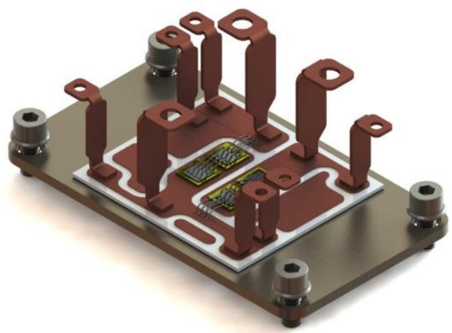
Next generation power devices challenges, possibilities, opportunities in Wind Turbine applications



10kV SiC MOSFET Power Modules

MW Electrolyzes

MW turbines

By: Stig Munk-Nielsen, Professor, smn@energy.aau.dk

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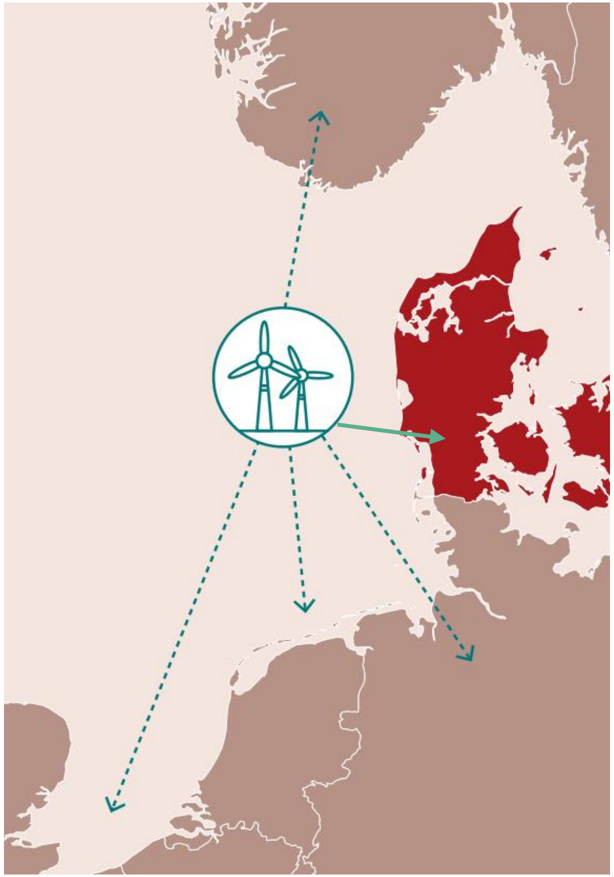
Electrification of Europe - Offshore Wind

- EU-commissions goal:
  300 GW offshore wind by 2050
- Belgium, Denmark, Netherlands, Germany:
  150 GW offshore wind by 2050
- Denmark:
  10 GW offshore wind by 2030 (4x 2022)
  35 GW offshore wind by 2050 (15x 2022)
- Germany:
  30 GW offshore wind by 2030
  70 GW offshore wind by 2045

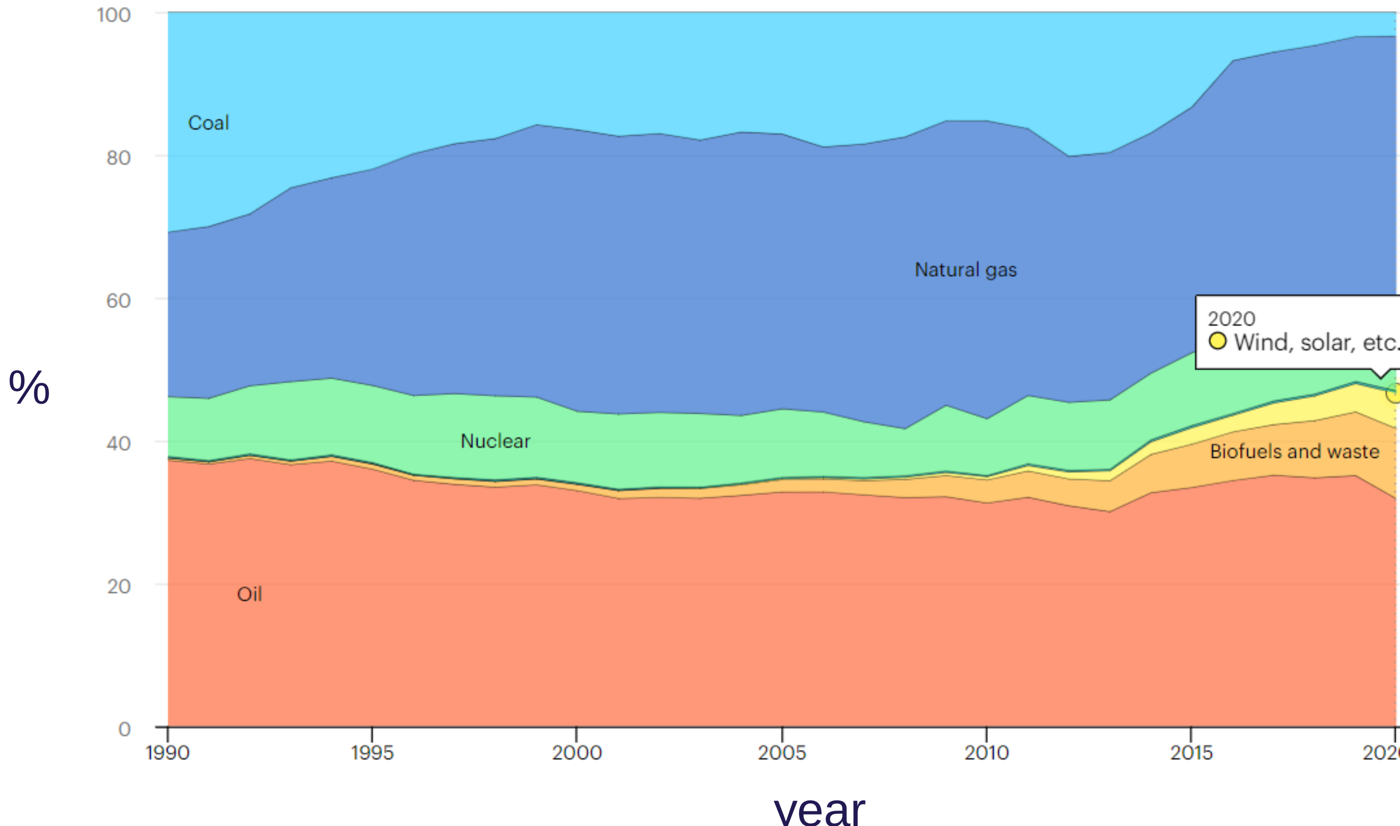


Source: Danish government (Danmark kan mere II)

THE ESBJERG DECLARATION in 2022
on The North Sea as a Green Power Plant of Europe
(Germany, Belgium, Netherlands, Denmark)

Source: The Esbjerg declaration
https://kefm.dk/Media/637884570050166016/Declaration%20of%20Energy%20Ministers%20(002).pdf

Total energy supply, United Kingdom energy supply 1990-2020 by sources: IEA



https://www.iea.org/countries/united-kingdom

Transportation and how to survive moving from fossile energy ?

In 2020: about 5-10% of energy was from Wind and Solar

That journey took +30 years.

Challenges:

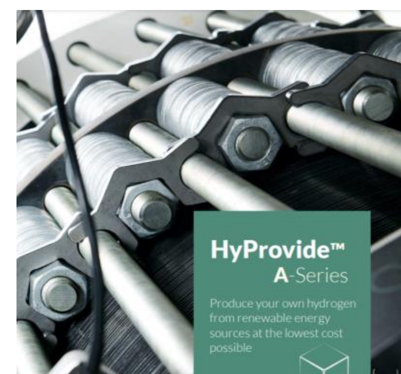
Replace about 30% of oil energy with something else for transportation within next 30 years.

Storage: How much oil, gas and coal (fossil or Green) will be used to produce electricity for EVs?

Powering EVs from grid, can we extend grid in time?

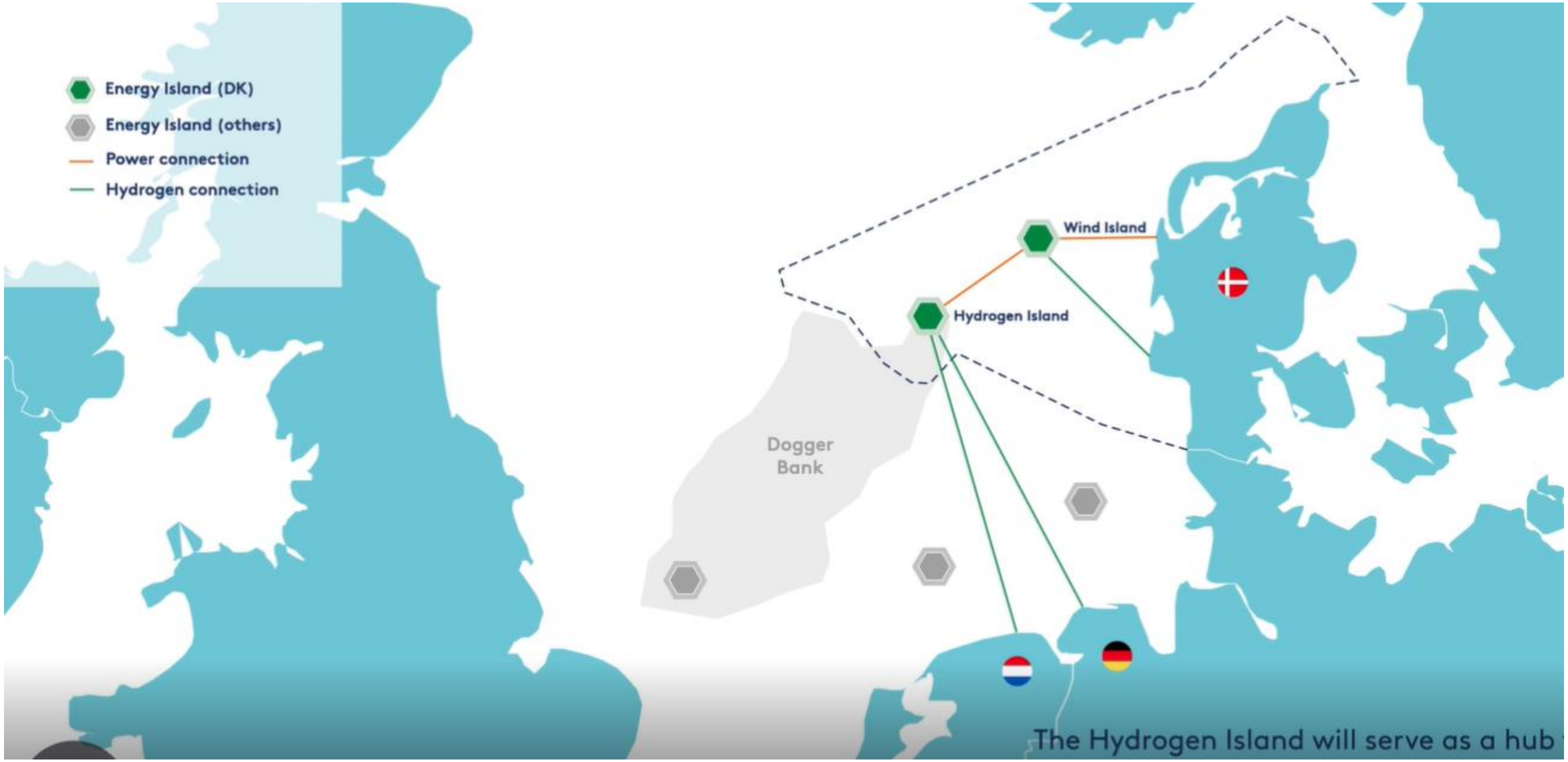
https://www.mini.co.uk/en_GB/home/range/mini-electric.html

Electro fuel based on electrolysis



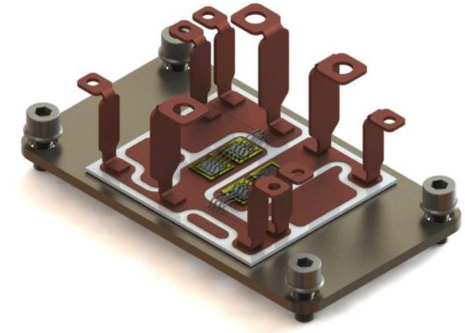
https://greenhydrogen.dk/wp-content/uploads/2021/02/A-series-brochure.pdf

Electro fuels vision from private operator CIP 10GW Hydrogen island.



https://www.oedigital.com/news/496723-cip-proposes-to-build-hydrogen-island-in-danish-dogger-bank-area

Technology for wind, solar and electrolysers



So we look in to a future of additional several 100 GW's wind, solar plants.

We need MW range power converters for Wind, Solar and Electrolyzers

One challenge

Can we use the same technology for Wind, Solar and Electrolyzers?

Power technology for Wind, Solar and Electrolyzers using WBG

	Power Components: Today	Power Components: Future
Wind offshore +10MW Grid Inverter Low voltage (690V) High current (+9kA)	IGBT, Diode	MosFet
Electrolyzer fx. 2 MW Grid rectifier Low voltage (690V) High current (1.8kA)	Diode, Thyristor, IGBT	?

Wind offshore
10MW LV vs. MV

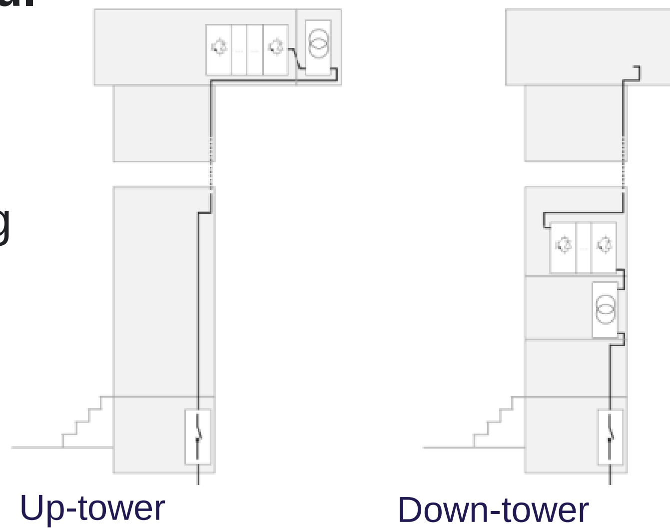
	Power Components	Power Converter
Grid Inverter Low Voltage (690V) current (9kA)	IGBT, Diode 1700V	2-Level
x 6 $\quad \frac{1}{6}$		
Grid Inverter Medium Voltage (4160V) current (1.5kA)	MOSFET 10000V	2-Level

Wind turbine Cost of Energy- can it be reduced?

CoE the average cost per kWh of useful electrical energy produced by the system.

CoE is traditionally reduced by increasing size of Wind turbines.

- Electrical subsystem has impact on CoE in other subsystems.
- Up-tower versus down-tower electricals
  - Conduction losses
  - Amount of copper
  - Nacelle weight



Catalin Dincan, Philip Kjær, Lars Helle Vestas Wind Systems A/S, EPE'20, ISBN: 978-9-0758-1536-8*

Efficiency of Power electronic converter systems

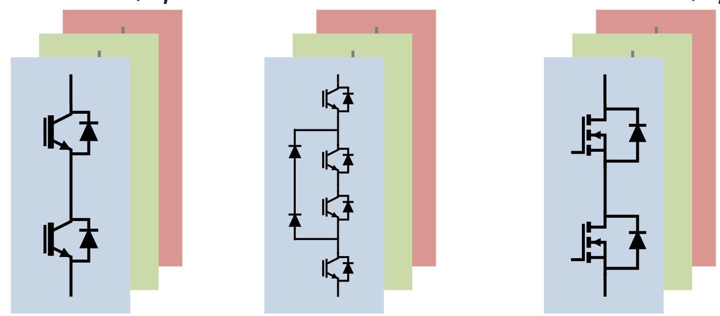
- 97% efficiency of 690 V Si based converter*
- 98% efficiency of 3.3/3.0 kV Si based converter* **
- How about 99% efficiency??

- Challenges?
  dV/dt, common mode current, EMI/EMC…
  and probably more

  Test to maturity!

690 V 2L Si, $\eta \approx 97\%$

4.2 kV 2L SiC, $\eta \approx ??\%$



3/3.3 kV 3L Si, $\eta \approx 98\%$

Source: * Ingeteam - Wind converter catalogue ** ABB - PSC6000

So lets develop Medium Voltage 2-Level wind turbine power converter using 10kV MOSFETs

Target: +99% efficiency
face the challenges: higher dV/dt, common mode noise, PDs…and probably more

Content

- Historical review, possibilities, opportunities and challenges
- Design of power electronics Systematic digitalization of Power Module design process using 3D info
- Design, test and comparaison of: (i) models and (ii) measurement

  Case #1: Designing 10 kV SiC MOSFET power modul

  Case #2: Re-Designing 10 kV SiC MOSFET power modul
- Aalborg University Power Module Packaging Laboratory

  Case #3: 4160 V SiC MOSFET power converter
- Summary

Historical Review of Power Devices:

Development for structure and material

"Pre-Silicon" Age | **"Silicon" Era**

1930~1945
Mercury Valve
(Peter C. Hewitt)
First device for electric conversion of human history

1947
Transistor
(Bell Laboratories)
The start of all electronics

1957
Thyristor
(General Electric)
First of partially controllable power device

1959
MOSFET
(Bell Laboratories)
First of fully controllable low-power device

1980~1990
SiC Material
Starting of research on SiC material for power device *

1987
IGBT
(B. Jayant Baliga)
First of fully controllable high-power device

<2010
Diamond Material
Starting of research on diamond material for power device †

2011
SiC MOSFET
(Cree)
First of commercial SiC power device (1200V)

* Bhatnagar, M.; Baliga, B.J. (March 1993). "Comparison of 6H-SiC, 3C-SiC, and Si for power devices". *IEEE Transactions on Electron Devices*. **40** (3): 645–655.

† H. Umezawa, K. Ikeda, R. Kumaresan, N. Tatsumi and S. Shikata, "Increase in Reverse Operation Limit by Barrier Height Control of Diamond Schottky Barrier Diode," in IEEE Electron Device Letters, vol. 30, no. 9, pp. 960-962, Sept. 2009.

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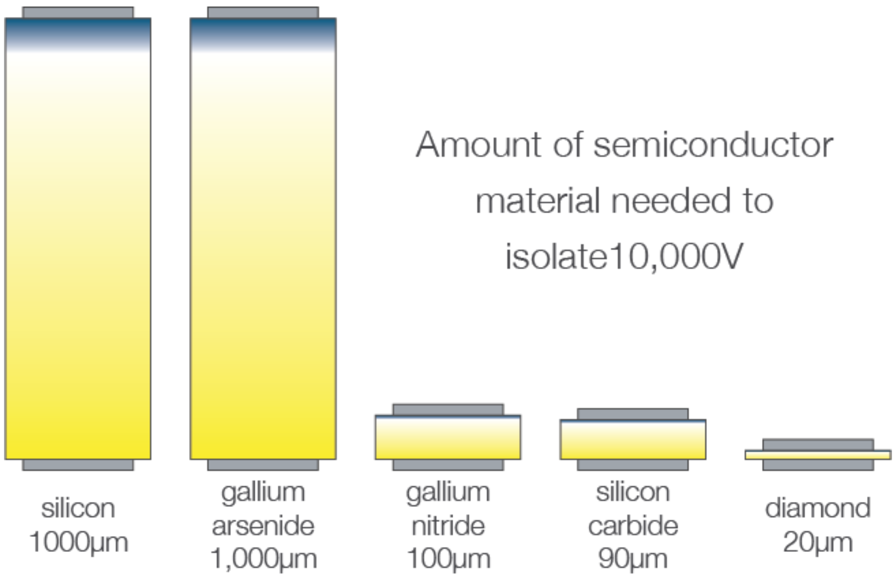
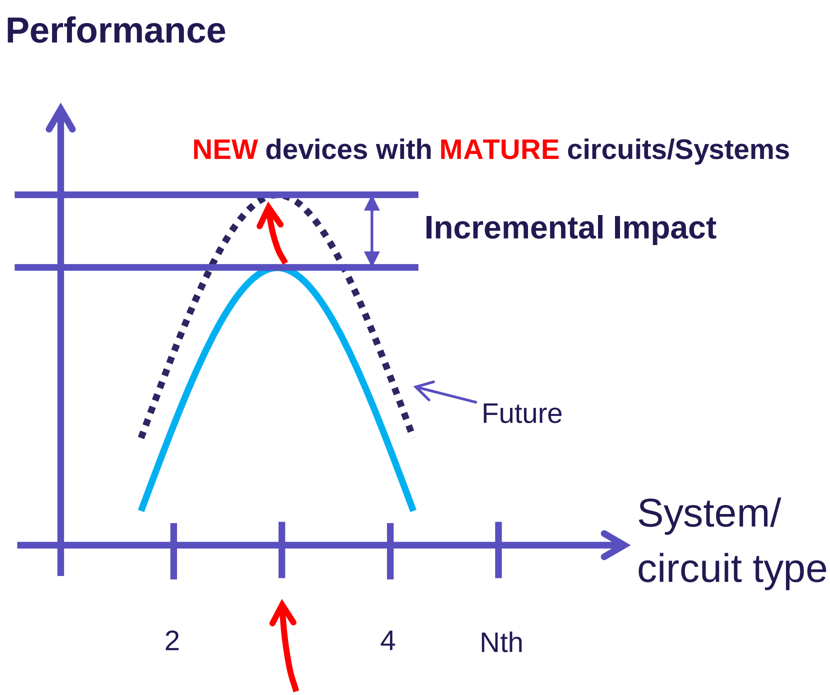
Next-Generation Power Device : Possibility



Si	MOSFET(commercial)	12~1200V
	IGBT(commercial)	650~6.5kV
SiC	MOSFET (commercial)	1.7kV (3.3kV)
	MOSFET (non-commercial)	10kV and 15kV
	IGBT (non-commercial)	up to 25kV (expected)
GaN	eHEMT(commercial)	30~650V
	Vertical Devices?	few kV (expected)
Diamond	eFET(researcher's test)	>1.5kV
	eFET(>10~15 years)	up to 50kV (expected)

http://www.evincetechnology.com/why_diamond.html

Next-Generation Power Device : Opportunities



The “winner” circuit/solution.
Identified by the MARKET

Approach: “Replacing”

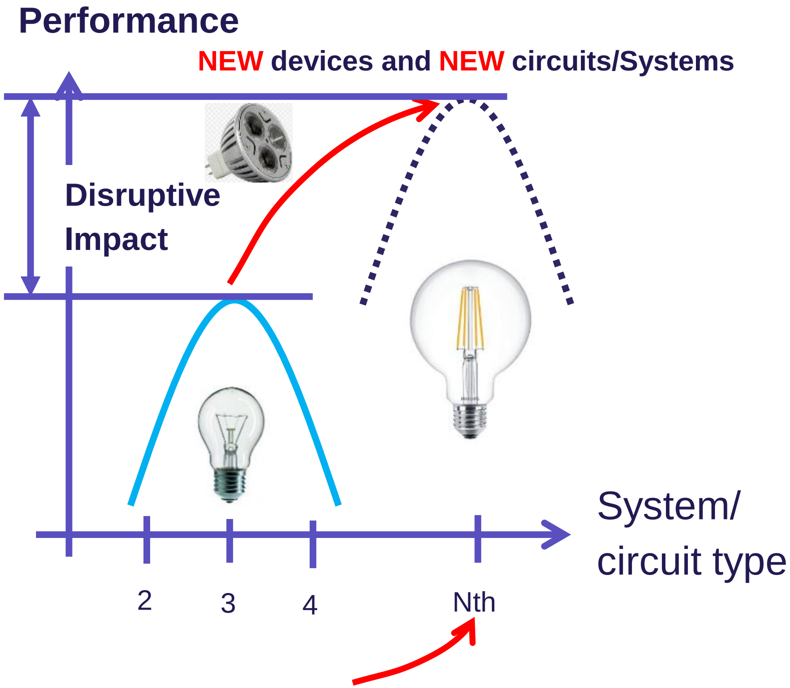
-Applying new devices to conventional systems

Opportunity:

- Low risk in system-level
- Reduce conduction and switching losses
- Reduce size of passive filter or auxiliary component
- Reduce cooling requirement
- Reduce switching harmonic component

https://www.iepe.et.aau.dk/electronic/motor-drive-sic-mosfets/

Next-Generation Power Device : Opportunities



The new “winner” circuit/solution.
Identified by the MARKET

Approach: “Renovation”

-Applying new devices to new circuits/systems

Opportunity:

- Increase efficiency – reduce losses
- Flexible system structure

Blue LED

We began as a start-up, a group out of North Carolina State University exploring the uses of silicon carbide as a foundational technology. In 1989, Cree created the first major application for silicon carbide with the introduction of the world’s first blue LED, the core technology that’s inside the vast majority of LEDs in use today.

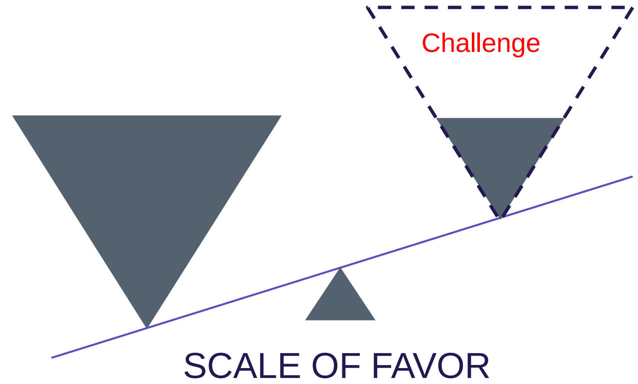
Martin Professional A/S Receives Grant for Development of Intelligent LED

On December 13th, 2007 Martin Professional A/S was awarded a technology grant from the Danish National Advanced Technology Foundation for the development of new LED technologies. The project, called INLED (Intelligent Light Emitting Diodes)

Next-Generation Power Device : Challenges

Silicon Power Devices:

- Cheap
- Stable supply chain
- Mature
- Low risk



Next-Generation Power Devices:

- Expensive
- Need strong supply chain
- Design and application challenge
- High risk

Challenges of next-generation power devices to fill the gap:

- High voltage
- Fast switching

→

- Partial discharge
- High di/dt and high dv/dt
- Sensitive to parasitic

→

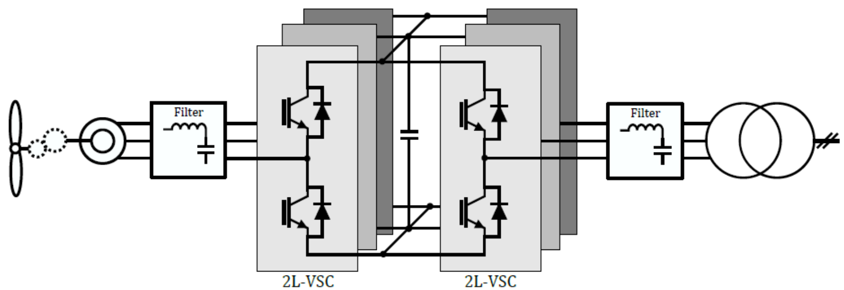
- Low lifespan
- EMI & common-mode current
- "Ringing" switching

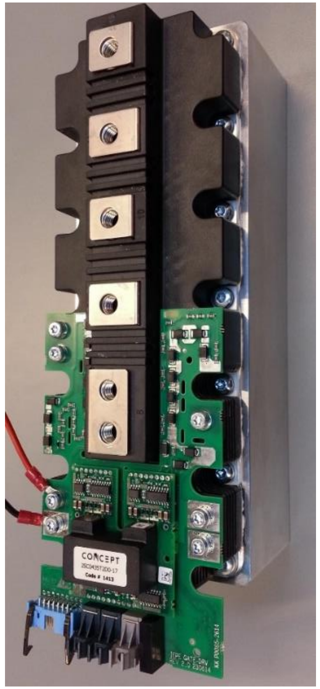
→ **Optimized Design & Guideline**

Safe and proven: Si IGBT Power Stack 1.2 MW (4x600kW) back-to-back transformer isolated (GURLI4)

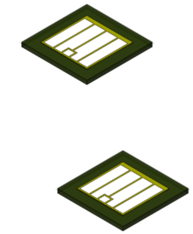
Case #1: Designing 10 kV SiC MOSFET power modul

- Commercially available high power Si IGBT package
- Develop for high power SiC MOSFETs power module
- Main challenges
  - Voltage rating: ~1.7 kV vs 10 kV
  - Switching time: 300-600 ns vs 200-500 ns

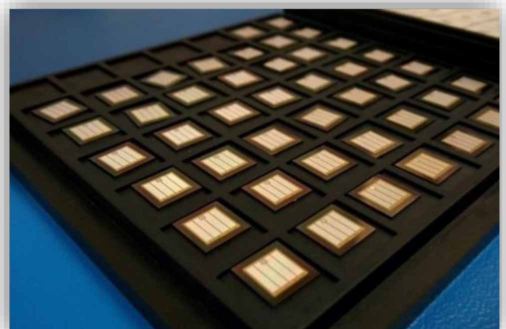


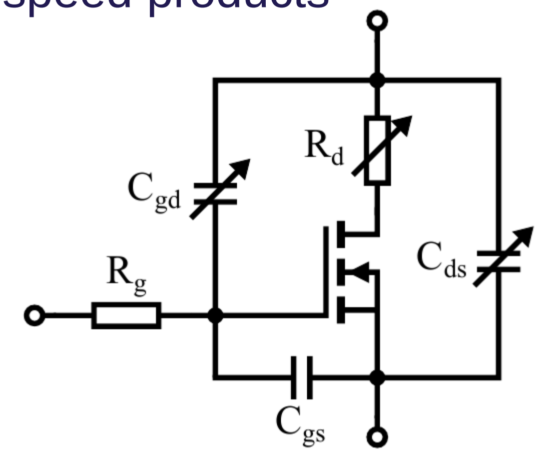


SiC MOSFET semiconductor model



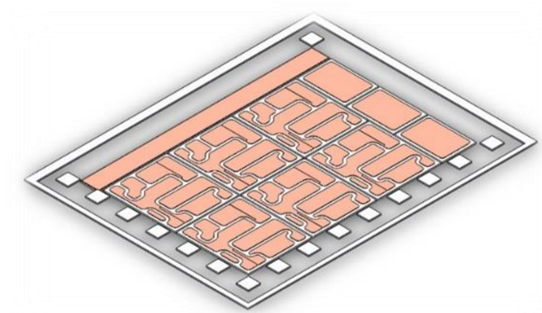
- Bare 10/15 kV SiC MOSFETs die from CREE/Wolfspeed
- Semiconductor device parasitics from datasheet or curve tracer
- SPICE models available for most Wolfspeed products

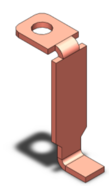


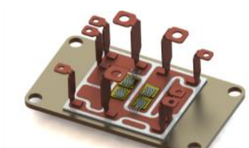


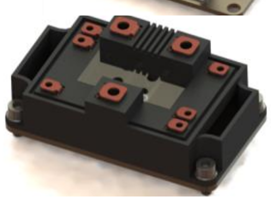
Solidworks 3D models for manufacturing

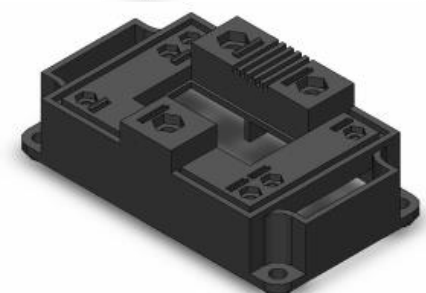
- Rapid prototyping
- After simulation - 3D models are used for manufacturing
  - Exposure masks
  - Terminal cutting
  - 3D printing of housing
  - Milling of fiber optic fixtures











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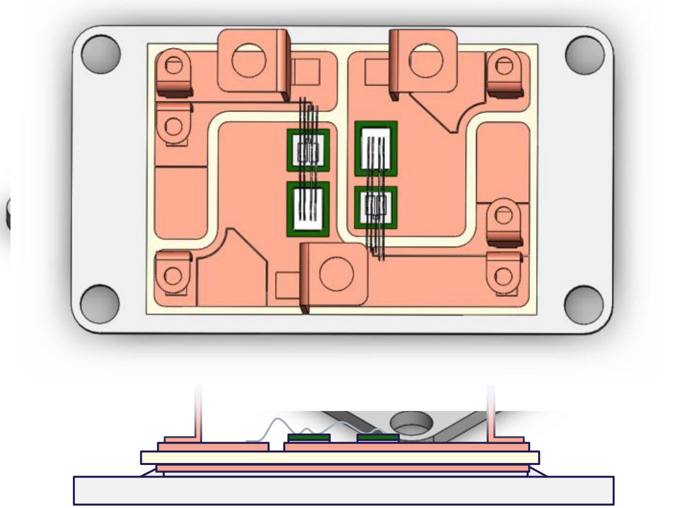
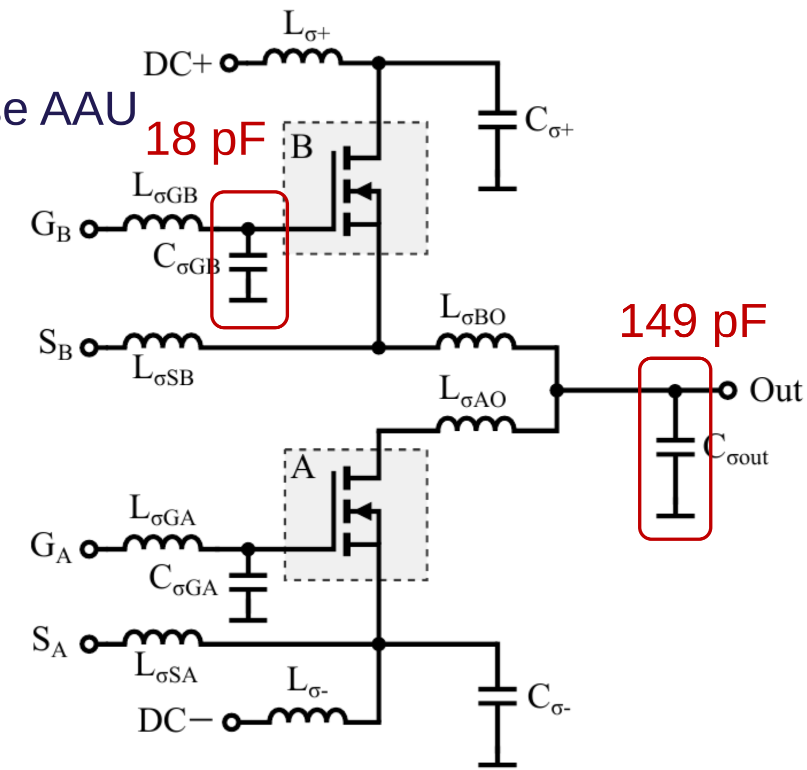
Case #1: Designing 10 kV SiC MOSFET power modul

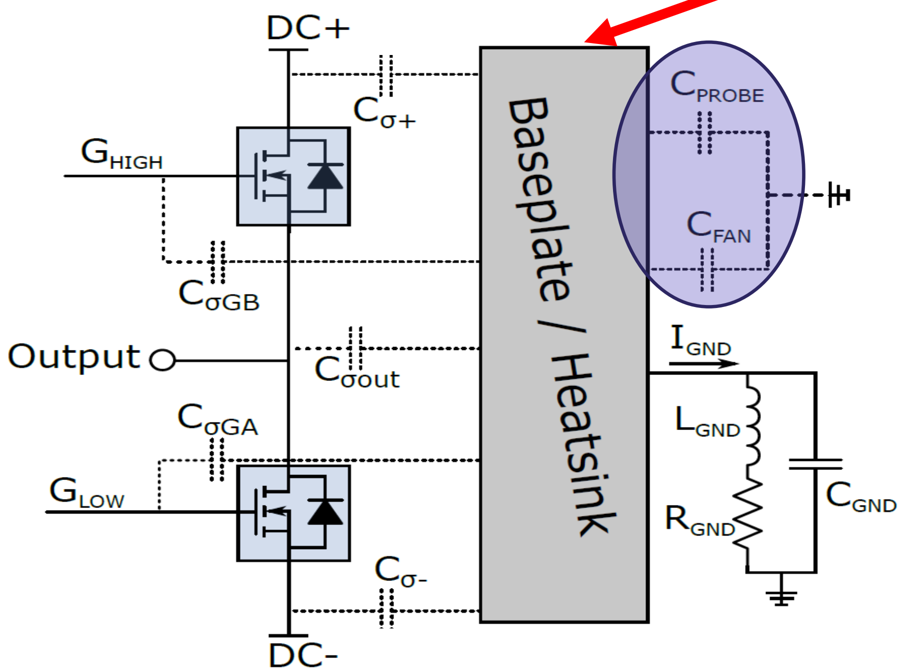
- Design in Solidworks, packaged in-house AAU
- Parasitics evaluated in ANSYS Q3D
  - 19 kV/µs switching ~3A to heatsink





Heatsink Modelling using: SolidWorks + ANSYS Q3D+Spice

Measure the Heatsink Voltage



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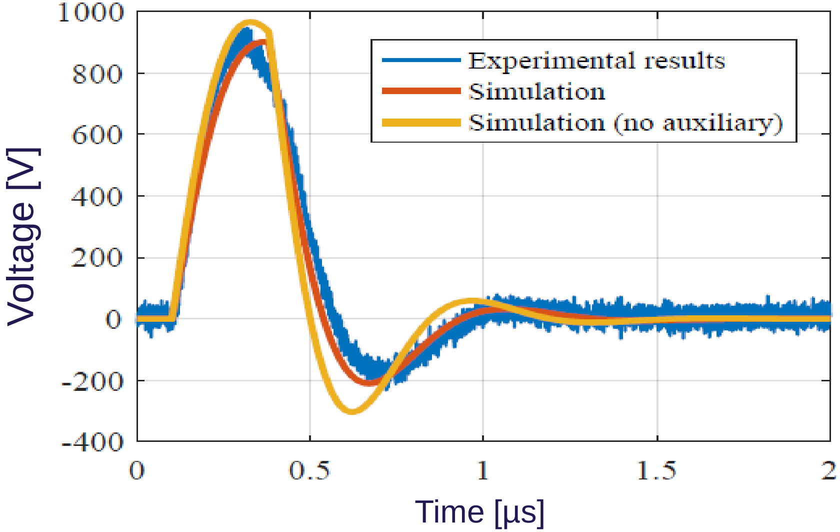
Heatsink Voltage Validation

Sensitivity of heatsink voltage



C_{fan} = 80 pF

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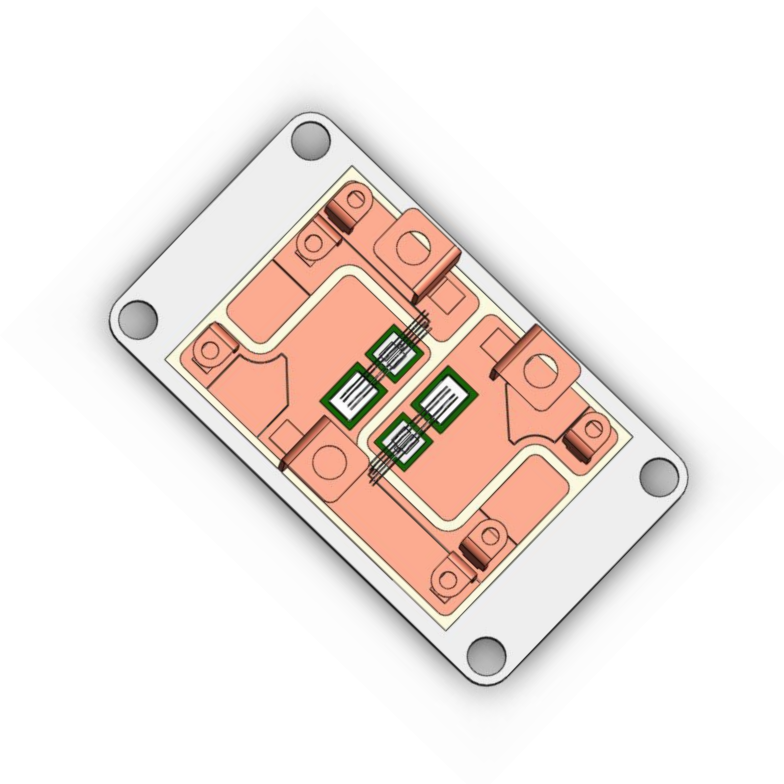
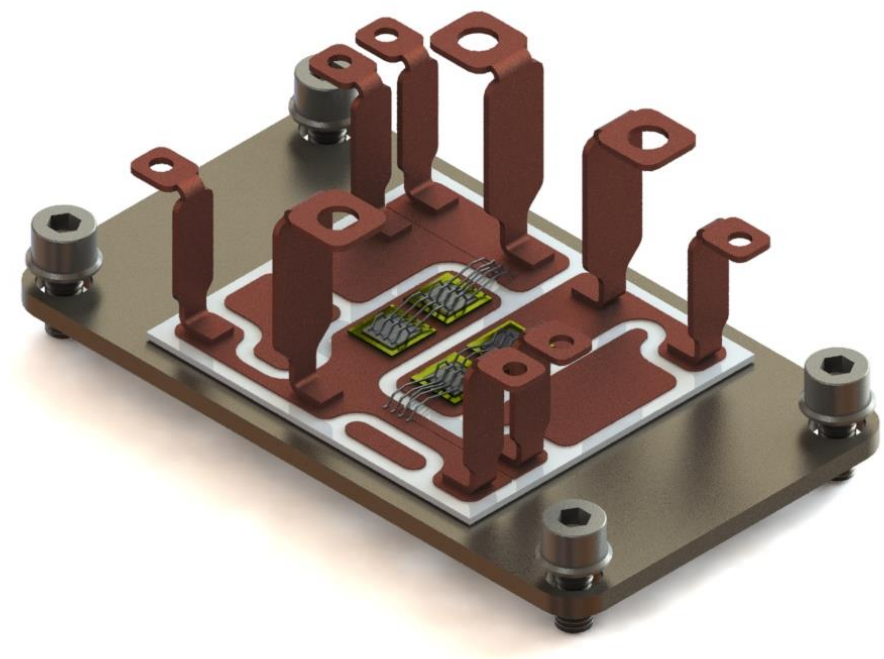
Case #2: Re-designing 10 kV SiC MOSFET power modul

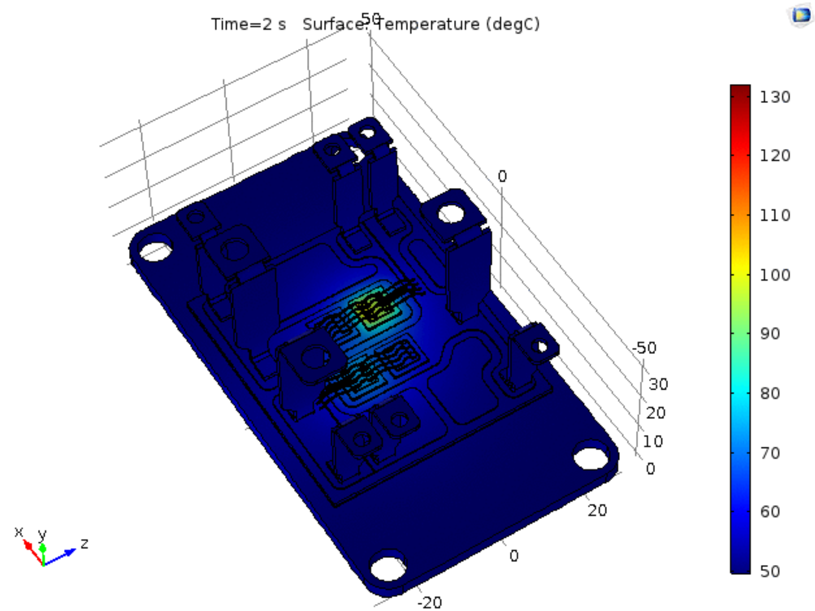
3th and 4th generation 10kV SiC power module design





Validate new design

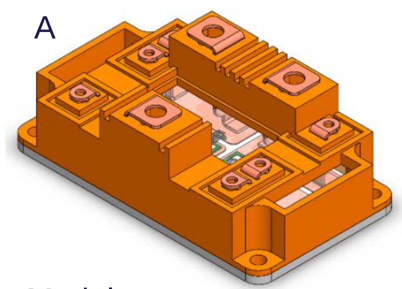
- Proposed designs based on electrical parameters C, L and R
- Ensure that performance is not violated for other metrics
  - Heat transfer
  - Electrostatics
    - Capacitive voltage divider
    - High electric field strength



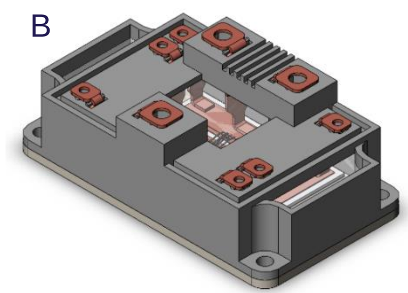
Next-Generation Power Device : Challenges

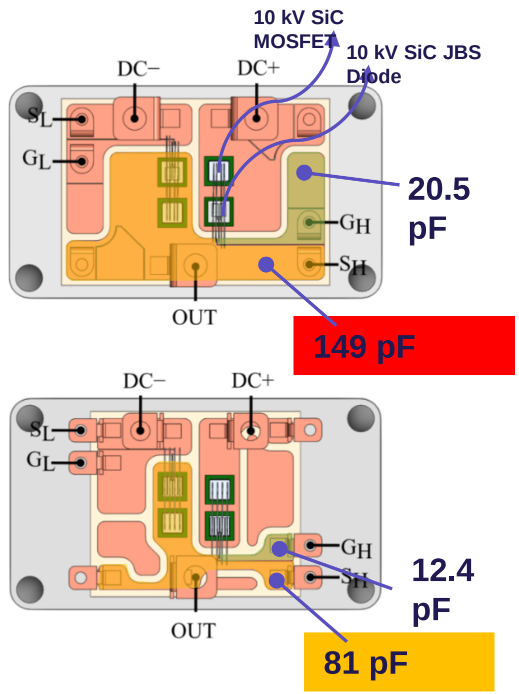
Digital Design Guideline using Power Device

Module A

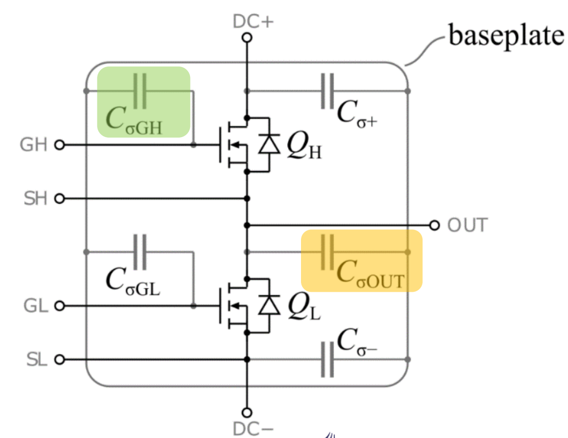


Module B





- Decrease parasitic capacitances



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Aalborg University Power Module Packaging Laboratory

Goals for laboratory :

- from idea to module prototype
- Fast workflow
- In house processing
- Research in packaging

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SiC Medium Voltage Platform · timeline

Start
2014

2018 10kV SiC
M4X PMs (20A)

2022 10kV SiC
M5X PMs (80A)

power module / packaging process established → 10 -15 kV system technology → System reliability testing

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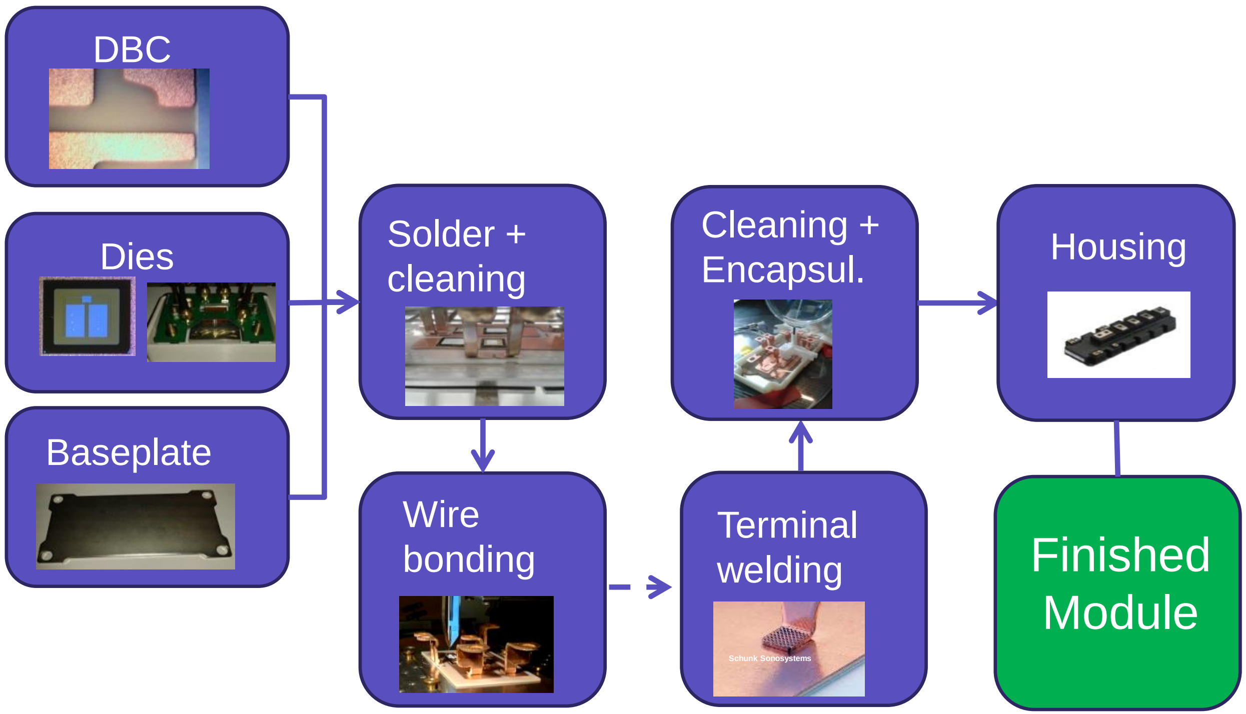
Aalborg University Power module assembly process steps



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Case #3: 4160 V SiC MOSFET power converter

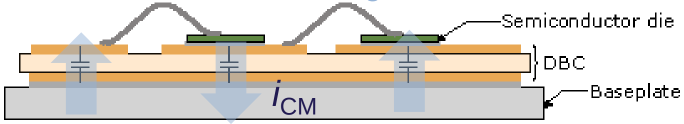
Power module design requirement

- **Advances in MV SiC Technology and increased interest for MV power conversion applications**

10 kV SiC MOSFET half bridge power module

Source:[1]

- **MV SiC MOSFET power modules:**
  - **MV SiC MOSFETS** → **High *dv/dt*..!**



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    - **EMI/EMC**
    - **Increased switching losses**
  - **In case of MV SiC MOSFETs the displacement currents can be comparable to the significant fraction of the SiC MOSFETs rated current**
  - **Parasitic capacitances are critical.**

- **Design requirement** → **low capacitive couplings**

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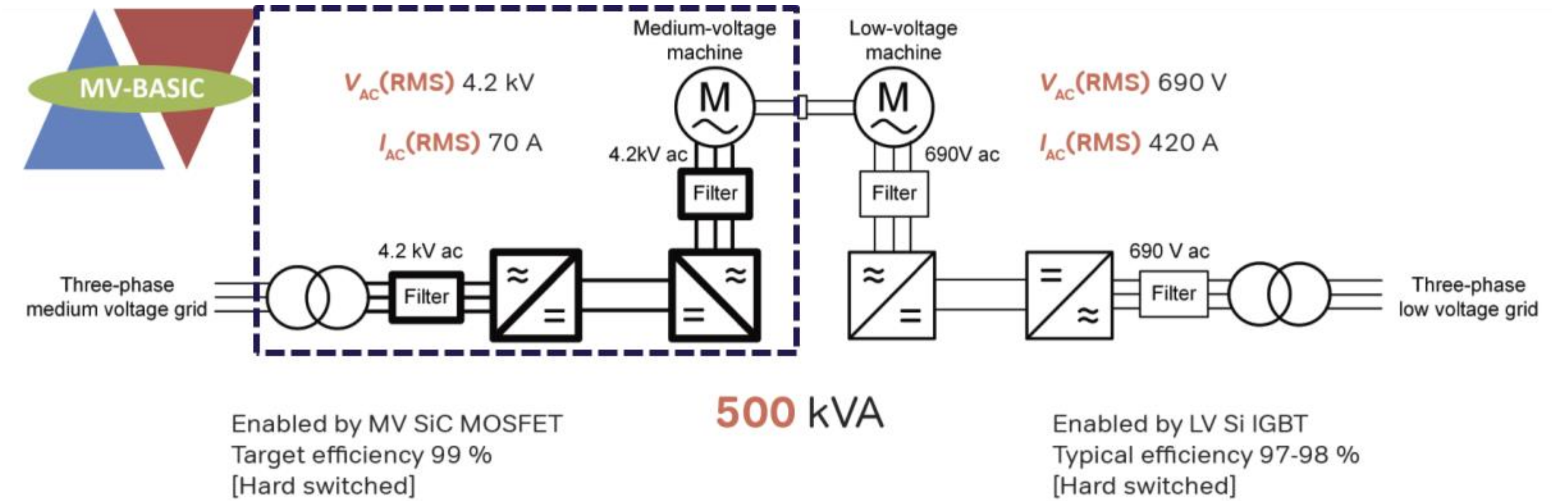
Next-Generation Power Device : Challenges

Validation of MV SiC Device based Converter



Prospective benefits：

- Higher switching frequency: 5 kHz - 10 kHz
- Higher efficiency: 1-2% more than Si IGBT
- Less copper: 17 % rated current compared to IGBT

Major challenges and research problems：

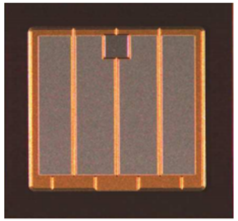
- High dv/dt: 30 kV/μs - 80 kV/μs
- Higher insulation requirement: 10 kV level
- Design of magnetics with reduced parasitic

Next-Generation Power Device : Challenges
Validation of MV SiC Device based Converter

Standard 690V 500kVA
3Ø-IGBT converter

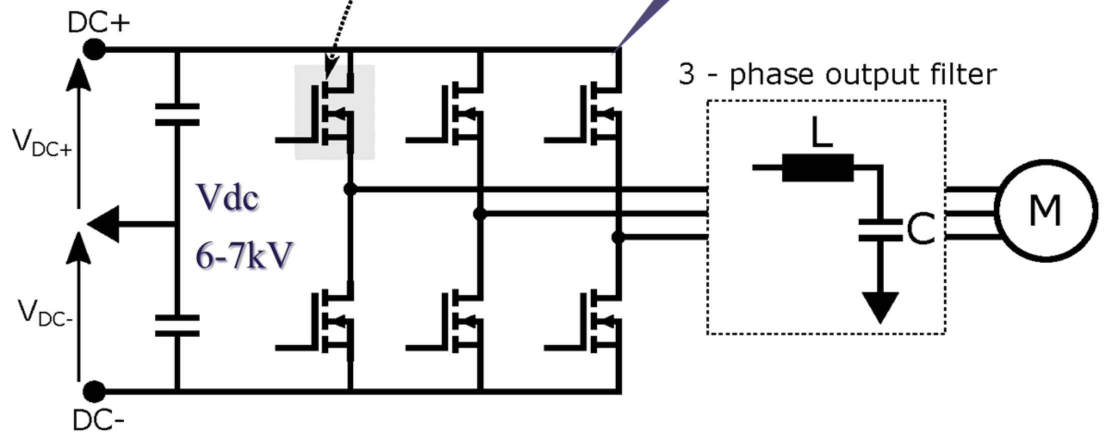
MV SiC
4.16 kV

LV Si
690 V



Gen3 10kV/350mΩ SiC MOSFET

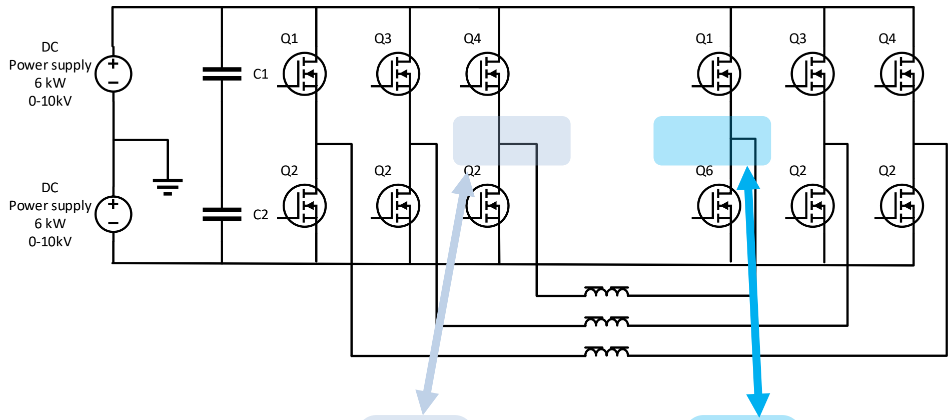
1 - 2 % target efficiency improvements

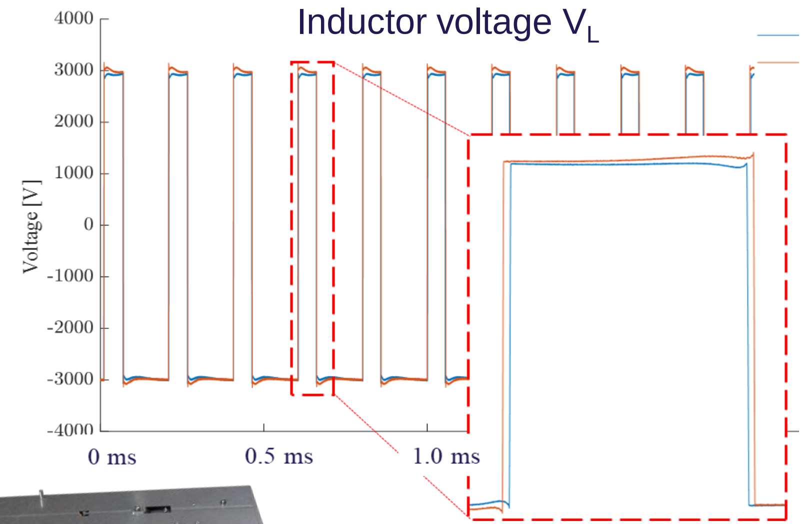


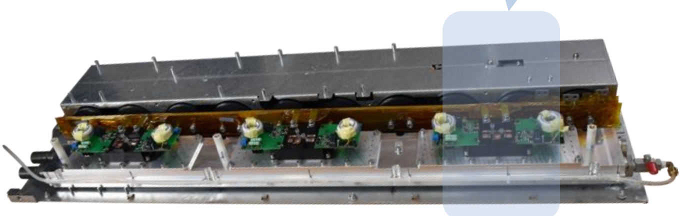
Next-Generation Power Device : Challenges

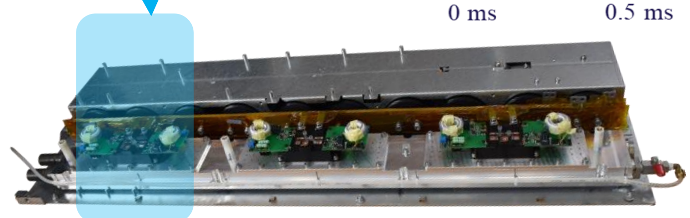
MV-BASIC: Validation of MV SiC Device based Converter

10kV SiC MOSFET 3 phase back-to-back converter









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Next-Generation Power Device : Challenges
Validation of 80kVA MV SiC Device based Converter

10kV 20A SiC MOSFET

Switching Frequency 5kHz

6000V DC link voltage

AC voltage: 4160Vrms

Line current: 6.6Arms

MV BASIC
10 kV SiC MOSFET based
3 Phase Back To Back
Converter

Next-Generation Power Device : Challenges

Dies (transistors)

10kV 20A

2019

Demonstrator MV1: Medium voltage 60 kVA 3 phase power stack using single die 10 kV half bridge power module

10kV 80A

2020

Demonstrator MV2: Medium voltage 500 kVA 3 phase power stack using multi chip 10 kV half bridge power module

2022

MV laboratory: Testing 500kVA of MV and LV power stacks. Key performance characteristics evaluation.

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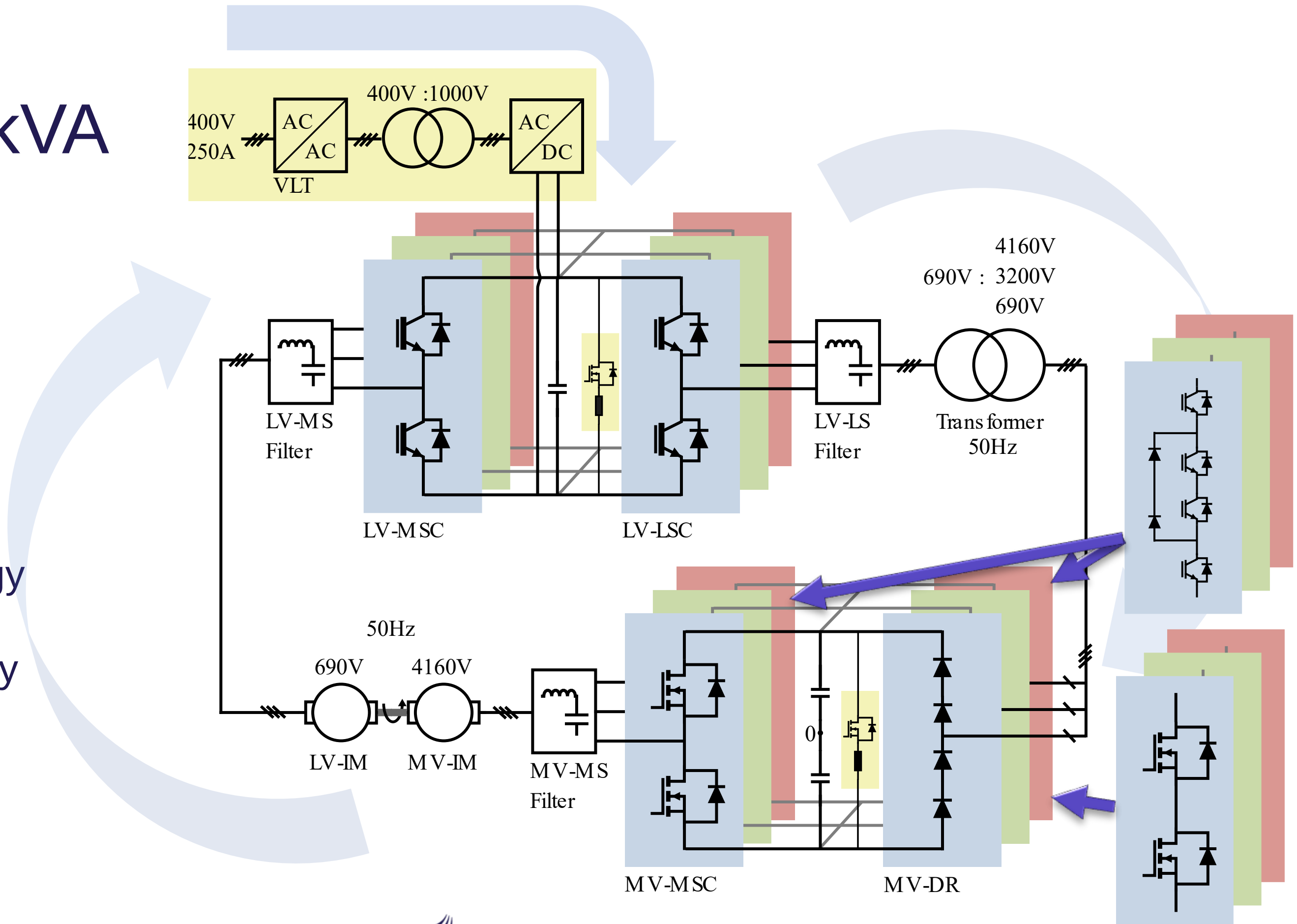
MVolt – 500 kVA test platform

- LV and MV in same power loop
- Realistic common mode connection
- 132 kJ kinetic energy at nominal speed
- 7 kJ potential energy at nominal DC-link voltages
- Flexibilty



MVOLT POWER A BETTER FUTURE

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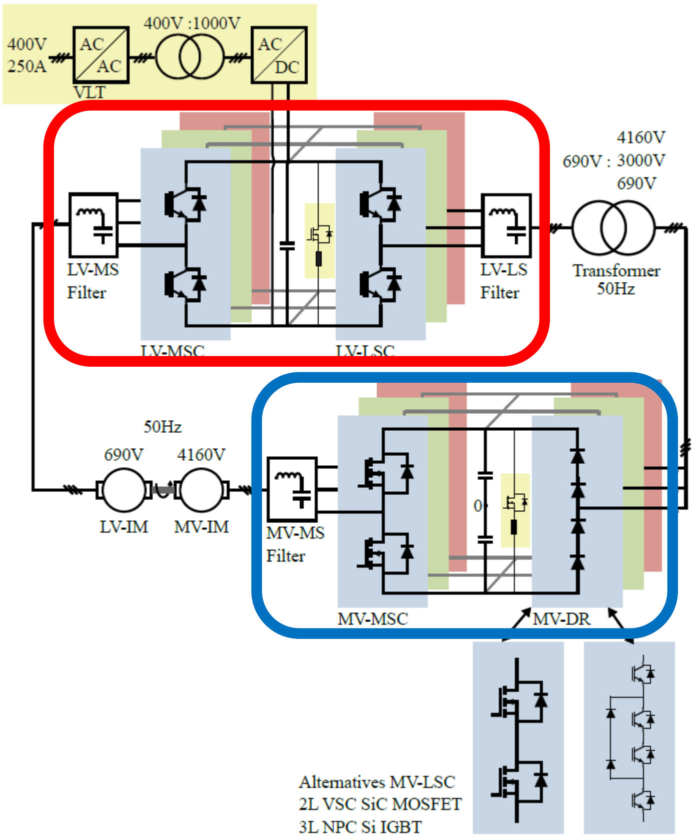
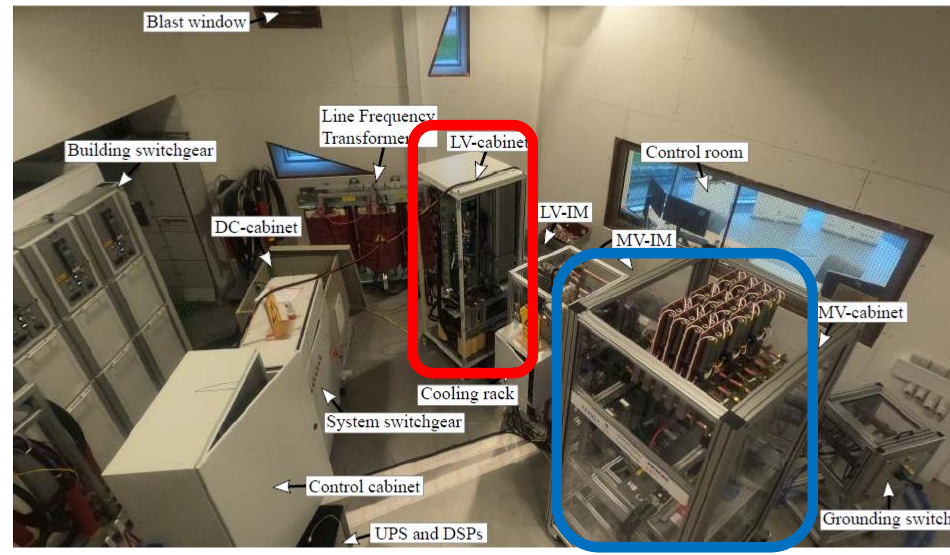
MV demonstrator 500kVA using 10kV SiC and 1.7kV Si technology





Summary

Possibility of next-generation power devices:

- In near future: commercially available SiC MOSFET will move to 3.3kV and more;
- In some years: 10kV and 15kV SiC MOSFET and SiC IGBT may be commercially available;
- In the long-term: new power devices with more than 15kV capability may be possible;

Opportunity of using next-generation power devices:

- Reduced power loss, cooling requirement, footprint;
- Simplify medium voltage power converters;
- Models of WBG devices is available from manufactures

Challenges of using next-generation power devices:

- Learn to use tools as FEM, circuit simulator and data exchange etc for design phase
- Need experimental converter-level validation;
- Reliability and robustness;

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Acknowledgement to Current Power Electronics Projects

MVOLT — POWER A BETTER FUTURE

2020 - 2024

- Design 2-level 500 kVA / 4.16 kV (AC) converter enabled by 10 kV SiC MOSFETs.
- Wind energy applications
- Module packaging, converter design, filter design, and system integration.

Innovation Fund Denmark

CODE

2021 - 2026

- Develop new digital design and product qualification processes allowing for higher efficiency and more compact power electronics systems.
- Only a single physical prototype has to be manufactured to achieve the specified performance.

POUL DUE JENSEN GRUNDFOS FOUNDATION

HEART PROJECT

ENGINEERING TOMORROW Danfoss

2021 - 2024

- Commercial-level EV charger enabled by SiC
- AAU is responsible for hardware design, manufacturing, and testing, with the collaboration of Danfoss.

Innovation Fund Denmark

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THANK YOU FOR YOUR ATTENTION

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