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MegaCube

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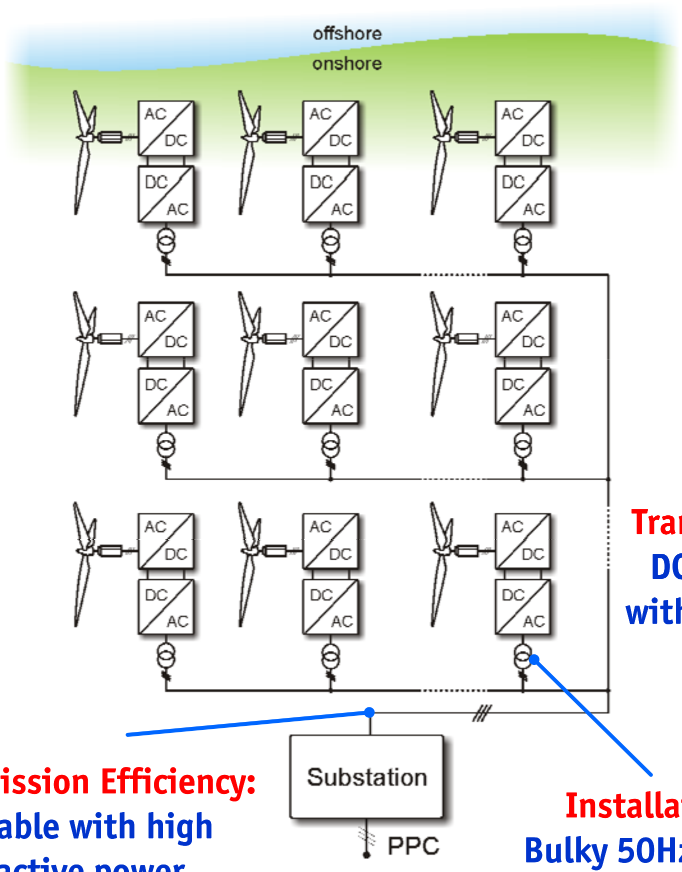
Traditional AC collection grid for onshore wind power generation.

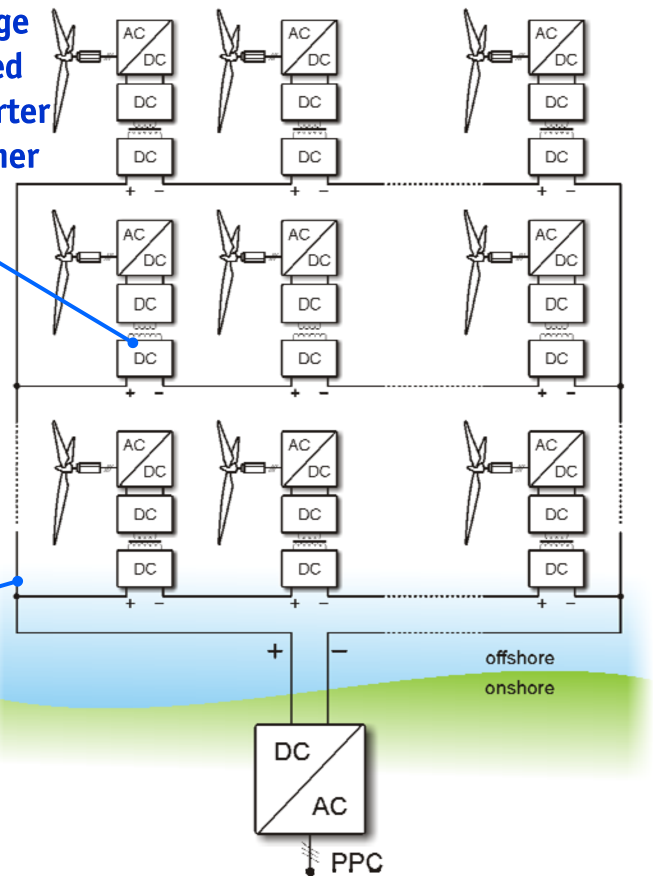
Future HVDC collection grid for offshore wind power generation.



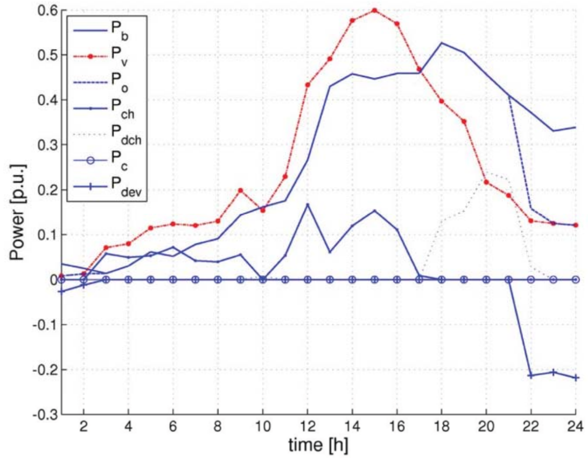
Transmission Efficiency:
AC cable with high reactive power consumption/generation

Installation Costs:
Bulky 50Hz transformer required to step voltage to transmission/distribution level

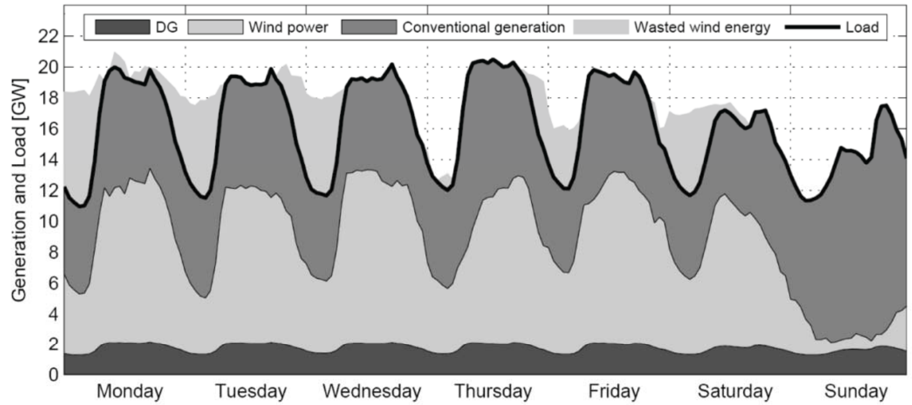
Installation Costs:
No Bulky 50Hz transformer required. Instead, the voltage step-up is achieved with a DC-DC converter and a MF transformer



Transmission Efficiency:
DC High Voltage cable with better efficiency for long distances



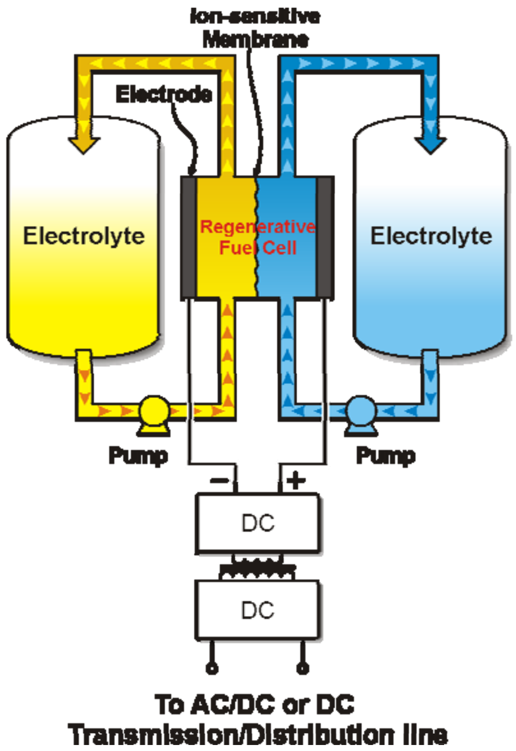
Pinson, P. et al, "Dynamic sizing of energy storage for hedging wind power forecast uncertainty," *Power & Energy Society General Meeting, 2009. PES '09. IEEE* ,July 2009.



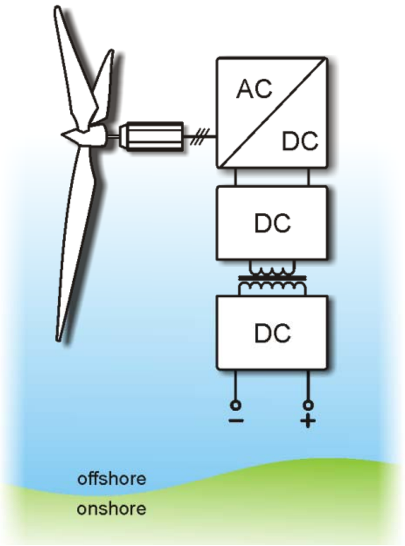
Gibescu, M. et al, "Case study for the integration of 12 GW wind power in the Dutch power system by 2020," *Integration of Wide-Scale Renewable Resources Into the Power Delivery System, 2009 CIGRE/IEEE PES Joint Symposium* , July 2009.

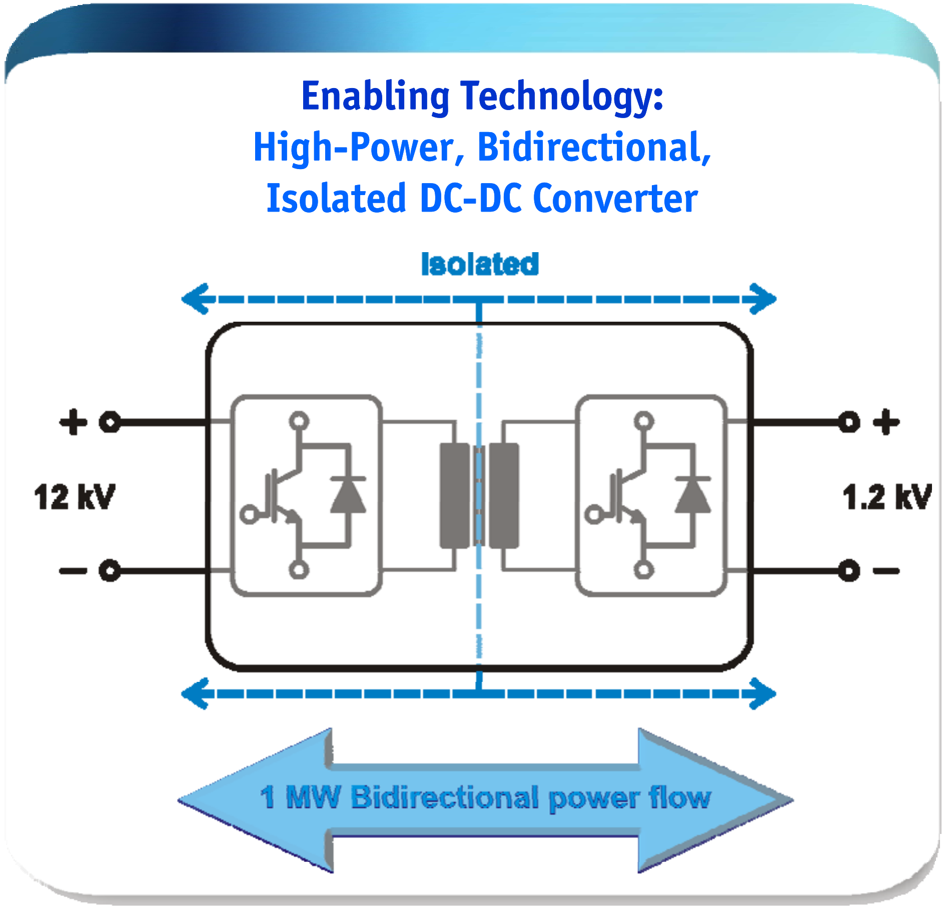
Energy storage systems

- Pumped hydro storage.
- Compressed air.
- Fuel cells.
- Flywheel.
- Superconducting magnetic energy storage.
- Super capacitors.
- Flow batteries.

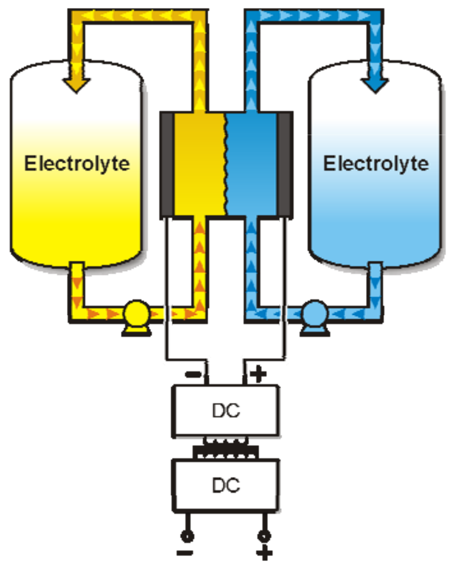


Offshore wind farm



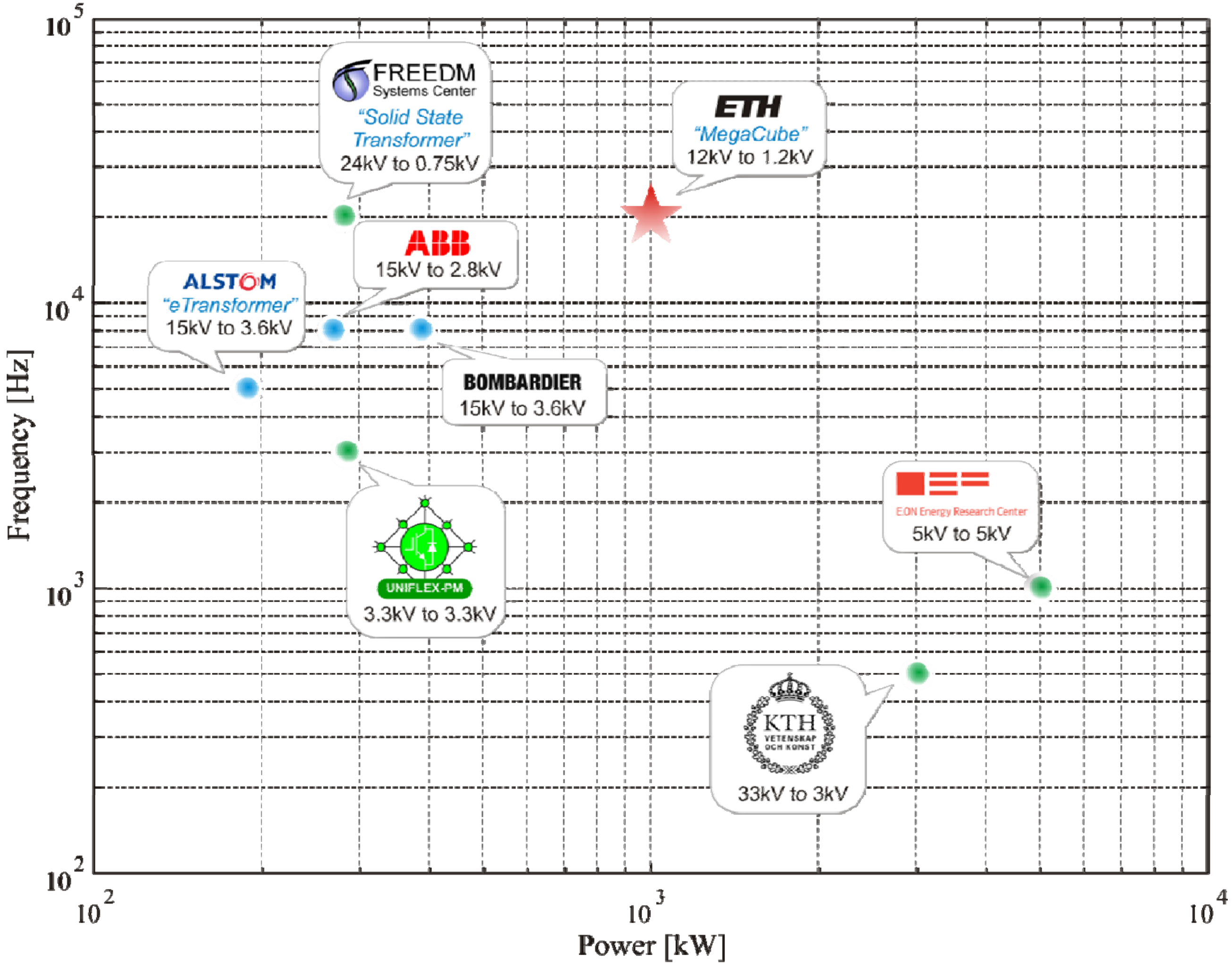


Energy Storage



Specifications:

- 1MW Nominal Power.
- 20kHz Switching Freq.
- Port 1: 12kV.
- Port 2: 1.2kV.
- Bidirectional.
- 100 kV DC Isolated.
- 99+ efficiency.



Traction Applications:

(Bombardier, Alstom, ABB)

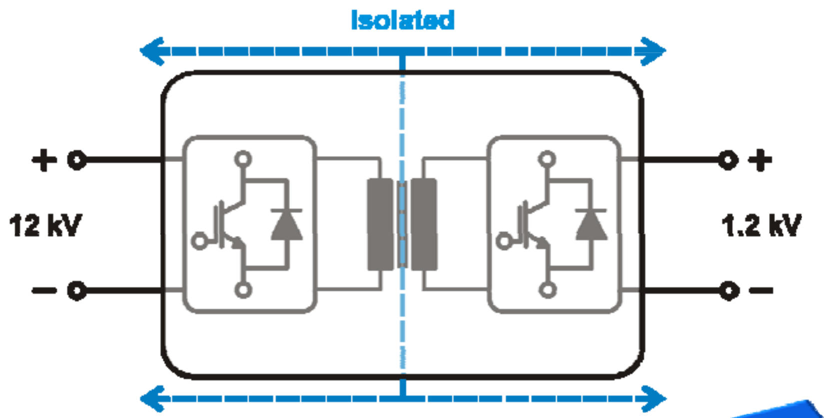
- **Semi-modular construction:**
  - **Modular HV side.**
  - **Single LV converter.**
  - **Power given for single HV module.**

UNIFLEX EU

- **Full modular construction.**
- **Full scale converter: 5MW.**

Specifications:

- 1MW Nominal Power.
- 20kHz Switching Freq.
- Port 1: 12kV.
- Port 2: 1.2kV.
- Bidirectional.
- 100 kV DC Isolated.
- 99% efficiency.



Switches:

- LV → 600V IGBTs, MOSFETS.
- LV → 1200V SiC JFETs.
- HV → 6.5kV SiC JFET.
- HV → 4.5kV Press Pack.

Topology & Modulation:

- Focus on ZCS on HV side.

Studied Options:

- Series Parallel Resonant Converter.
- Dual Active Bridge with ZCS on HV side.

MF Transformer

- Provide 100kVDC isolation.
- Step up voltage.

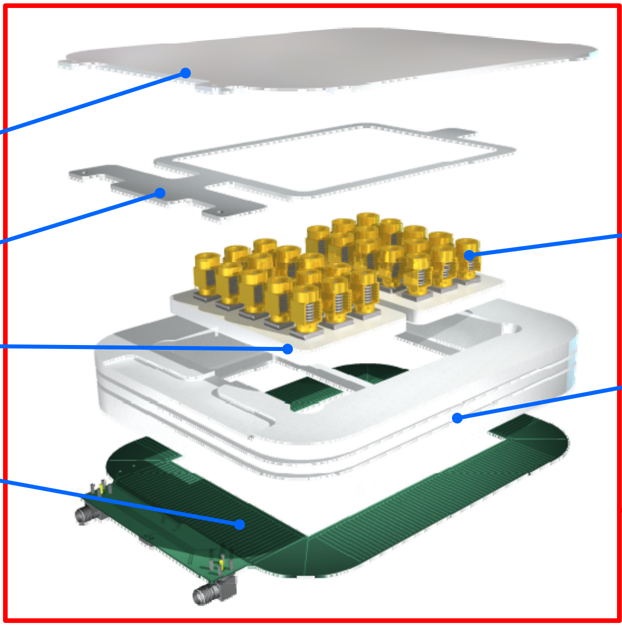
Studied Options:

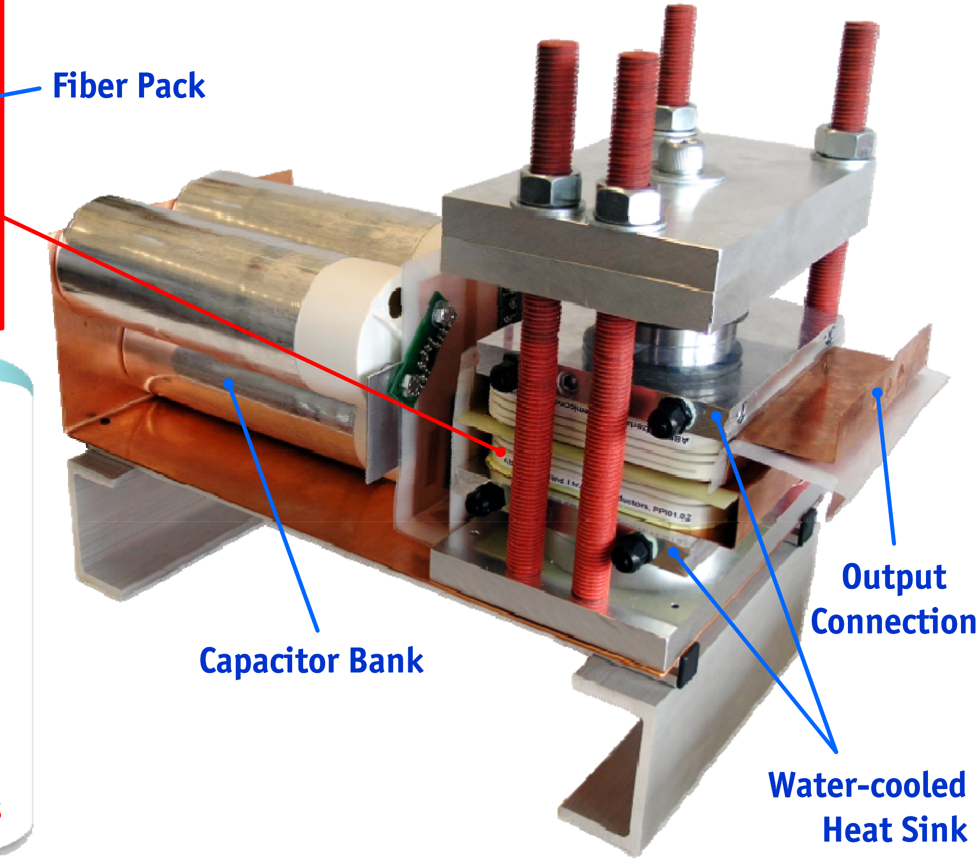
- Core-type.
- Shell-type.
- Matrix.

HV Switch: 4.5kV Press-Pack IGBT Testbench

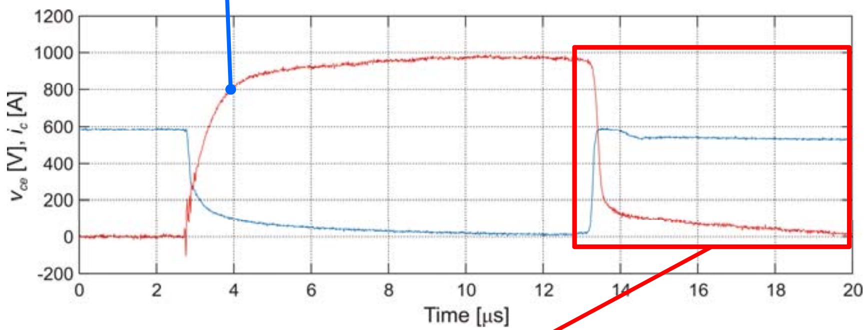
Press-Pack IGBT Features:

- 4.5kV Blocking Voltage.
- ~400A continuous current.
- dv/dt → Measurement.





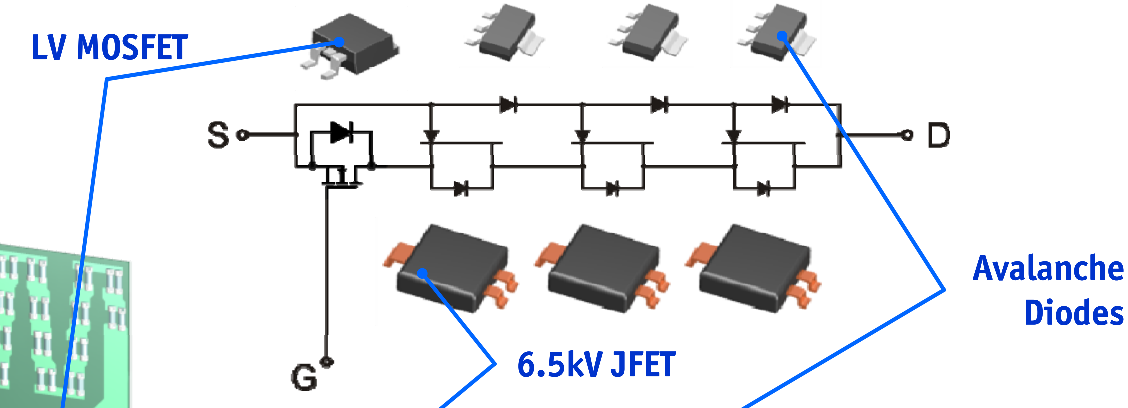
Resistive Switching behavior

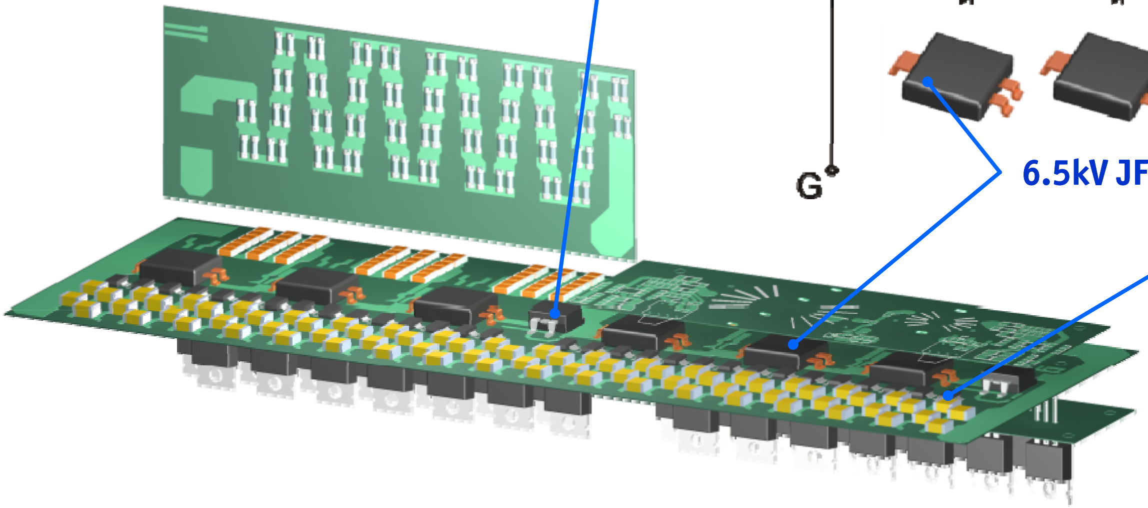


Extremely long current tailing → High Switching losses

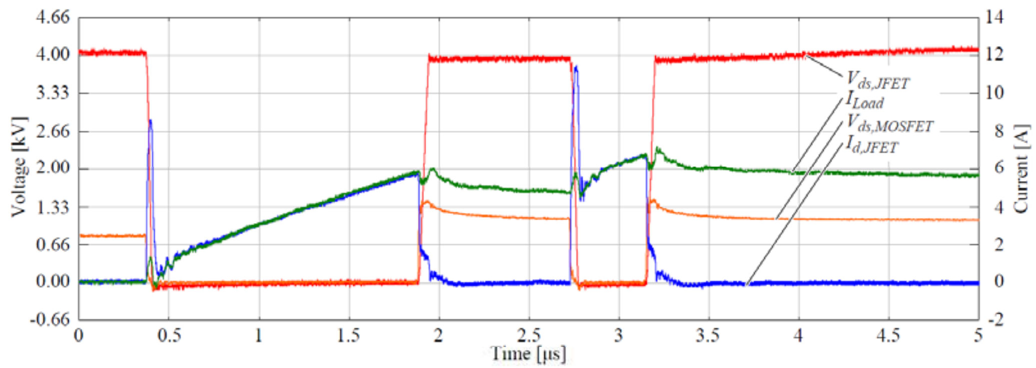
6.5kV JFET:

- 6.5kV blocking voltage.
- 5A continuous current.
- dv/dt = 100kV/µs.





Results for JFET half bridge with inductive load



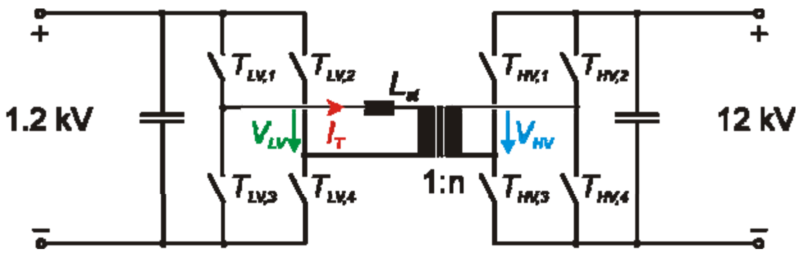
Increase Voltage:

→ Super Cascode.

→ Testing of 12kV Switch .
 based on 3 x 6.5kV SiC JFETs.

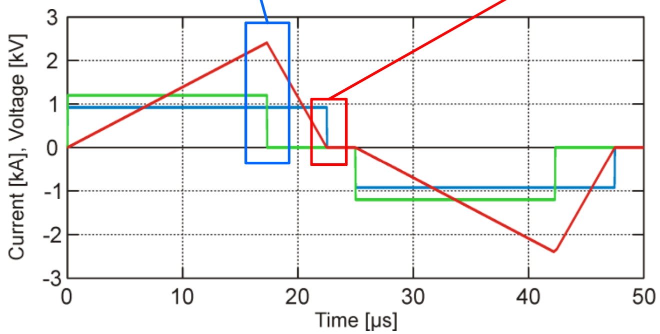
- **HV Switch main issues:**
  - The under-test 4.5kV PressPack IGBT presents long tail currents which lead to high switching losses at the aimed 20kHz switching frequency.
  - 6.5 kV SiC JFET technology offers promising switching behavior but can not be implemented in the near future due to low current driving capability.
  - In order to minimize turn-off currents in HV side, the modulation scheme must consider Zero Current Switching (ZCS) or quasi zero current switching for the HV-side devices.
- **Topology requirements**
  - The topology must be suitable for ZCS on the HV side as well as bidirectional power flow.
  - In order to reach higher reliability, a ±5% voltage variation is included for both the HV and LV DC voltages. Within this range, nominal power is delivered.
- **Considered topologies:**
  - Dual Active Bridge (DAB) with triangular modulation.
  - Series Resonant Converter (SRC) with constant frequency operation.

Dual Active Bridge with Triangular Modulation



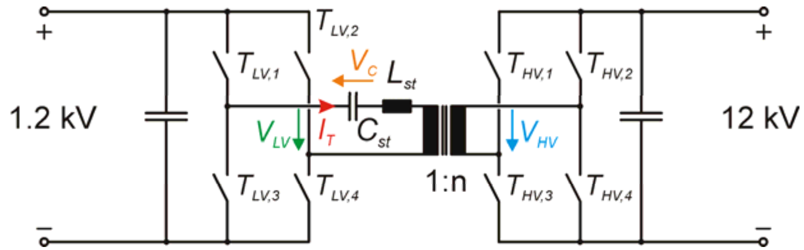
Turn-off losses only on LV side

ZCS on HV side

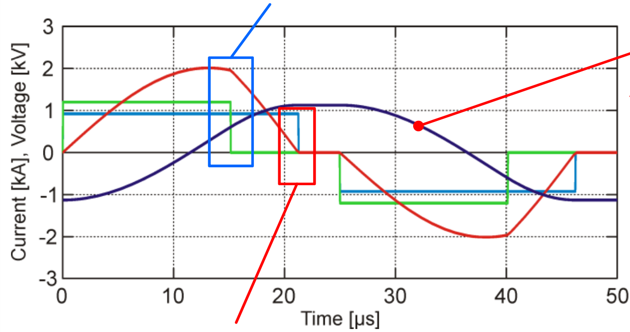


All turn-on processes are performed with ZVS

Series Resonant Converter with Constant Frequency



Turn-off losses only on LV side



High voltage and current stress on series capacitor

ZCS on HV side

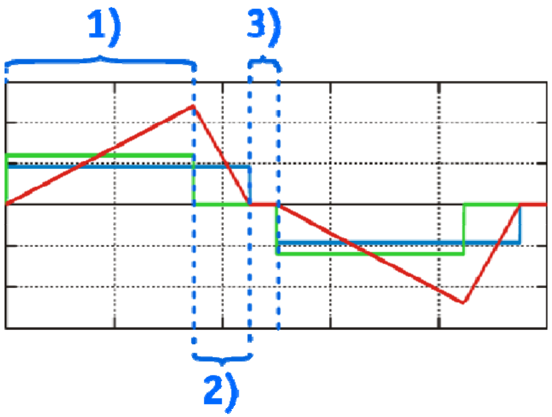
All turn-on processes are performed with ZVS

If no duty cycle control is implemented:

- Over resonant HV side ZCS not possible when transferring power from HV to the LV side.
- Under resonant HV ZCS only possible with stiff input output voltage ranges.

Power from 1.2kV to 12kV

Buck Operation



Remarks:

- There is a minimum turns ratio in order to reach 12+5% kV at HV side at full power with 1.2-5% kV on the LV side.
- Duty cycle on LV side is adjusted to transfer the required power, generating turn-off losses only on LV side switches for both directions of the power.

Buck Modulation Sequence

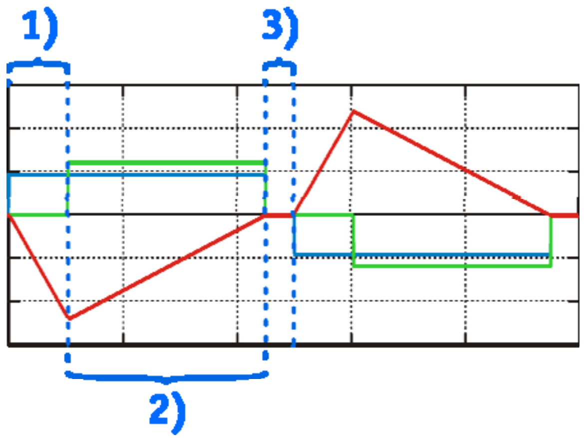
1) The voltage difference between LV and HV side voltages is applied to the inductor/tank, rising the transformer current.

2) The LV side is switched and now applies zero voltage to the transformer where the full HV side DC voltage is applied to the inductor/tank decreasing the current quickly.

3) When the current reaches zero, the HV side is switched and zero voltage is applied to the inductor/tank until the next half period begins.

Power from 12kV to 1.2kV

Boost operation



Boost Modulation Sequence

1) The LV side applies zero voltage to the inductor/tank whereas the HV voltage side applies full voltage, rising the current with high slope.

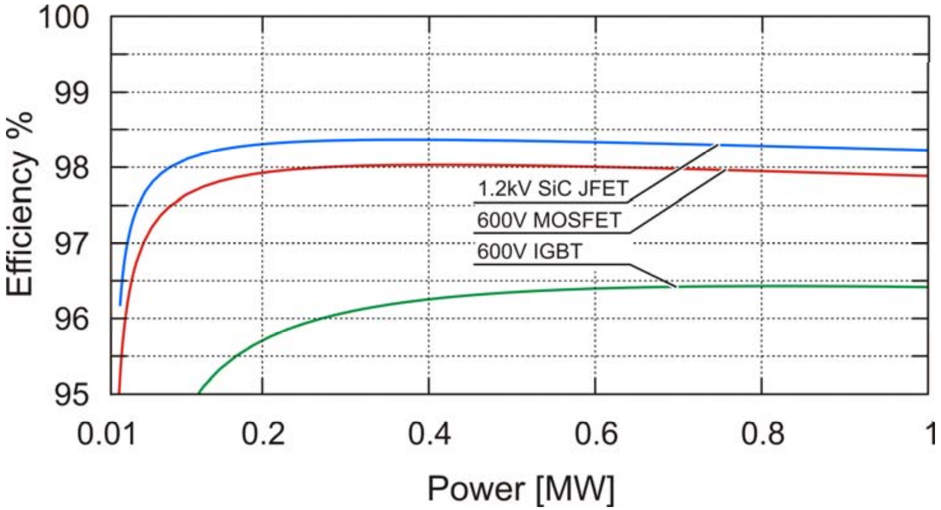
2) The LV side is switched and the difference between LV and HV side voltages is applied to the inductor/tank, decreasing the transformer current.

3) When the current reaches zero, the HV side is switched and zero voltage is applied to the inductor/tank until the next half period begins.

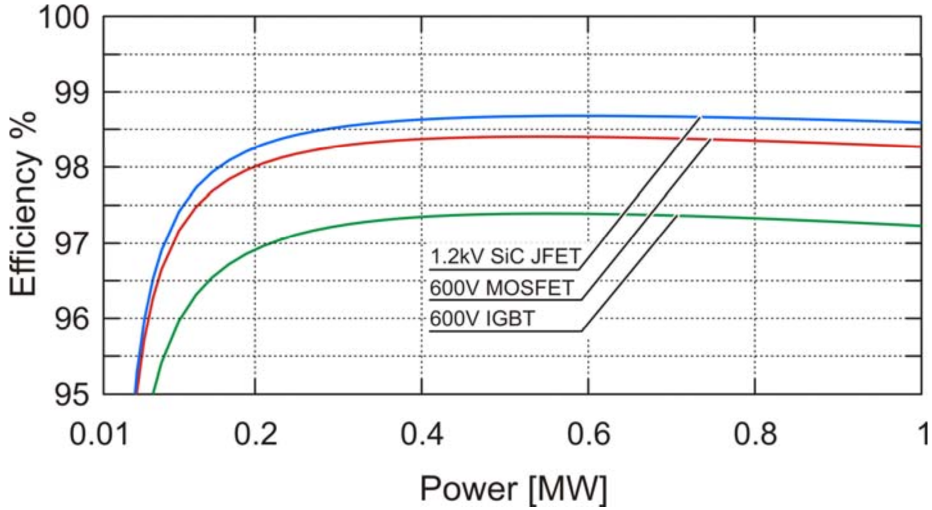
Considered LV Switch Technologies

- Paralleled 600V IGBTs in 5 level NPC configuration: IGW75N60T Infineon.
- Paralleled 600V MOSFET in 5 level NPC configuration : IPW60R045CP (CoolMOS) Infineon.
- Paralleled 1200V SiC JFET in 3 level NPC configuration: SJEP120R063 Semisouth.

Dual Active Bridge with Triangular Modulation



Series Resonant Converter with Constant Frequency



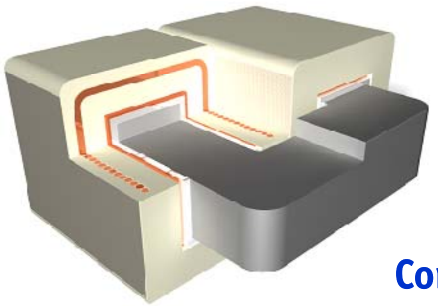
Transformer losses included

Efficiency at 1 MW transferred power			
	600V IGBT	600V MOSFET	1.2kV SiC JFET
DAB	96.4%	97.8%	98.2%
SRC	97.2%	98.3%	98.6%

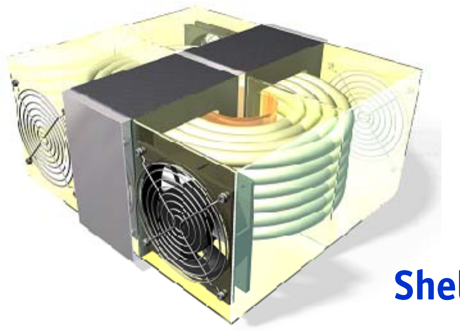
- Dual Active Bridge v/s Series Resonant Converter aiming for ZCS on the HV side
  - Both topologies can achieve ZCS on the HV side with bidirectional power flow.
  - Variable frequency control without duty cycle control is not suitable for the SRC. At over resonant operation ZCS on the HV side is not achievable at all operating conditions. At under resonant operation, input-output voltage ranges can not be achieved.
- Switches technologies and efficiency for the LV side switch
  - The SRC shows higher efficiency at nominal operation in comparison to the DAB for all switch technologies due to the lower switched current at the LV side.
  - The main drawback of the SRC topology is the required resonant capacitor, which must work under extremely high electrical stresses.
  - 1200V SiC JFET technology shows the best performance with an efficiency of 98.2% at nominal power in case of the DAB and 98.6% in case of the SRC.
  - Regarding efficiency, the ZCS on the HV side modulation appears as a highly attractive solution for the 1MW 20kHz bidirectional DC-DC converter.

- **Main Design Aspects:**
  - Isolation: 100kVDC dry type isolation complying with IEEE C57 standard on Basic Lightning Impulse.
  - High power density and efficiency.
  - Low complexity on the mechanical construction.

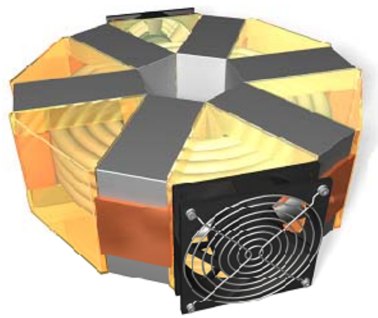
- **Options:**



Core-Type



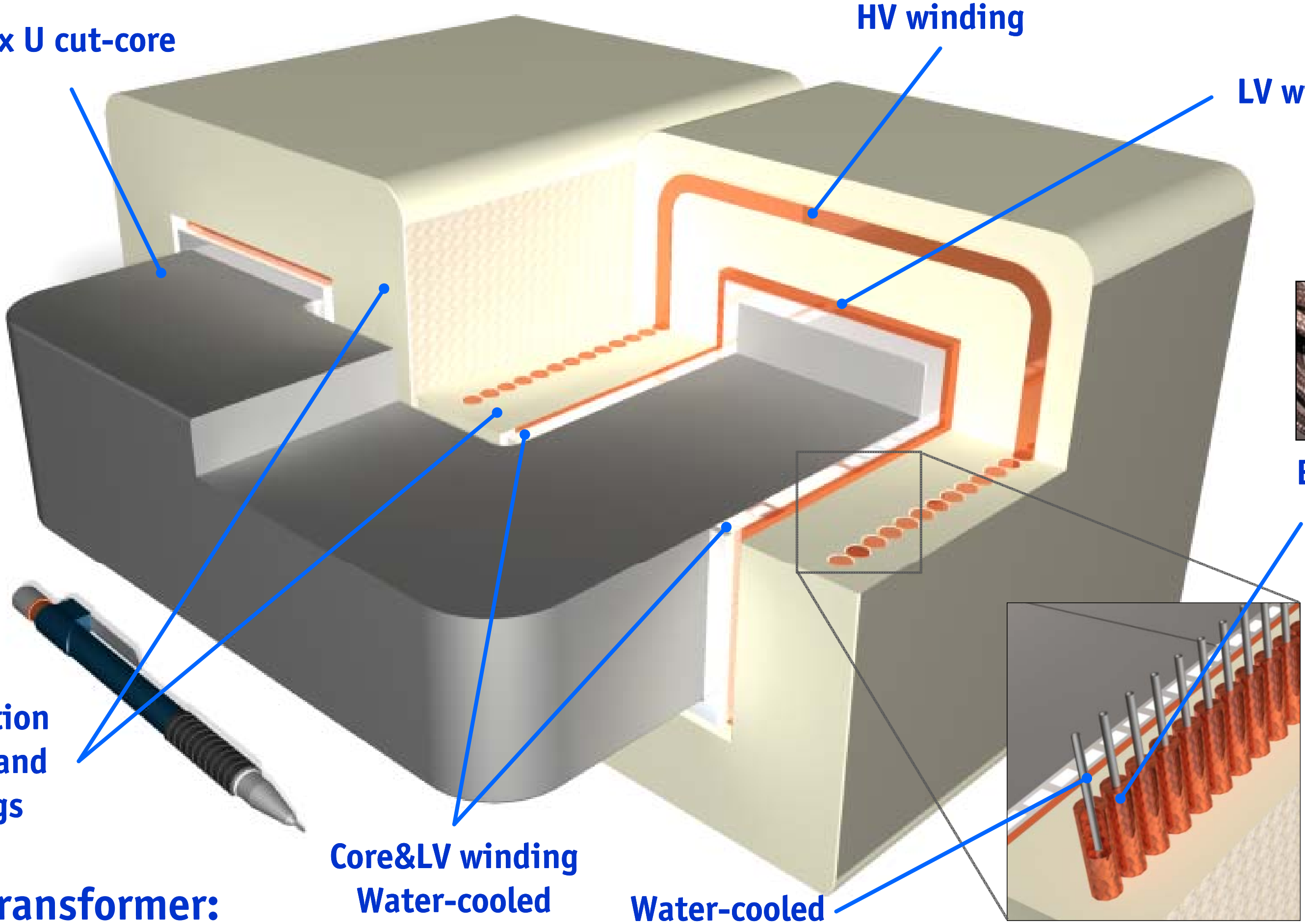
Shell-Type



Matrix

  - Core Material: Vitroperm 500F.
  - LV winding: Low-loss optimized copper foil.
  - HV winding:
    - HF litz wire.
    - HV litz cable.
  - Turns ratio: n = 12.

Transformer Concept 1: Core-type

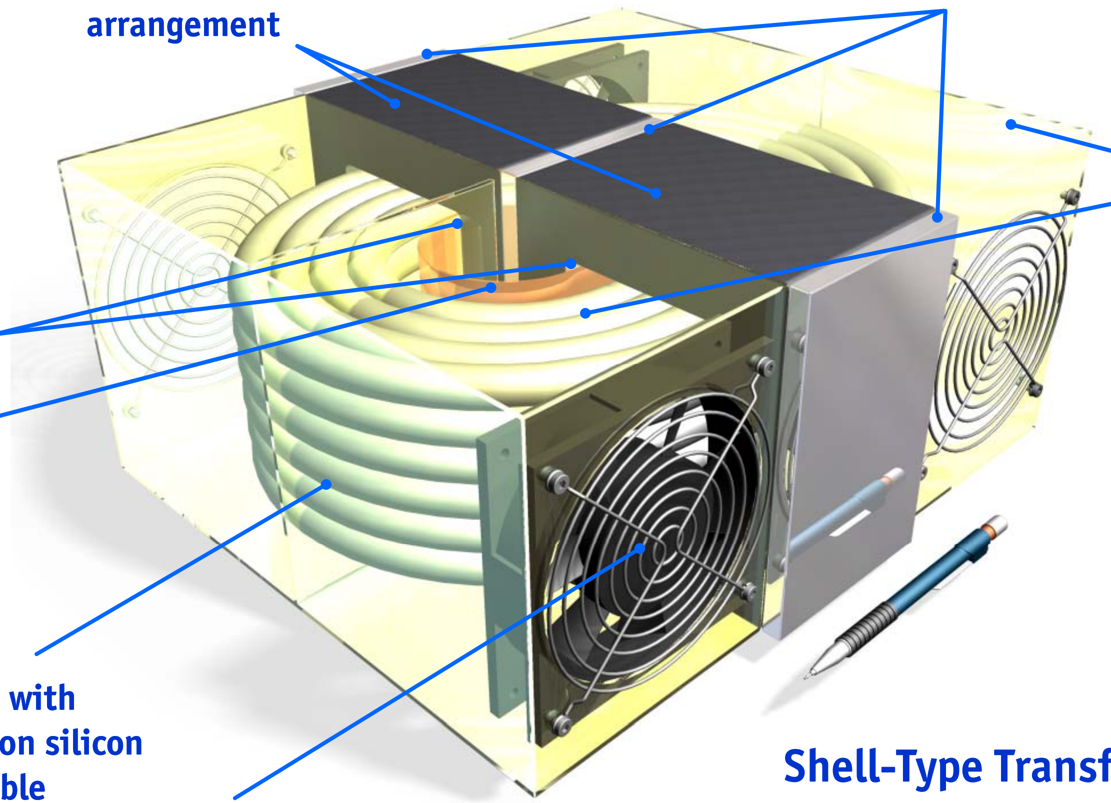


Core-Type Transformer:

- Isolation: Potted HV winding
- Losses: 3.5kW
- Volume: 4.3 liter

Shell-Type Transformer option 1 (picture):

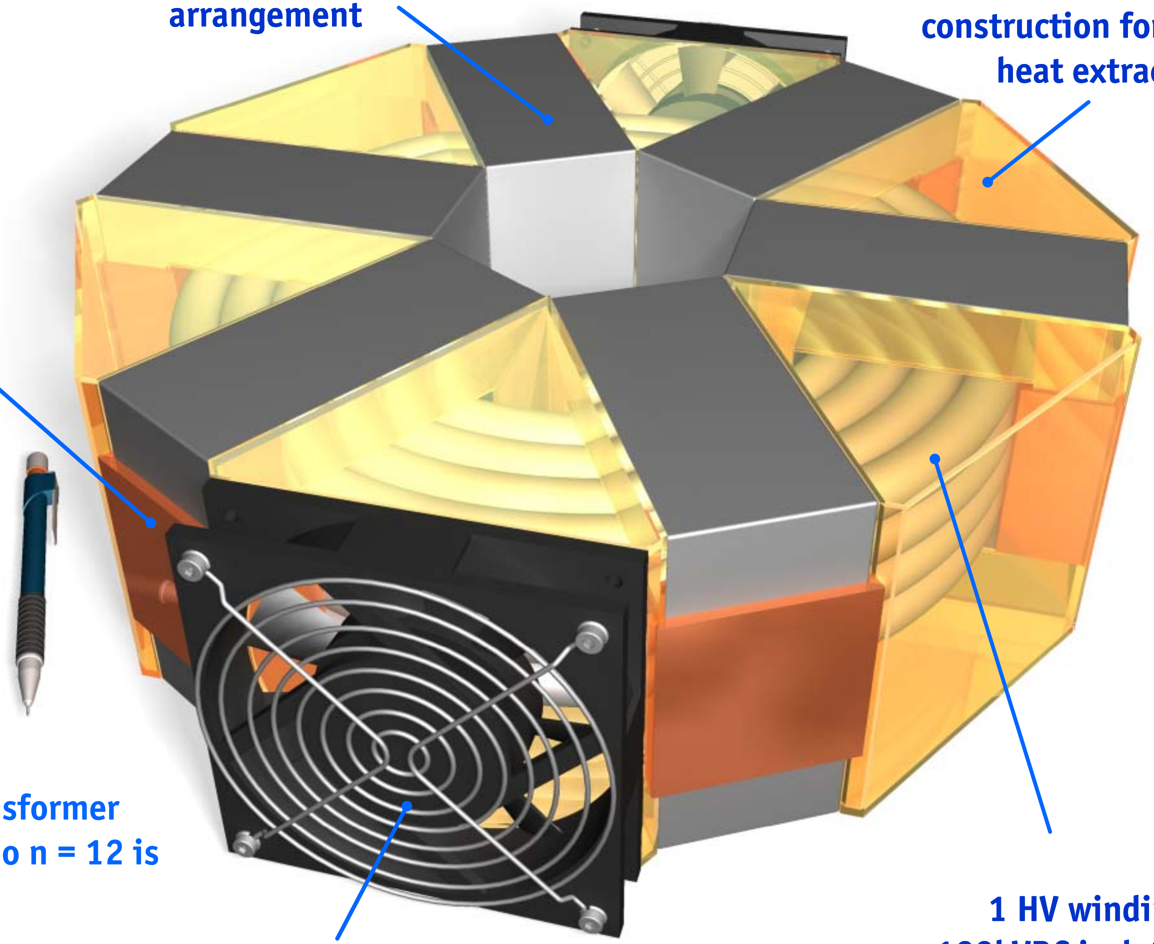
- Isolation: HV cable
- Losses: 4 kW
- Volume: 11.9 liter



Shell-Type Transformer option 2:

- Isolation: Potted HV winding
- Losses: 3.37 kW
- Volume: 3.5 liter

Matrix Transformer:
- Isolation: HV cable
- Losses: 4.5 kW
- Volume: 11 liter



Concept
- Each core builds a 1:2 transformer
- With 6 cores the turns ratio n = 12 is achieved

- Power losses, volume and isolation summary:

	Core-Type	Shell-Type 1	Shell-Type 2	Matrix
Losses	3.5 kW	4 kW	3.37 kW	4.5 kW
Volume	4.3 liter	11.9 liter	3.5 liter	11 liter
Isolation	Potted	HV Cable	Potted	HV Cable

- The isolation type has a strong impact over the efficiency and volume of the MF transformer:
  - Potted isolation enables higher power density and efficiency with a high mechanical construction complexity.
  - Achieving isolation with a HV litz cable enables a reduced complexity in the mechanical construction of the transformer with the price of lower efficiency and power density.
- The high isolation requirements introduces considerable challenges in the transformer's thermal management.

- **HV side switch**
  - If no ZCS is implemented, the available HV IGBT technology (4.5kV) presents an unsuitable switching performance for the aimed 20kHz switching frequency.
  - The topology and modulation must allow a ZCS operation for the HV side.
- **Topologies which allow ZCS in the HV side**
  - Dual Active Bridge (DAB) with triangular modulation.
  - Series Resonant Converter (SRC) with constant frequency operation.
  - The SRC converter reaches a higher efficiency in relation to the DAB caused by the reduced switched currents in the LV side and lower RMS currents. However, the price of the highly stressed series capacitor must be considered.
- **MF transformer: Core-type, Shell-type and Matrix**
  - Among the studied transformer concepts, the Core-type transformer reaches the highest efficiency and power density with a potted 100kVDC isolation, which increases considerably the transformer mechanical construction.
  - The Matrix and Shell-type transformers with isolation provided by a HV cable present a considerably easier mechanical construction, with reduced overall efficiency

- **Switches**
  - Finish PressPack IGBT testing to evaluate experimentally the switching performance.
  - Perform switching measurements on 12kV SiC JFET-based Cascode to evaluate the performance of a future solution with SiC-based HV switches.
- **Modulation & Topology**
  - Validate proposed HV ZCS modulation scheme with experimental switching data from HV and LV switches for DAB and SRC topologies.
  - Realize efficiency-optimized design of both concepts which would allow to choose the best performance topology.
- **MF Transformer**
  - Compare potted and HV cable isolation solutions regarding partial discharge, thermo-mechanical behavior and construction complexity.
  - Validate through FEM simulation proposed thermal management solutions for the presented transformer concepts.

Thank you!