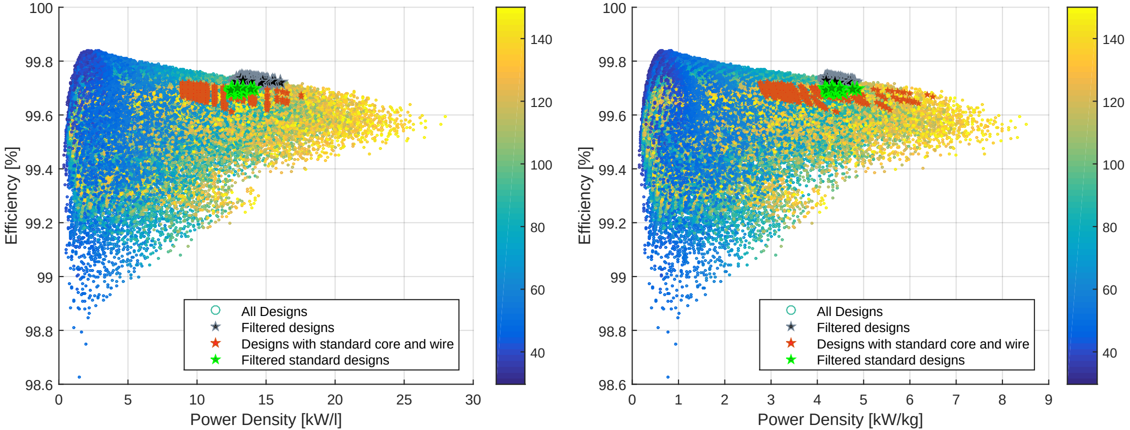

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135	80	10	24	99.6

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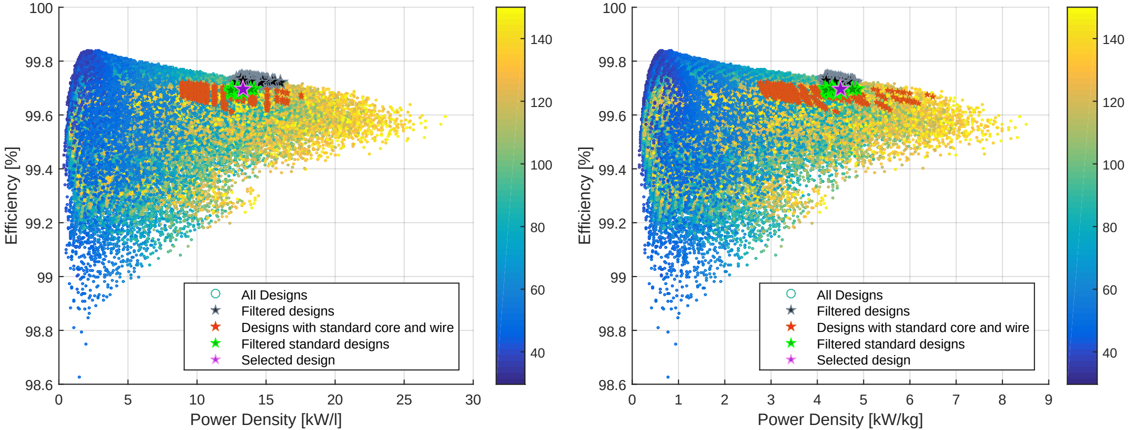

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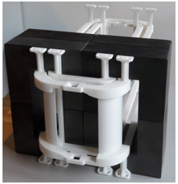
MFT PROTOTYPE ASSEMBLY

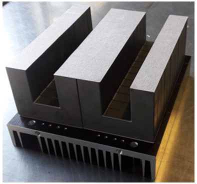

Optimal MFT Design 3D-CAD

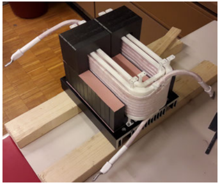

Coil-Formers 3D-CAD

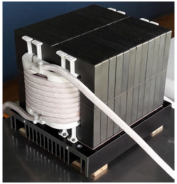

Coil-Formers 3D-Print


Primary Winding


Secondary Winding


Core Assembly


MFT Assembly1

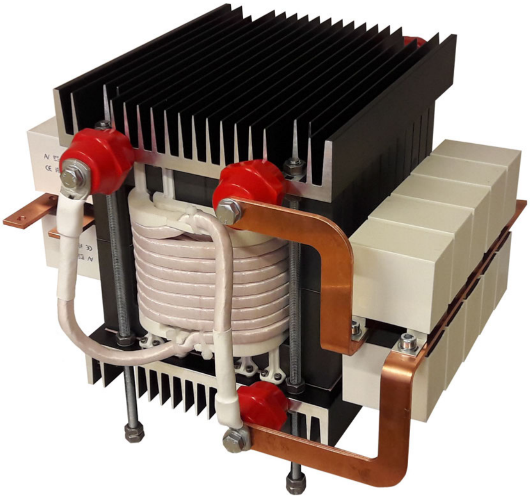

MFT Assembly2


Litz-Wire Termination


MFT Prototype

OPTIMAL MFT PROTOTYPE

MFT Prototype With Distributed Resonant Capacitor Bank:



Prototype Specifications:

- Core:
  - 12 stacks of 4 x SiFERRITE U-Cores (UU9316 - CF139)
- Windings:
  - 8-Turns
  - Square Litz Wire ($8.7x8.7mm$, 1400 strands, AWG 32, $43.69mm^2$)
- Coil-Formers:
  - Additive manufacturing process (3-D printing)
  - High strength thermally resistant plastic (PA2200)
- Resonant Capacitor Banks:
  - ($7x5\mu F$ + $1x2.5\mu F$) AC film capacitors in parallel
  - Custom designed copper bus-bars
- Electrical Ratings:

P_n	$100kW$	V_1	$750V$	$L_{\sigma 1,2}$	$4.2\mu H$
f_{sw}	$10kHz$	V_2	$750V$	L_m	$750\mu H$

MFT MEASUREMENTS: ELECTRIC & DIELECTRIC PARAMETERS

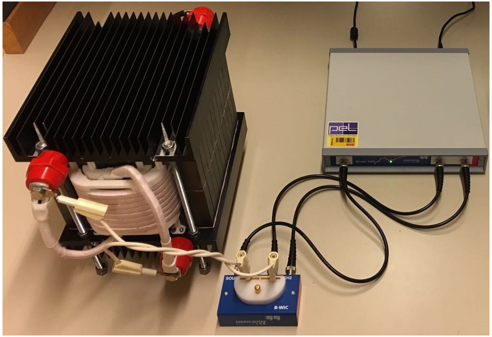
Leakage and Magnetizing Inductance Measurement:

- Network Analyzer Bode100
- Impedance Measurement
- Results at $10kHz$: $L_{\sigma 1} = L_{\sigma 2} = 4.2\mu H$, $L_m = 750\mu H$

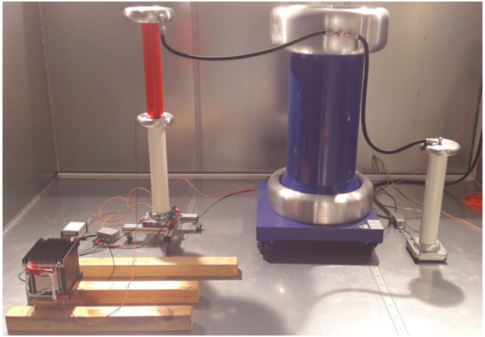
Dielectric Withstand Test:

- Partial Discharge Measurement Between All Conductive parts
- High Voltage $50Hz$ Source Within Faraday Cage
- $10pC$ - between primary and secondary winding at $4kV$

LV Measurement Setup:



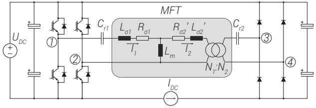
HV Measurement Setup:



MFT MEASUREMENTS: LOAD TEST

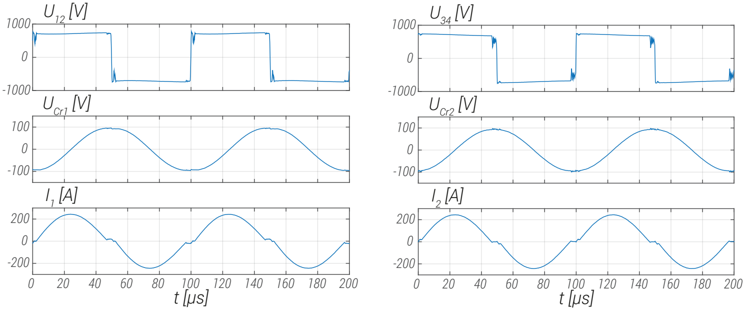
Test Setup Topology:

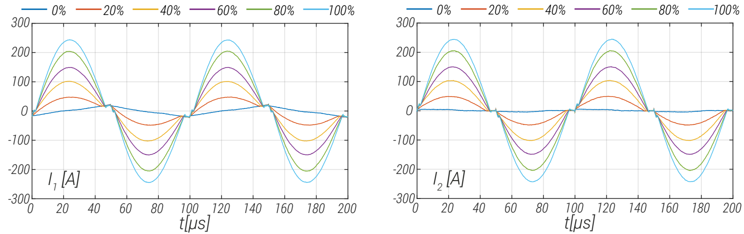
- B2B Resonant Converter
- Input voltage maintained by U_{DC}
- Power circulation via I_{DC}



Test Setup:

Measurement Results:





ENABLING MVDC TECHNOLOGIES - RESEARCH FACILITIES

Medium Voltage Electrical Supply

- MVDC: up to 10 kV (777 kVA)
- MVAC: 3.3, 6, 9, 11, 15, 20 kV (625 kVA)

Medium Voltage Electric Machines

- IM, 6 kV, 4-poles, 500 kVA (355 frame size)
- SM, 6 kV, 4-poles, 500 kVA (355 frame size)

Equipment

- High Voltage / Partial Discharge test setup (100 kV, 20 kVA)
- HVDC supply (20 kV, 5 A)
- LV Grid Simulator (50 kVA, 400 V)
- High Current DC supply (20 V, 2250 A)
- De-Ionized WCU (90 kW)
- Breaking resistor (300 kW)
- Variable AC supplies (250 kW)
- Variable frequency supply (up to 400 Hz)

RESEARCH FUNDING AND PARTNERS

Agencies

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

Industry

plexim

ABB

GE

CERN

HYUNDAI
HEAVY INDUSTRIES

LEMSYS

ECPE

POWER ELECTRONICS ENABLING TECHNOLOGIES

High Power Medium Voltage Conversion

- Efficient and controllable bulk power processing [MW]
- Flexible, Modular and Scalable Conversion
- Advanced control and Communication
- Reliability, Availability

MVDC Research Opportunities

- System level studies (Features, Advantages, Benefits)
- Modeling and simulations (off-line or real-time)
- Power Electronics Converters
- Control Design
- Protection (Devices and protection coordination)

Academic Research - Industrial Development

MVDC

ENERGY CONVERSION TECHNOLOGIES AND SYSTEMS

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Q AND A

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