Laboratory for High Power Electronic Systems

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Comparison of High Power Non-Isolated Multilevel DC-DC Converters for Medium-Voltage Battery Storage Applications

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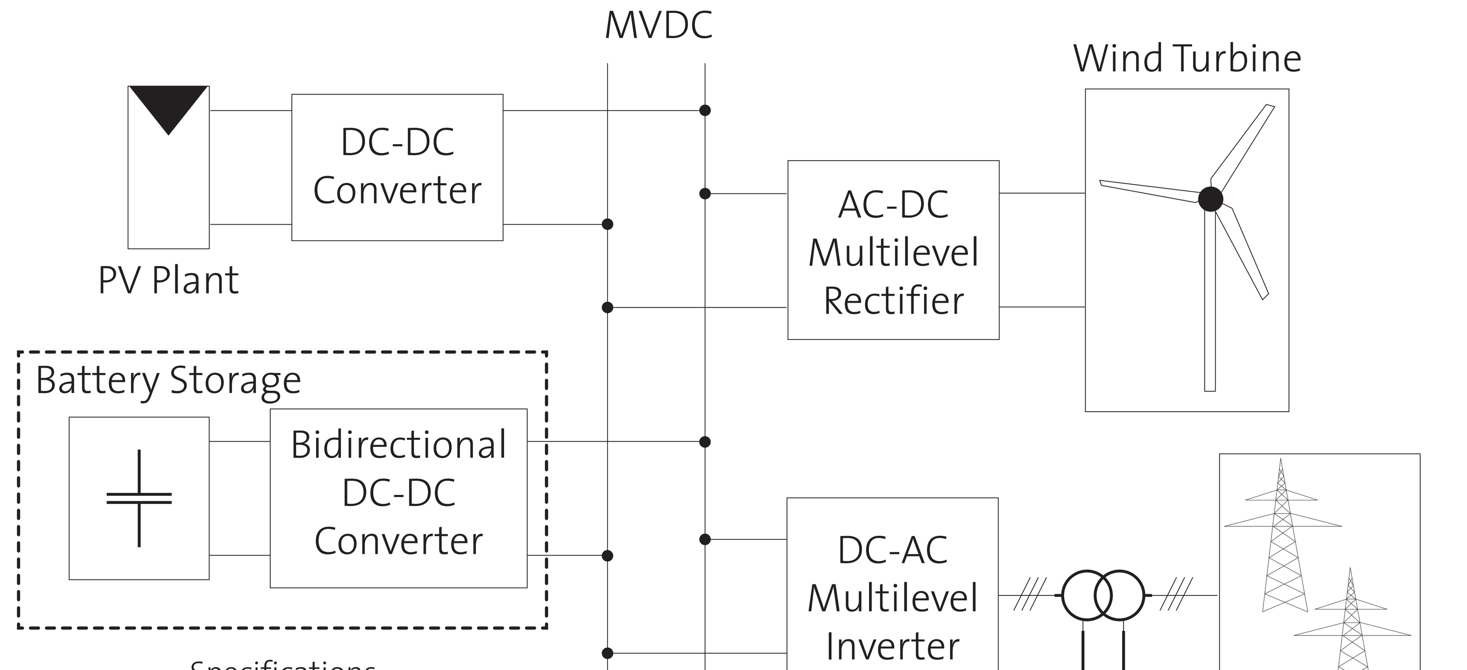


Specifications

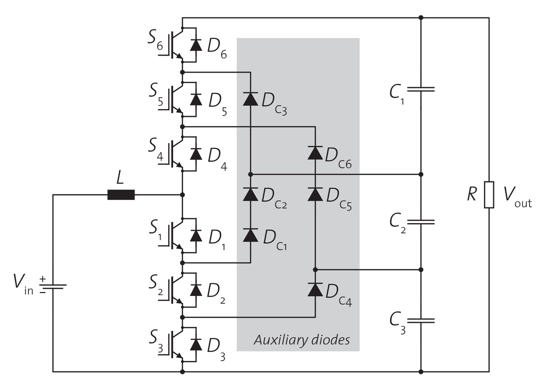
Battery Voltage V_{in}	530 ... 890 V
DC Link Voltage V_{out}	2800 V
System Power	4 MW
Efficiency	> 95 %

Abstract

In this paper 4-level neutral-point-clamped (4L-NPC), 4-level flying-capacitor (4L-FC) and 4-level neutral-point clamped Cuk (4L-NPC-Cuk) converter topologies for multilevel DC-DC buck-boost converter for medium-voltage battery storage applications are compared with respect to efficiency and power density. The comprehensive comparison is performed with multi domain models and optimization procedures. For the converters, pareto-fronts are calculated for different operating frequencies in order to find the optimal design with respect to the specified minimum efficiency.

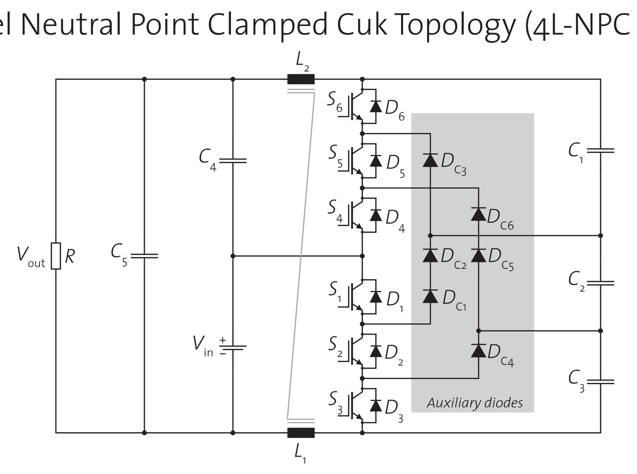
Multi-Level Converter Topologies

4-Level Neutral-Point Clamped Topology (4L-NPC)



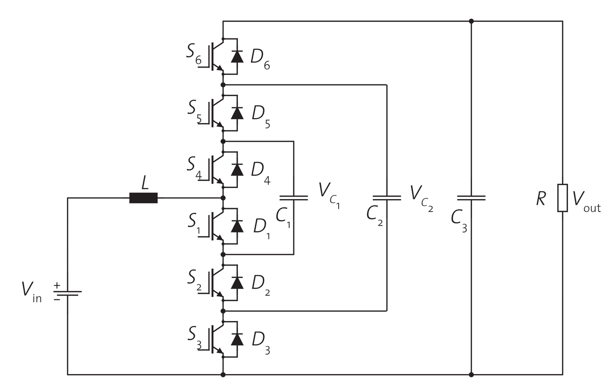
- Two level operation identical to basic buck-boost operation.
- Diodes $D_{C1} - D_{C6}$ are low current devices used for clamping only.

4-Level Neutral Point Clamped Cuk Topology (4L-NPC Cuk)



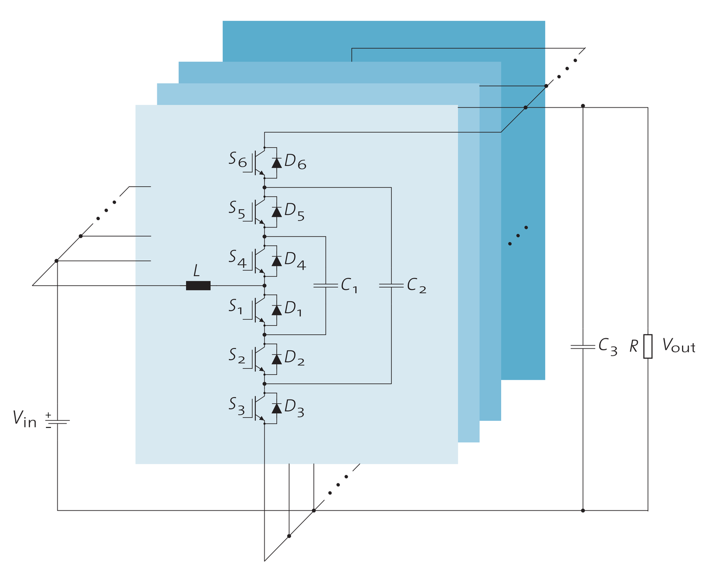
- Reduced inductor size due to coupling compared to regular NPC topology.
- Larger volume of the capacitor bank compared to regular NPC topology.
- Current ripple reduction sensitive to magnetic component parameter change.

4-Level Flying-Capacitor Topology (4L-FC)



- Frequency multiplication of the inductor current ripple (i.e. lower inductance compared to NPC topology).
  - $\frac{L_{FC}}{L_{NPC}} = \frac{1}{3} \cdot \left(1 - \frac{2V_{in}}{V_{out} - V_{in}}\right)$
- High currents flowing through capacitors C_1 and C_2.
- $V_{C_1} > V_{in}$ for proper operation.

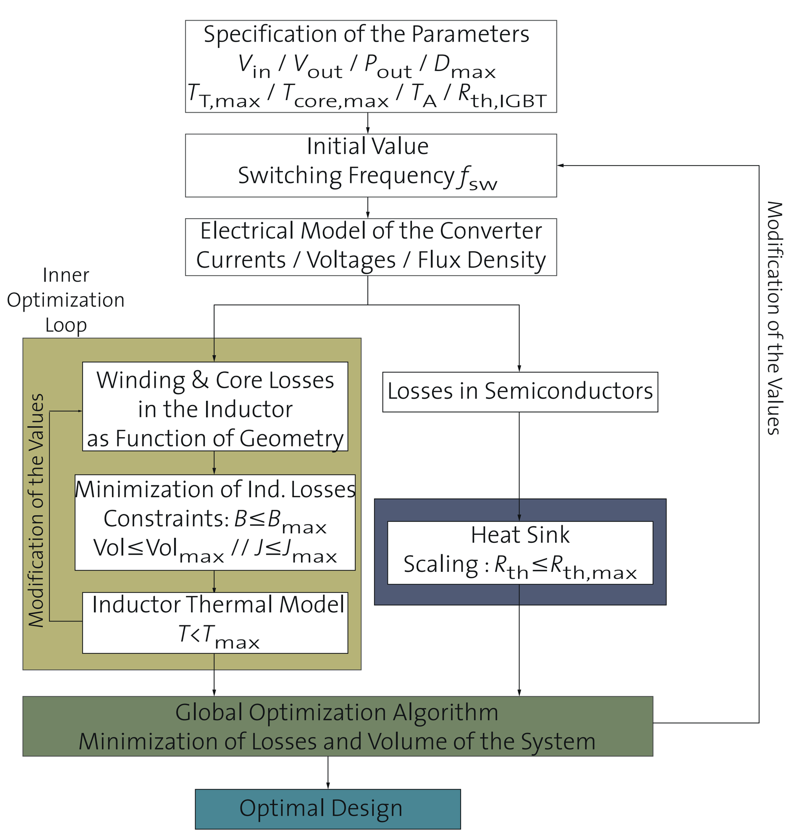
System Design



Example circuit schematic of the modular system with 4L-FC topology (8 interleaved modules).

Optimization Results

Optimization Algorithm

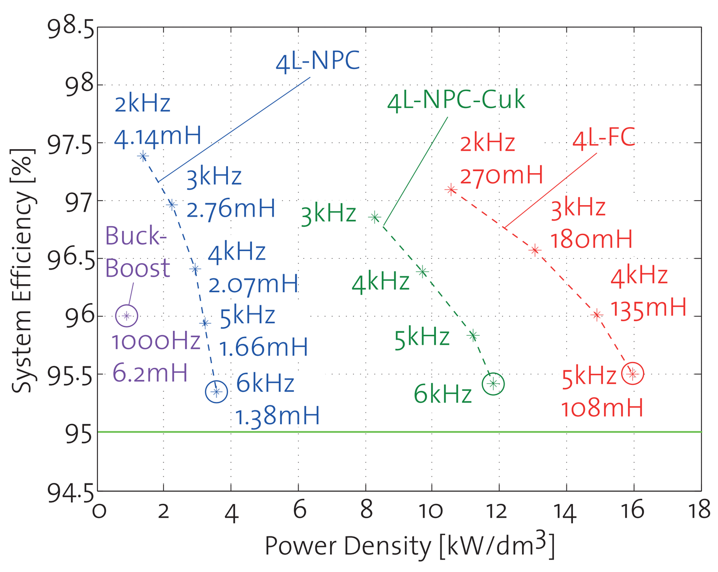


Optimization procedure with an inner loop for inductor optimization.

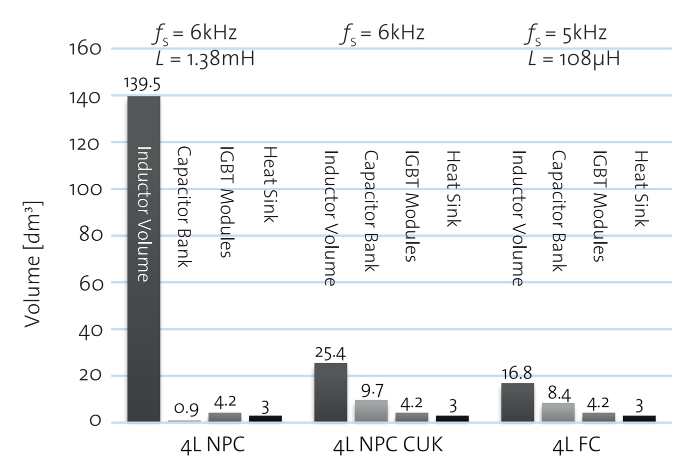
Nominal Conditions

Output Power	4 MW
Input Voltage	530 V
Output Voltage	2800 V

Results for Nominal Conditions



Pareto-fronts.

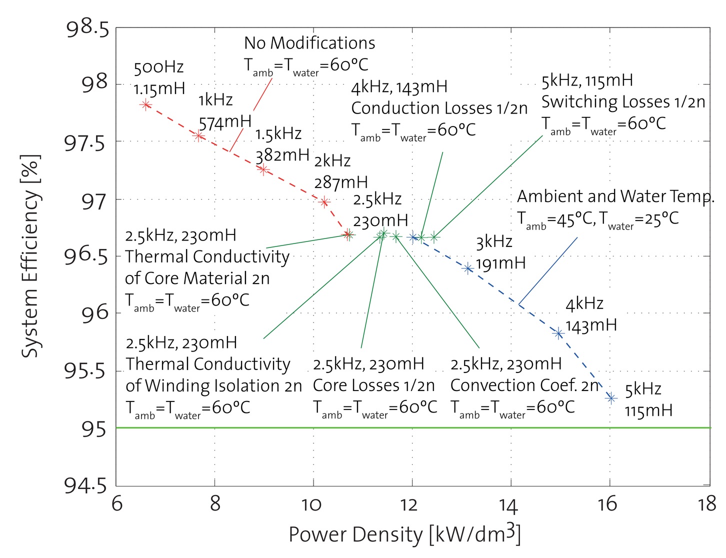


Component volume comparison.

Sensitivity Analysis

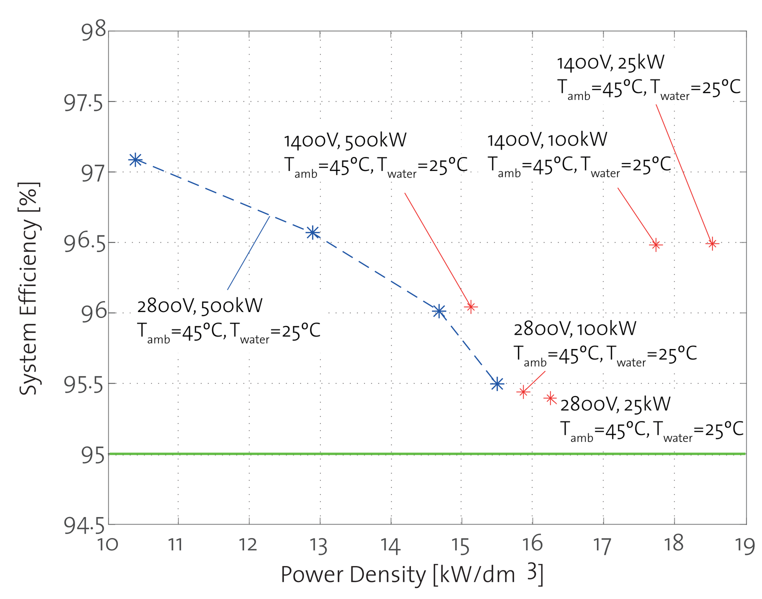
Modified Technologies for the Sensitivity Analysis.

Heat Transfer Coefficient	2x increase
Thermal Conductivity of Core Material	2x increase
Thermal Conductivity of Winding	2x increase
Core Losses	2x decrease
Semiconductor Conduction Losses	2x decrease
Semiconductor Switching Losses	2x decrease
Temperature of the Ambient	T=60 °C → 45 °C
and Cooling Water	T=60 °C → 25 °C



Pareto front with the added points resulting from the technology value modifications for the 4L-FC converter

Scalability Analysis

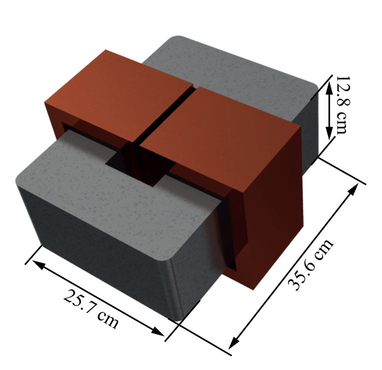


System pareto-fronts for the 4L-FC converter with scaled operating points.

- Sensitivity Analysis: Modification of the technology values and the influence it has on power density of the system.
- Scalability Analysis: Reduction in the module power and output voltage values and the influence it has on power density of the system.

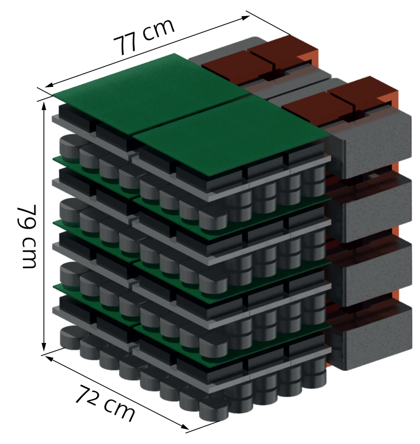
Optimal Design of 4L-FC for Nominal Load

Optimal Inductor Design for the 4L-FC Circuit.



Core Material	METGLAS2605SA1
Inductance	115 μH
Number of Turns	9
HF Litz Wire	5.000 x 0.36 mm
Current Density	1.8 A/mm²
Total Losses	357 W
Temperature Rise	75 K
Ambient Temperature	25 °C

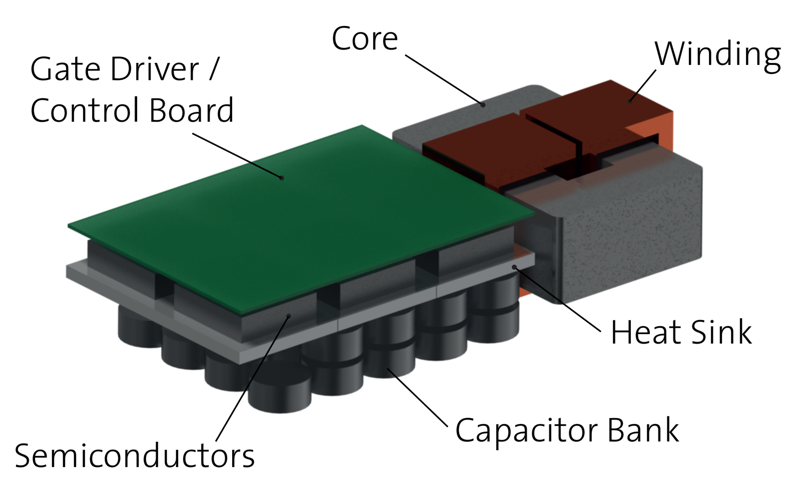
Resulting System with 8 Interleaved Modules.



Power (8 Modules Interleaved)	4 MW
Module Power	500 kW
Frequency	5000 Hz
Maximum Efficiency	97.4 %
Volume	438 dm³
Power Density	9.13 kW/dm³
Ambient Temperature	45 °C
Cooling Water Temperature	25 °C

Module Design & Conclusion

Simplified Mechanical Drawing of a Single Module of the 4L-FC Interleaved System



Components

Semiconductors	Infineon FZ1600R17HP4
Capacitors	Cornell Dubilier 944U
Core Material	METGLAS2605SA1
Heat Sink	AavFin Liquid Cold Plates

In this paper, 4L-NPC, 4L-FC and 4L-NPC-Cuk converters are evaluated with respect to power density and efficiency for medium-voltage battery storage applications.

- 4L-FC topology results in the most compact system.
- From the sensitivity analysis, biggest increase of the power density is achieved by investing in a better colling system and more efficient switching components.
- From the scalability analysis, further volume reductions can be achieved by properly selecting the module power level.

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