THE ROYAL SOCIETY

What do I work on for the next 30 years? Power-Electronics, Renewables, and the Path to 2050

Dr Paul Judge

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& Royal Society Industry Fellow

Context – UK Targets towards 2050

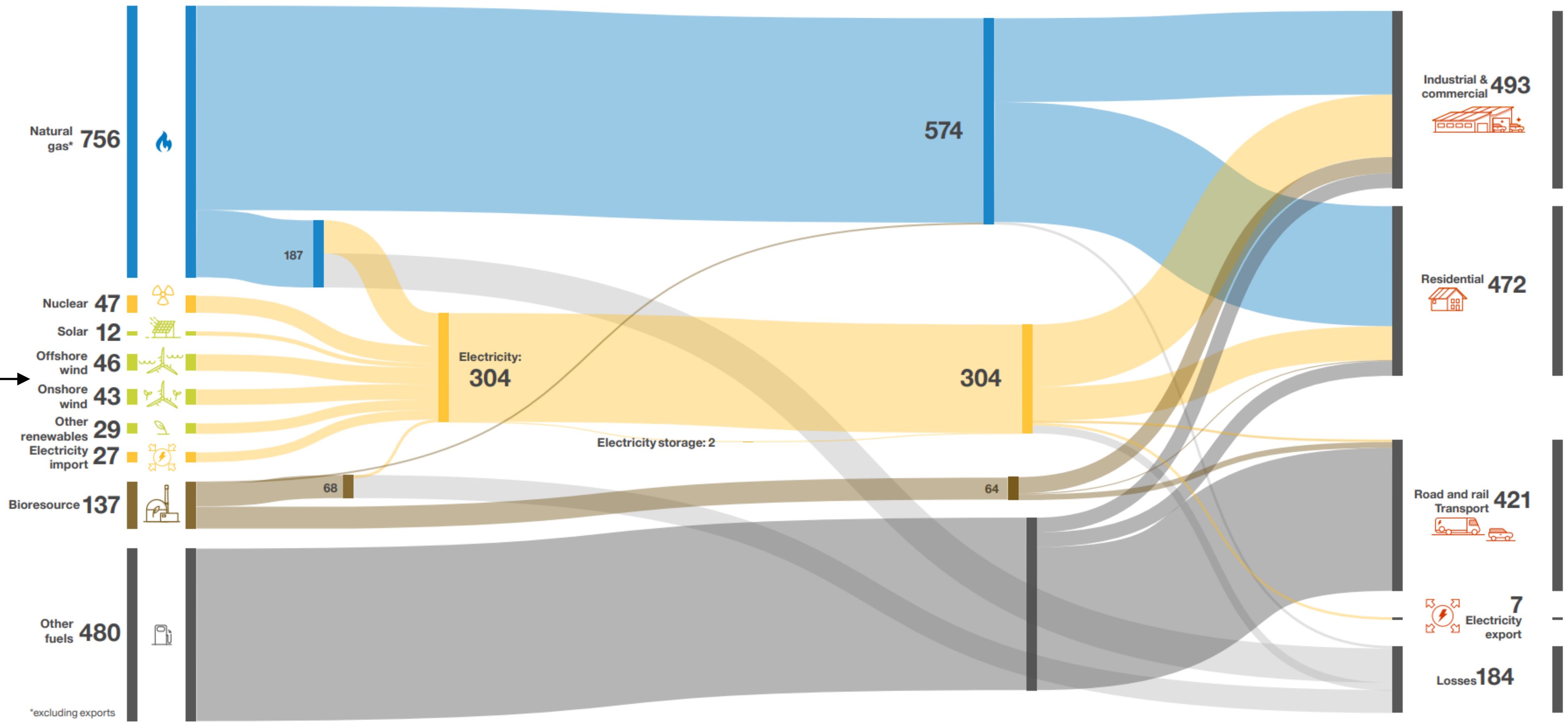
The UK is Currently:

- Committed to fully decarbonised the overall energy system by 2050
- Committed to Decarbonising the Power System by 2035 (subject to security of supply).
- Targeting 40 GW of offshore wind by 2030
- 1 GW of floating wind by 2030
- 5 GW of Hydrogen Production by 2030

Net Zero Strategy: Build Back Greener

National Grid ESO – Future Energy Scenarios 2020
Energy Flows (TWh)

Wind Now Producing ~100 TWh

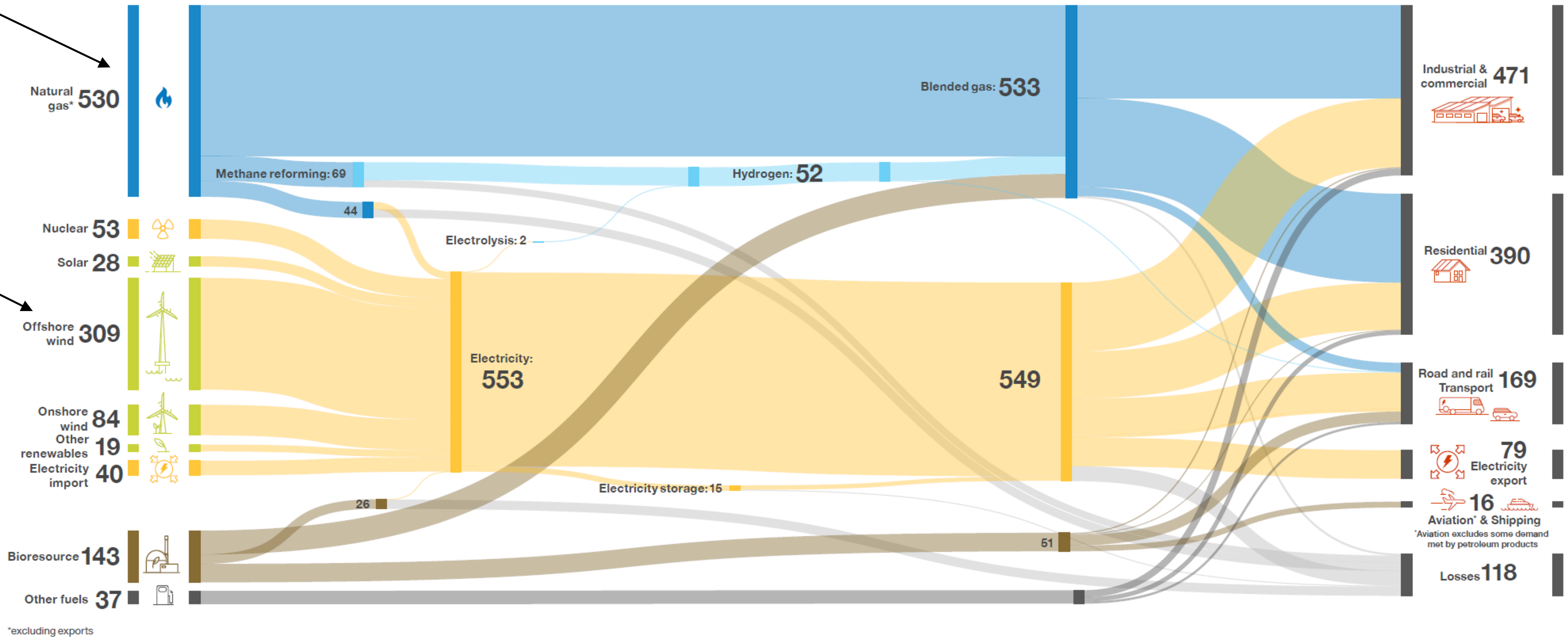


Taken From National Grid ESO – Future Energy Scenarios 2021

National Grid ESO – Future Energy Scenarios 2050
Steady Progression Energy Flows (TWh)

Electrical Energy Production Mostly Decarbonised, but Natural Gas Still the largest energy vector

6-Fold Increase in Offshore Wind Energy Production

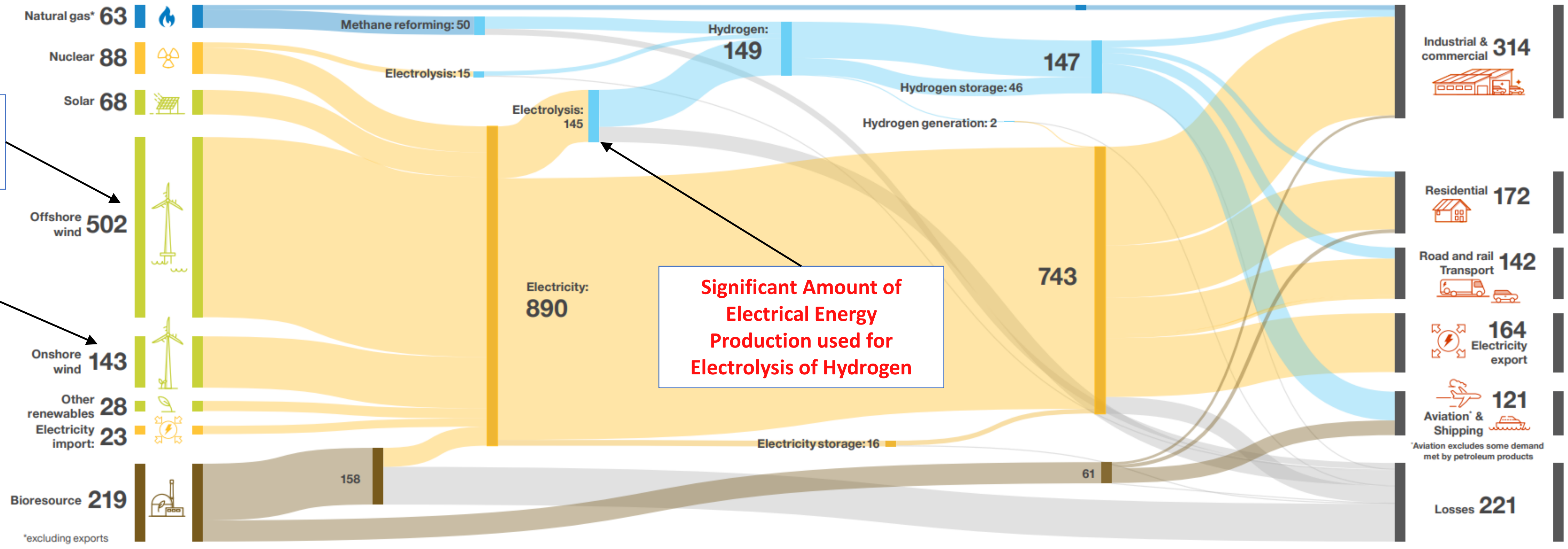


Taken From National Grid ESO – Future Energy Scenarios 2021

National Grid ESO – Future Energy Scenarios 2050
Consumer Transformation Energy Flows (TWh)

10-Fold Increase in Offshore Wind Energy Production

3-Fold Increase in Offshore Wind Energy Production



Significant Amount of Electrical Energy Production used for Electrolysis of Hydrogen

Taken From National Grid ESO – Future Energy Scenarios 2021

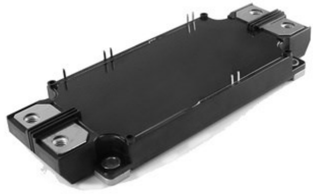
Latest Experimental/Commercial High-Power SiC MOSFETS

Wolfspeed

1200 V
450 A

Wolfspeed

1700 V
680 A



ROHM

1200 V
586 A

Wolfspeed

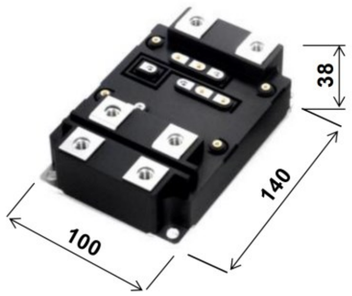
3300 V
541 A

Mitsubishi

3300 V
1500 A

Mitsubishi

3300 V
750 A

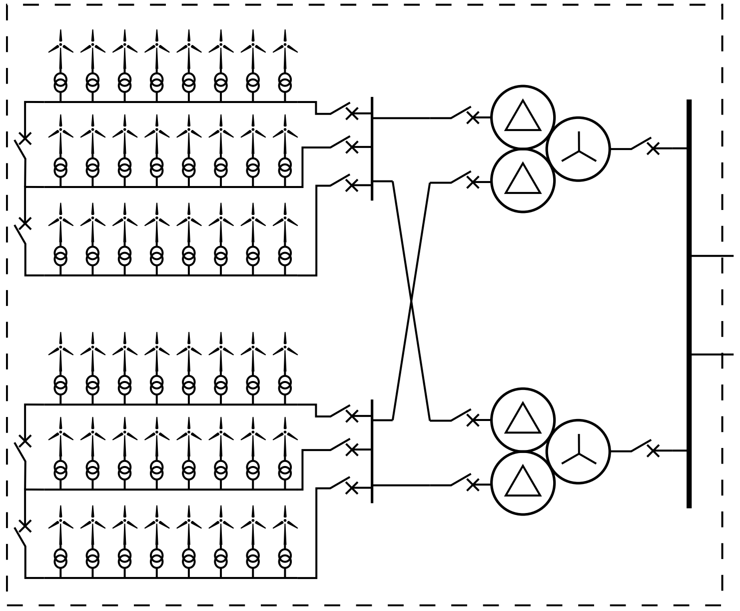


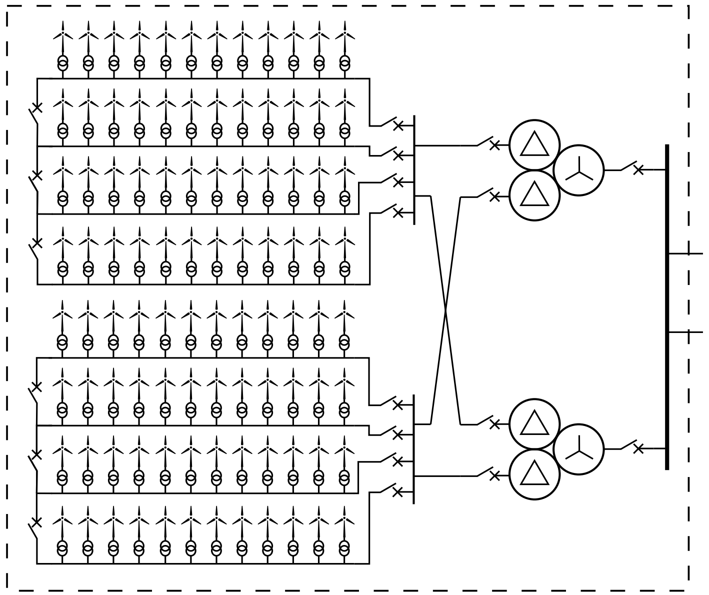
Hitachi

3300 V
800 A

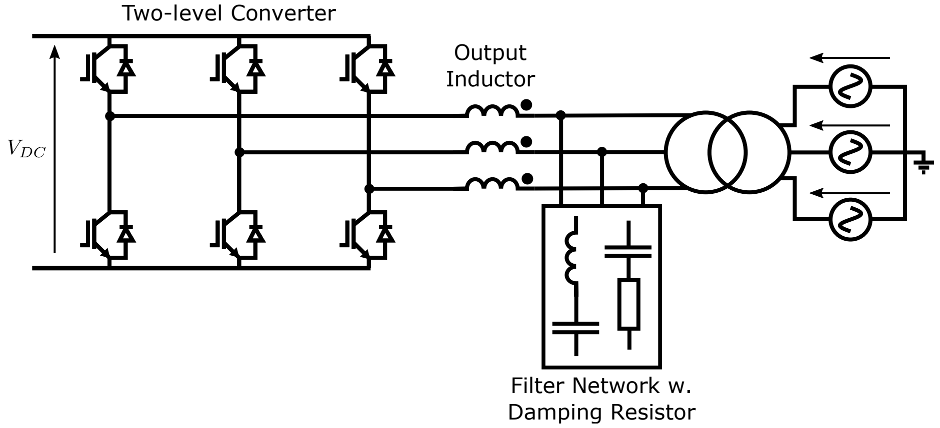
- SiC is now common for consumer EVs. Will continue to supplant Si IGBTs up the power level.
- Higher Power Traction, Wind and Solar generation next expansion areas

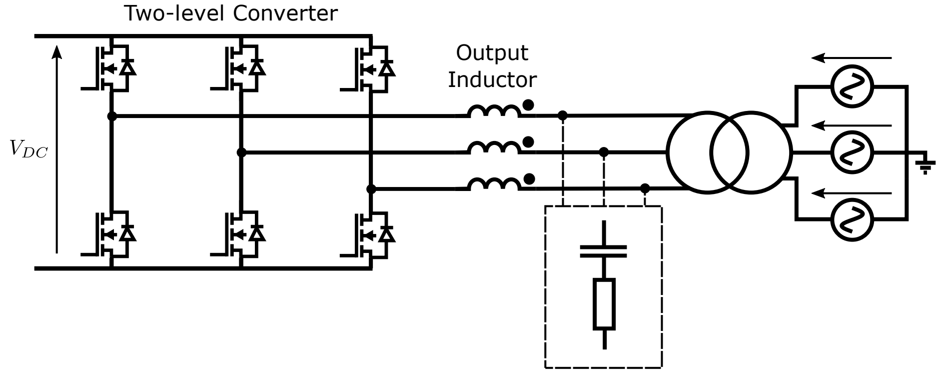
A Move to SiC Supports a Move to Larger Wind-Farms





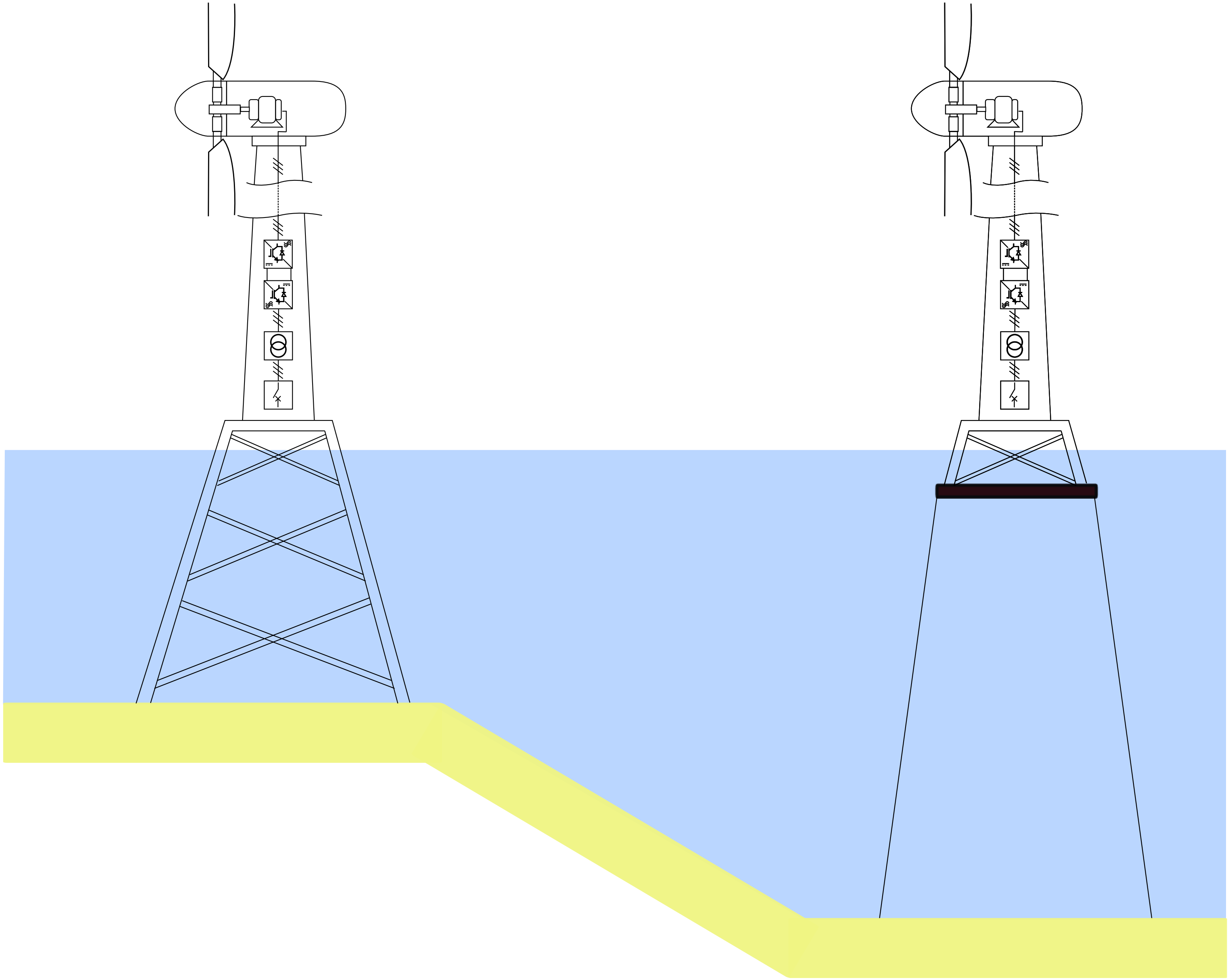
- LCL Filter Resonance Issues & Control bandwidth in Existing Wind-Turbine designs can act as a practical barrier to wind farm size





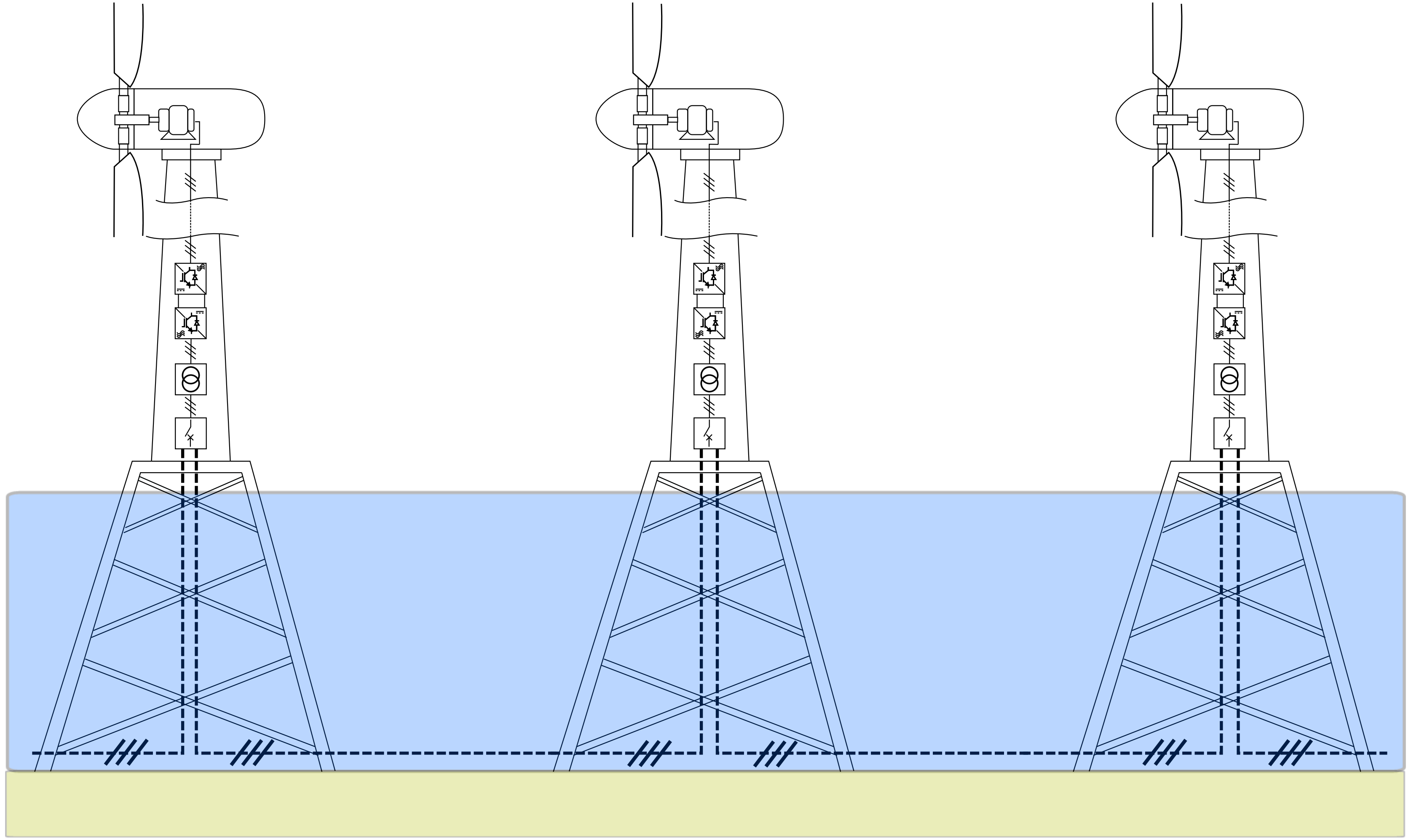
Floating Wind
A Driver to DC Collector Networks?

- The 2022 Scotwind Leasing round offered awards for 25 GW of wind resources, ~50% of which are in sea depths requiring floating foundations
- Offshore Renewable Energy Catapult have estimated up to 50 GW of floating wind required for UK to reach 2050 targets
- UK government target of 1 GW by 2030



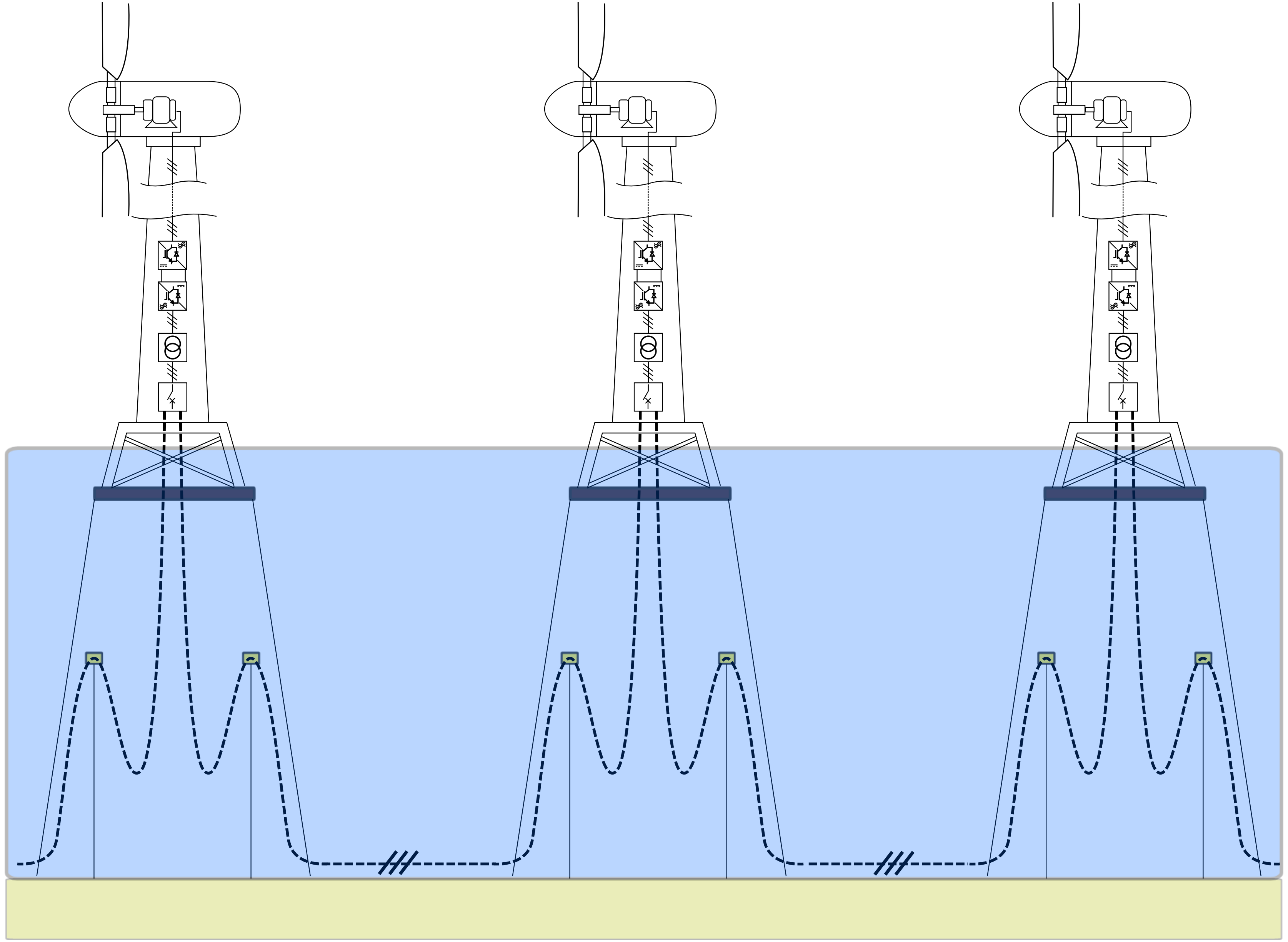
Floating Wind
A Driver to DC Collector Networks?

Conventional Fixed-Bottom AC String



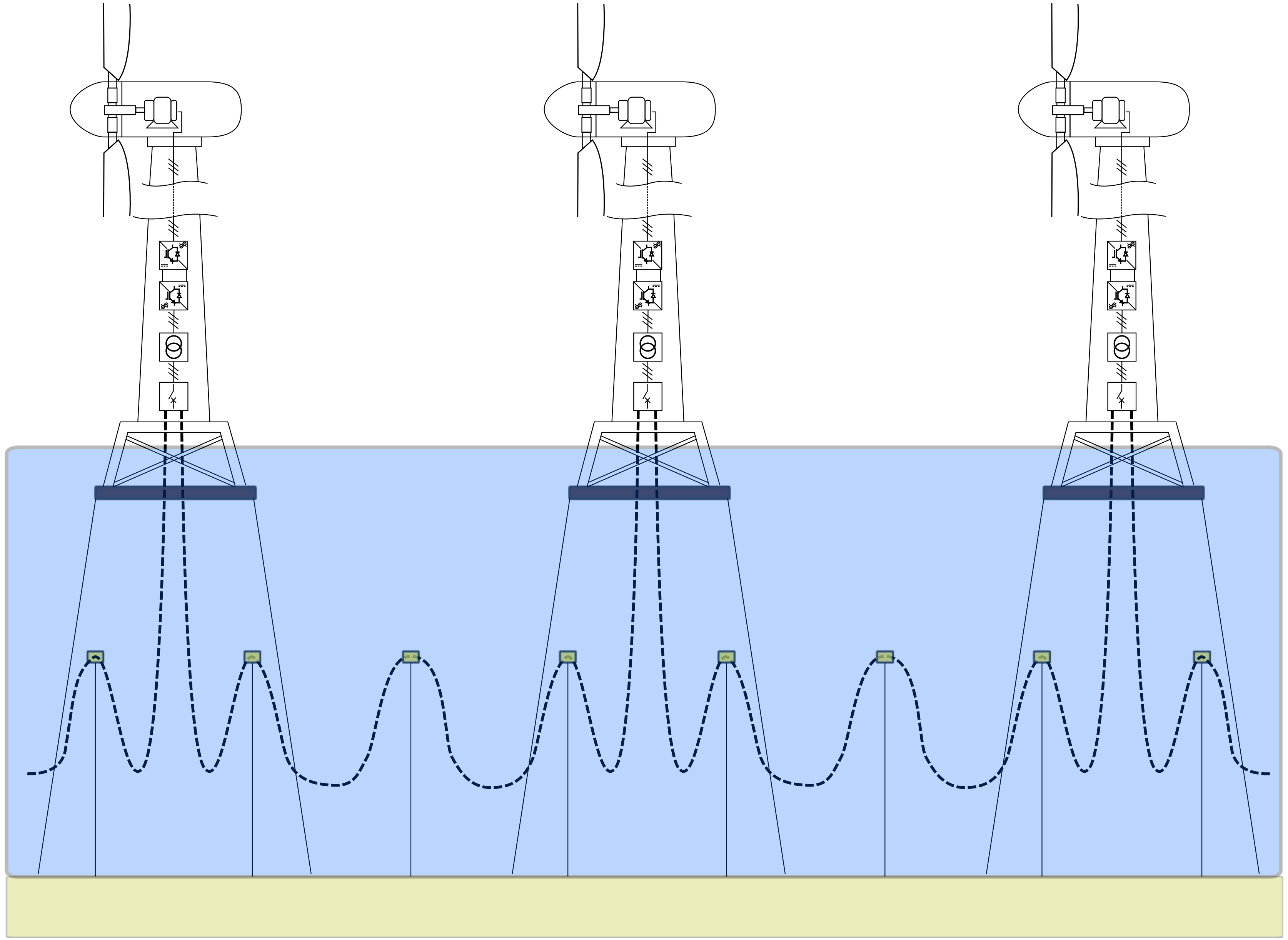
Floating Wind
A Driver to DC Collector Networks?

Floating Wind with Dynamic Cabling to Seabed



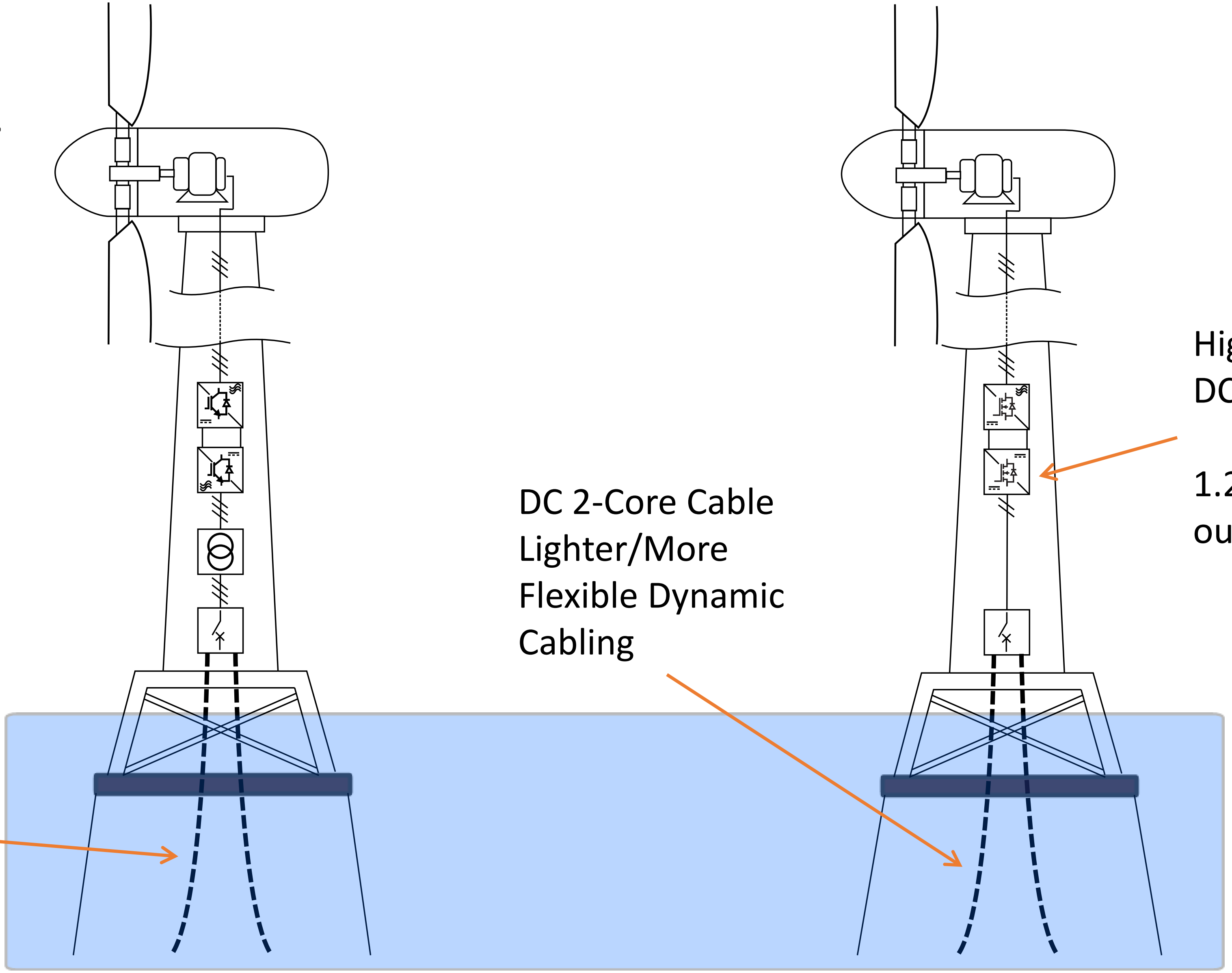
Floating Wind
A Driver to DC Collector Networks?

Floating Wind with Floating Dynamic Cabling

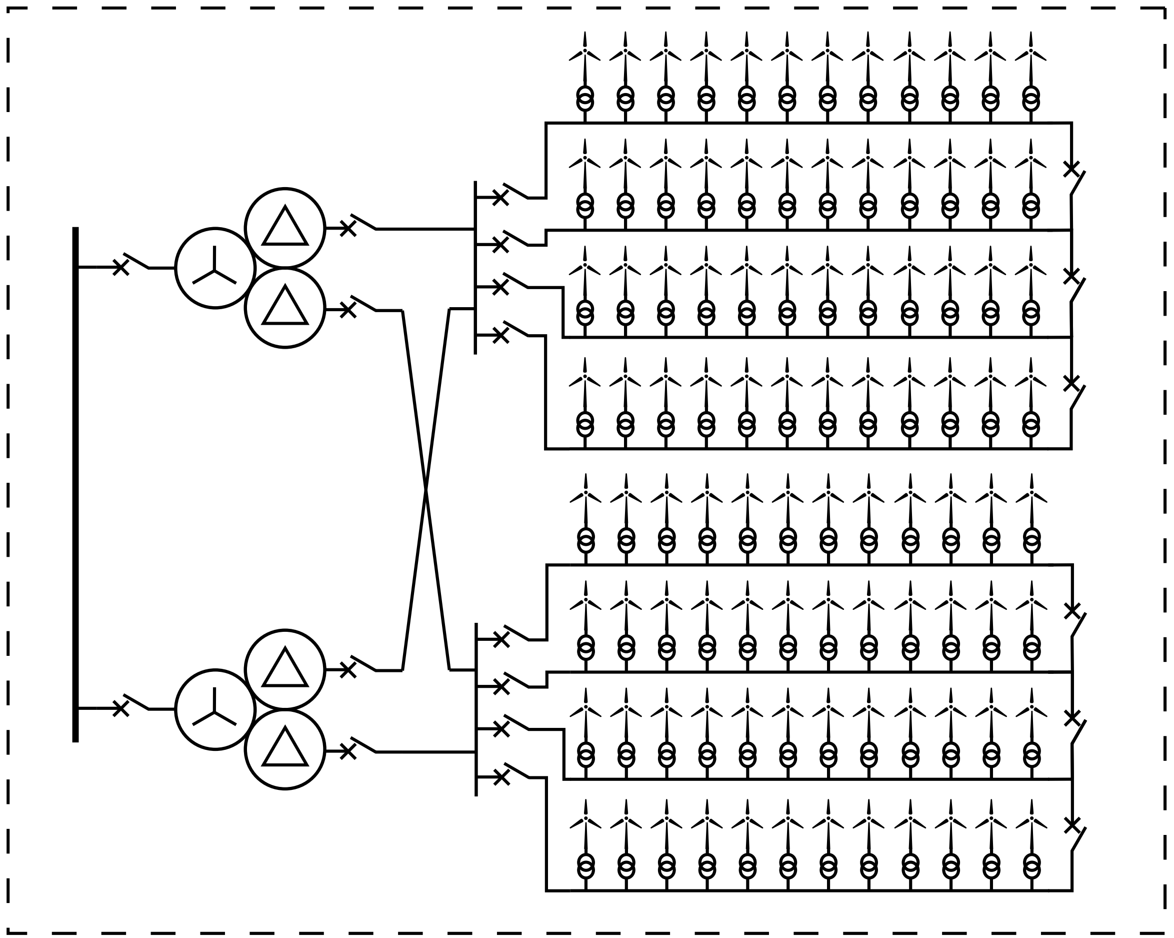


Floating Wind
A Driver to DC Collector Networks?

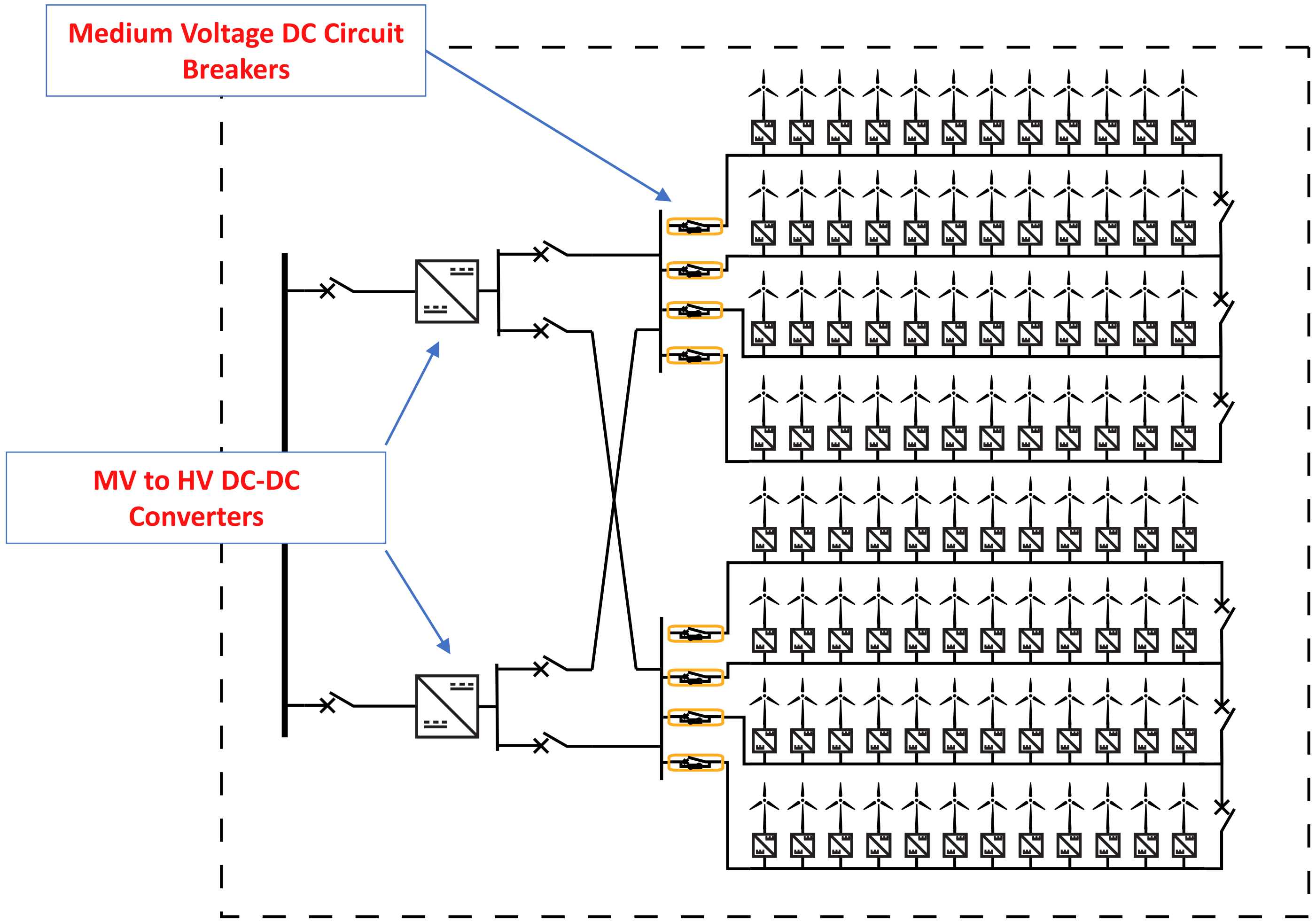
AC vs DC Wind Turbine



AC Collector Network



DC Collector Network



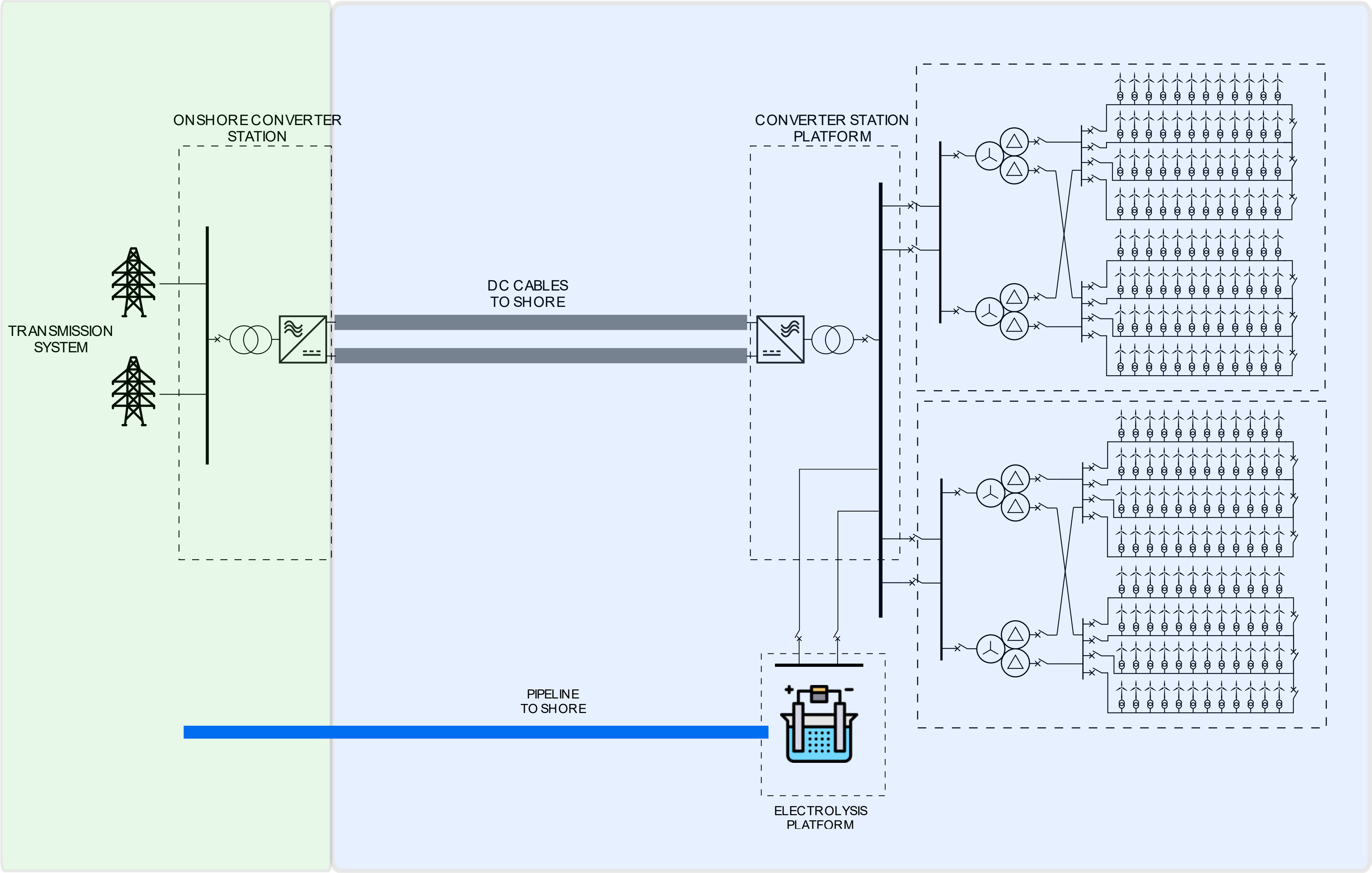
SiC MOSFETs - Application to HVDC Converters

	3.3 kV 1500 A Devices	
	Si IGBT	**SiC MOSFET**
	ABB 5SNA 1500E330305	**Mitsubishi Module [2]**
Turn On Energy (rated current)	2.15 J	1.44 J
Turn Off Energy (rated current)	2.8 J	0.53 J
Forward Voltage Drop (rated current)	3.2 V	2.1 V

- SiC MOSFETs have resistive on-state characteristics. They can be paralleled to decrease conduction losses – This is not possible with IGBTs due to their bipolar device conduction characteristic.
- MMC are conduction loss dominated so significant potential to trade off increased switching loss (resulting from parallel modules) with decreased conduction loss.
- Is it worth it? - Not likely for now. SiC MOSFETs are significantly more expensive that comparably rated IGBTs and 3.3 kV and 4.5 kV devices are not commercially available yet.
- 1 Decade down the line – Maybe.

Offshore Hydrogen Production

- Hydrogen acts as energy storage & enables Power system flexibility
  - Decreases curtailment of wind resources.
  - Offshore production increases conversion efficiency
  - UK targeting 5 GW of hydrogen production by 2030



Net Zero Strategy: Build Back Greener

Offshore Hydrogen Production

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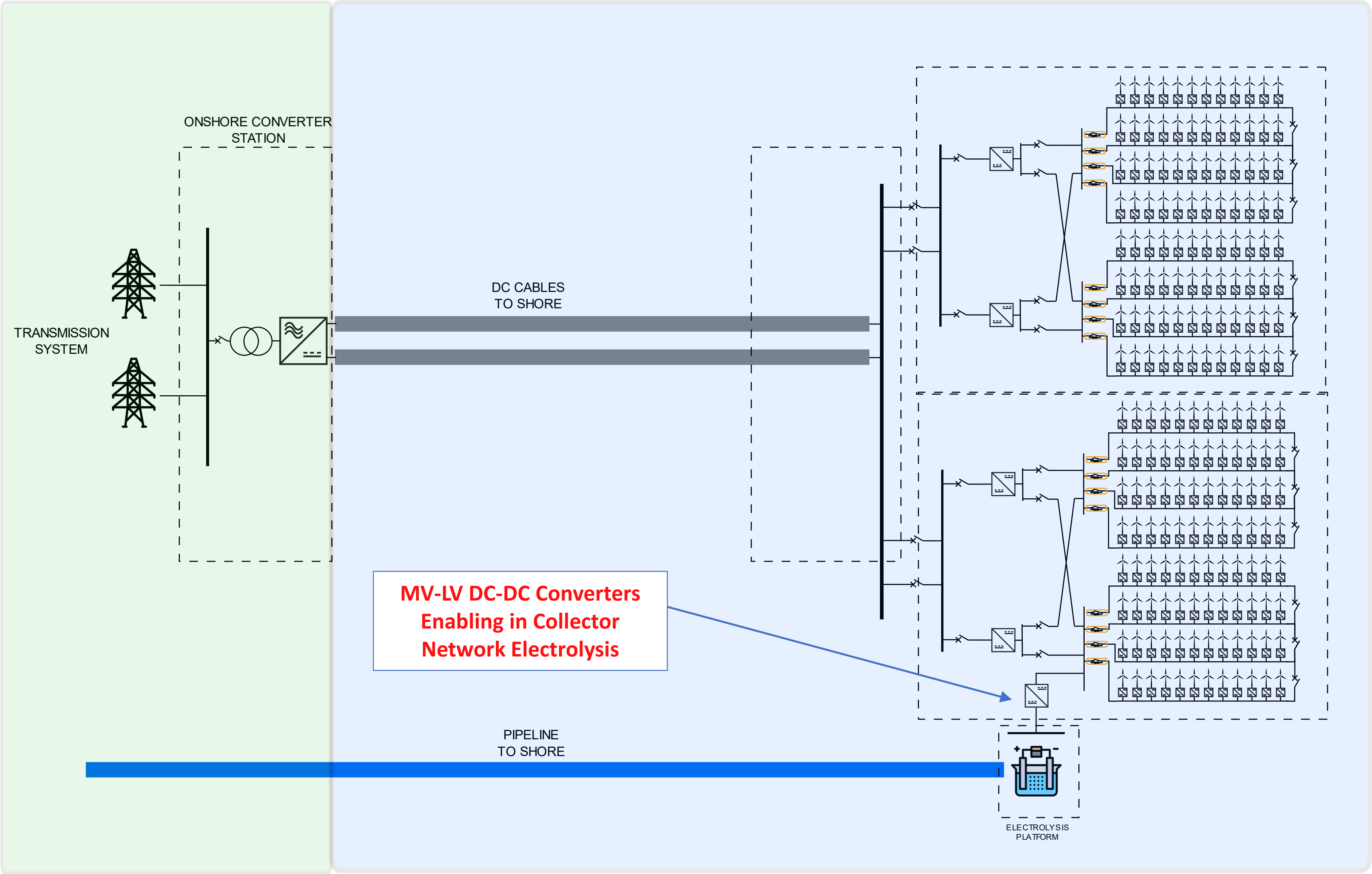
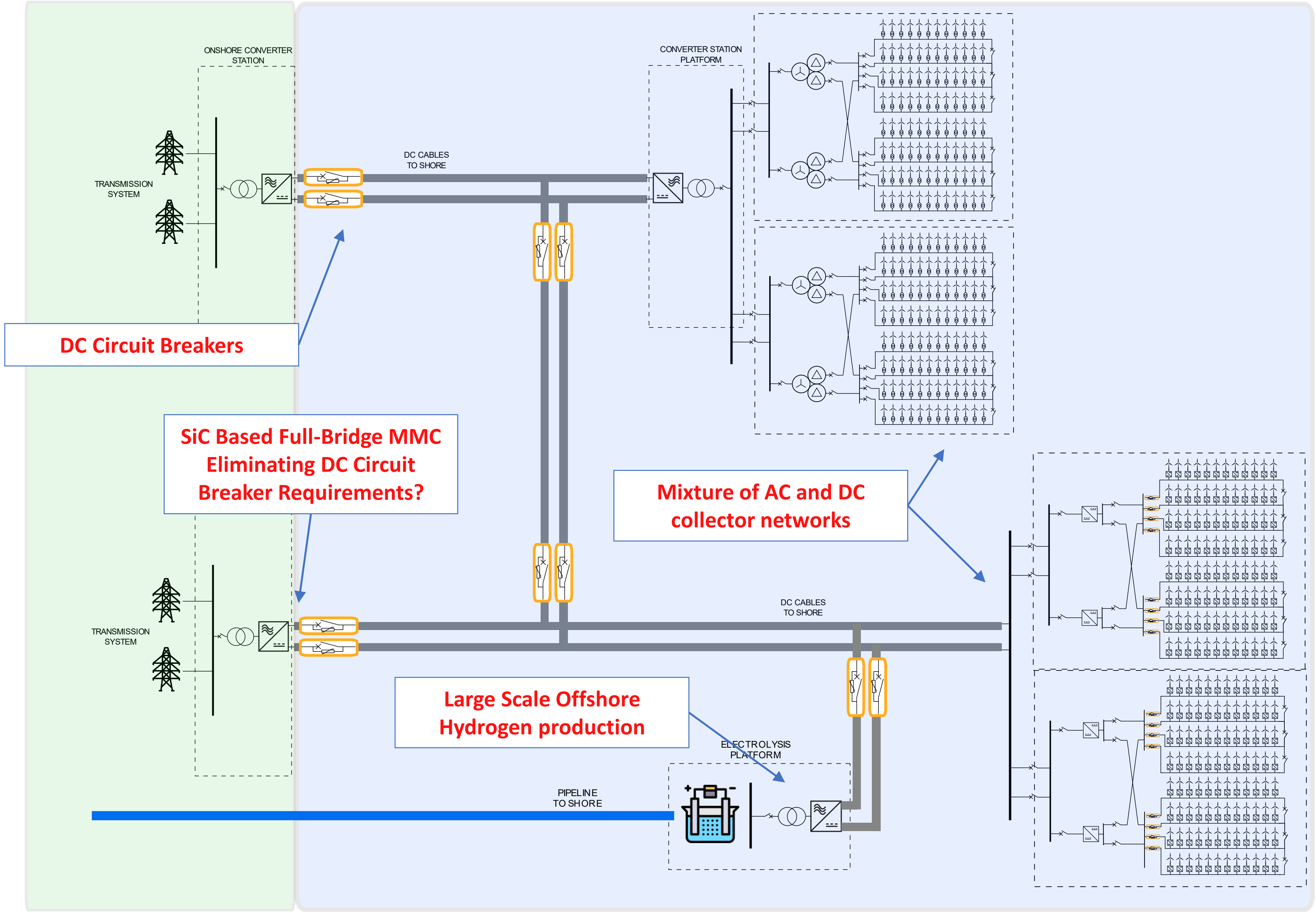


Net Zero Strategy: Build Back Greener

Multi-Terminal HVDC/Hydrogen Systems

- Hydrogen acts as ‘energy’ storage.
- Potential to retrofit/reuse obsolete oil/gas platforms
- Multi-terminal HVDC allows Electrolysis Platform to be shared between several wind farms
- Potential for depleted gas fields use as hydrogen stores.



Energy Storage in HVDC

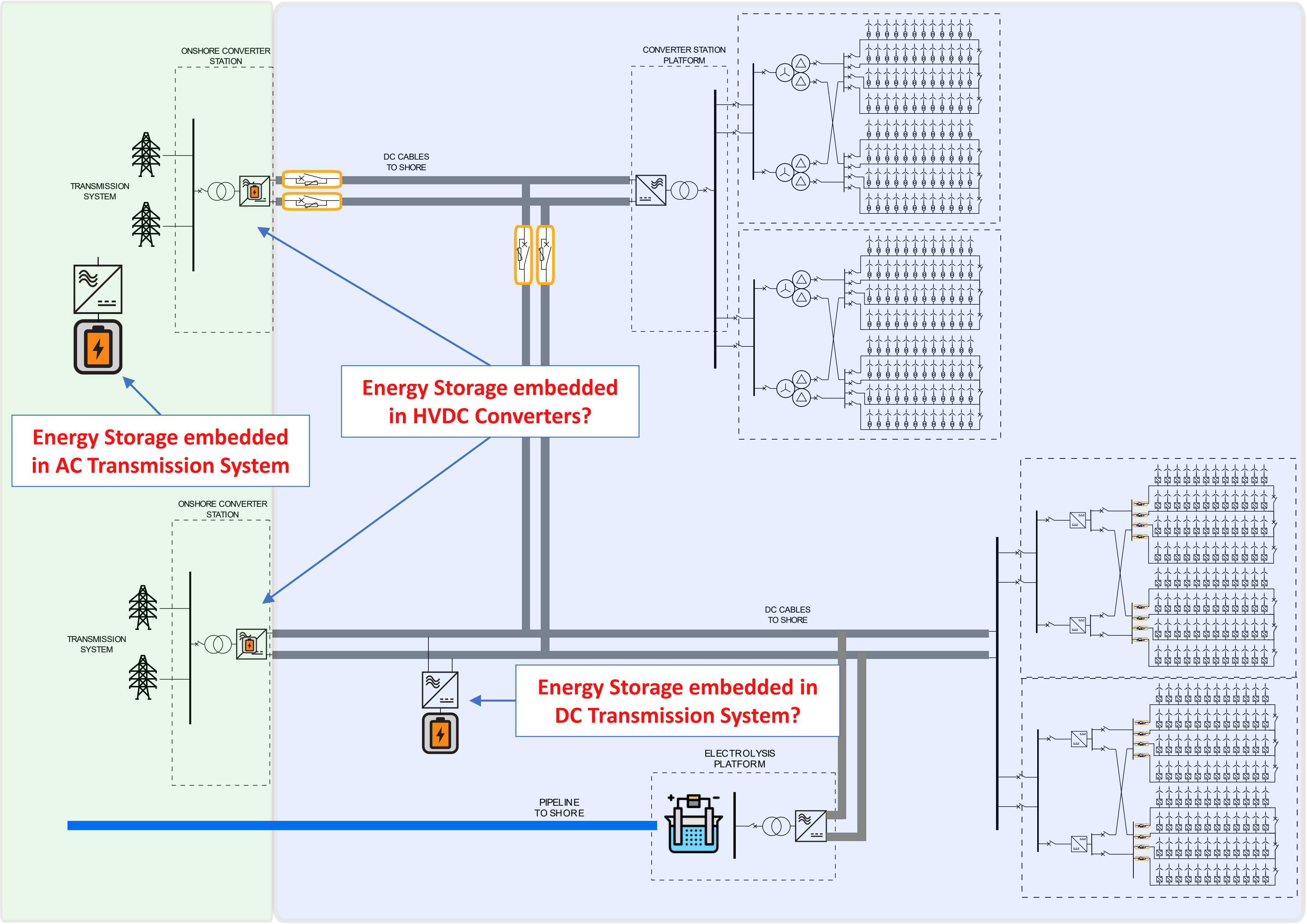
Reduced system inertia due to displacement of synchronous generators.

Hydrogen fired gas turbine and battery systems providing fast acting spinning reserve.

May still be a requirement for additional fast ms-to-second response may still be required

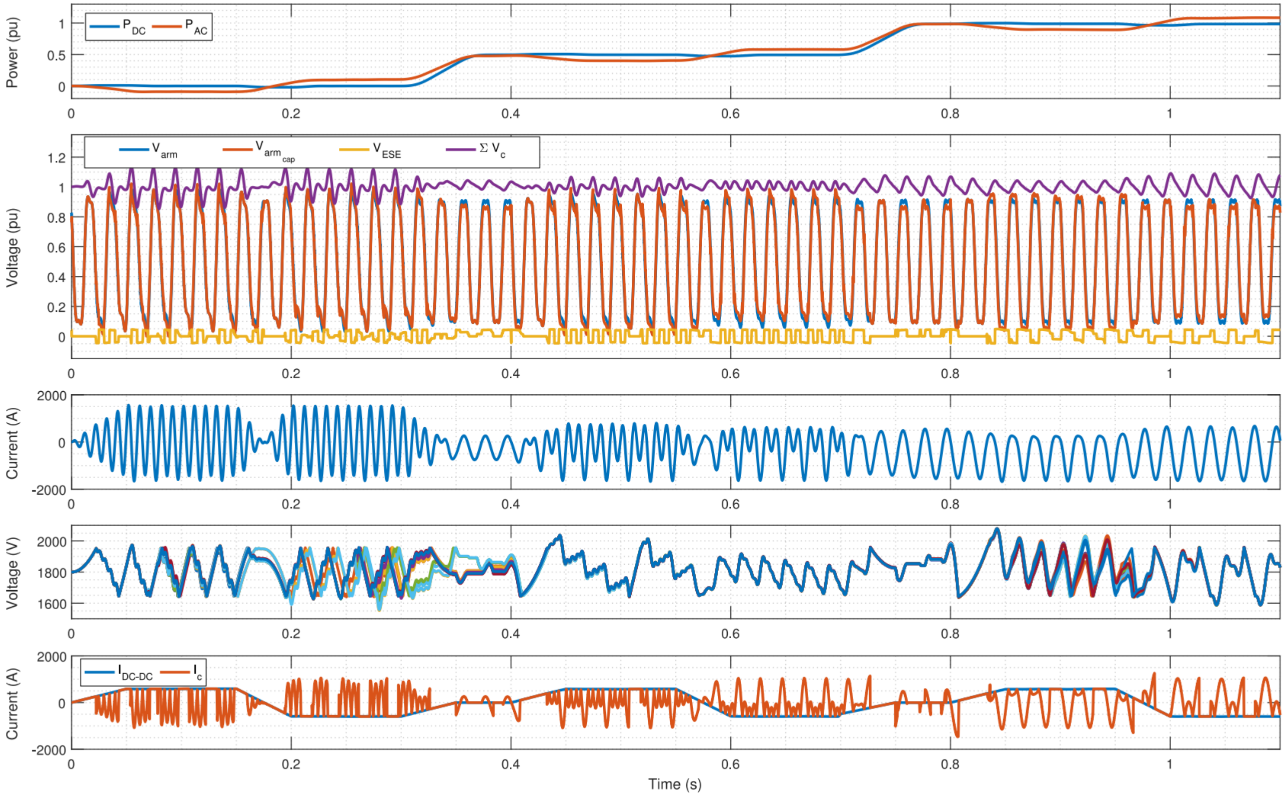
- Supercapacitor/Battery energy storage integrated in:
  - AC System - E-STATCOM solutions
  - DC System
  - Embedded within HVDC Converters

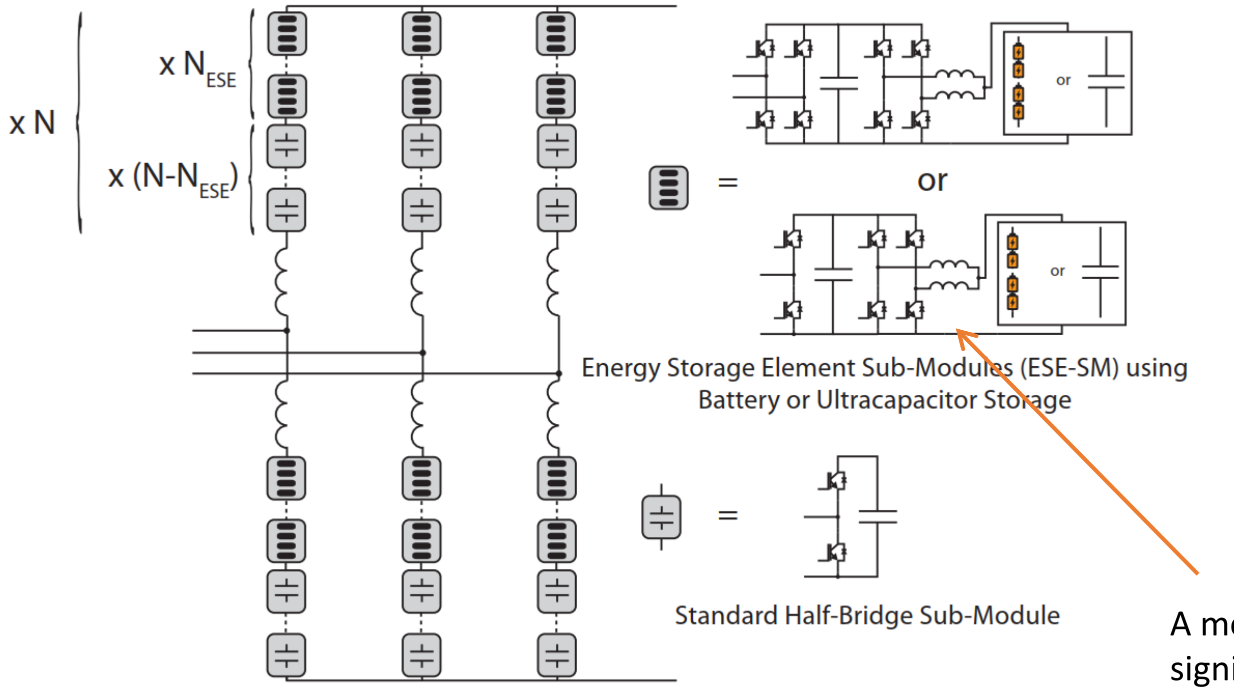
- B4-84 CIGRE Working Group examining option



Research at Edinburgh

MMC with Integrated Energy Storage





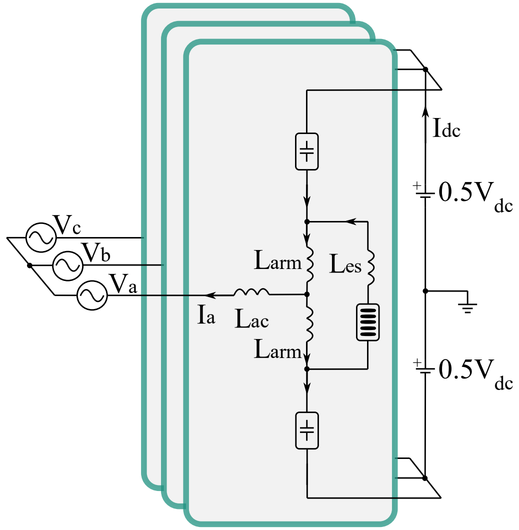
A move to SiC significantly reduces the additional converter mass that must be supported within the valve tower

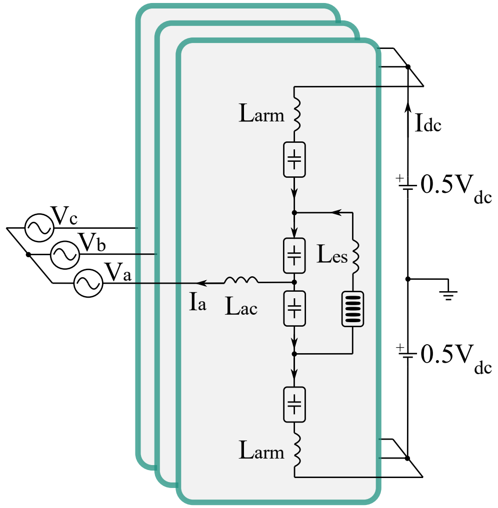
- **Converter is formed of** a **mixture** of **standard sub-modules** (SMs) and **SMs that are interfaced through DC-DC converters to** Energy Storage Elements (ESE-SMs), such as **ultracapacitors or batteries**.
- **Converting 4% of SMs to ESE-SMs allows the converter to have a 10% energy storage rating.**

P. D. Judge and T. Green, "Modular Multilevel Converter with Partially Rated Integrated Energy Storage Suitable for Frequency Support and Ancillary Service Provision," in IEEE Transactions on Power Delivery. doi: 10.1109/TPWRD.2018.2874209

10 kVA Modular Multilevel Converter Demonstrator

Designed to allow flexible integration of energy storage into the sub-modules of the converter





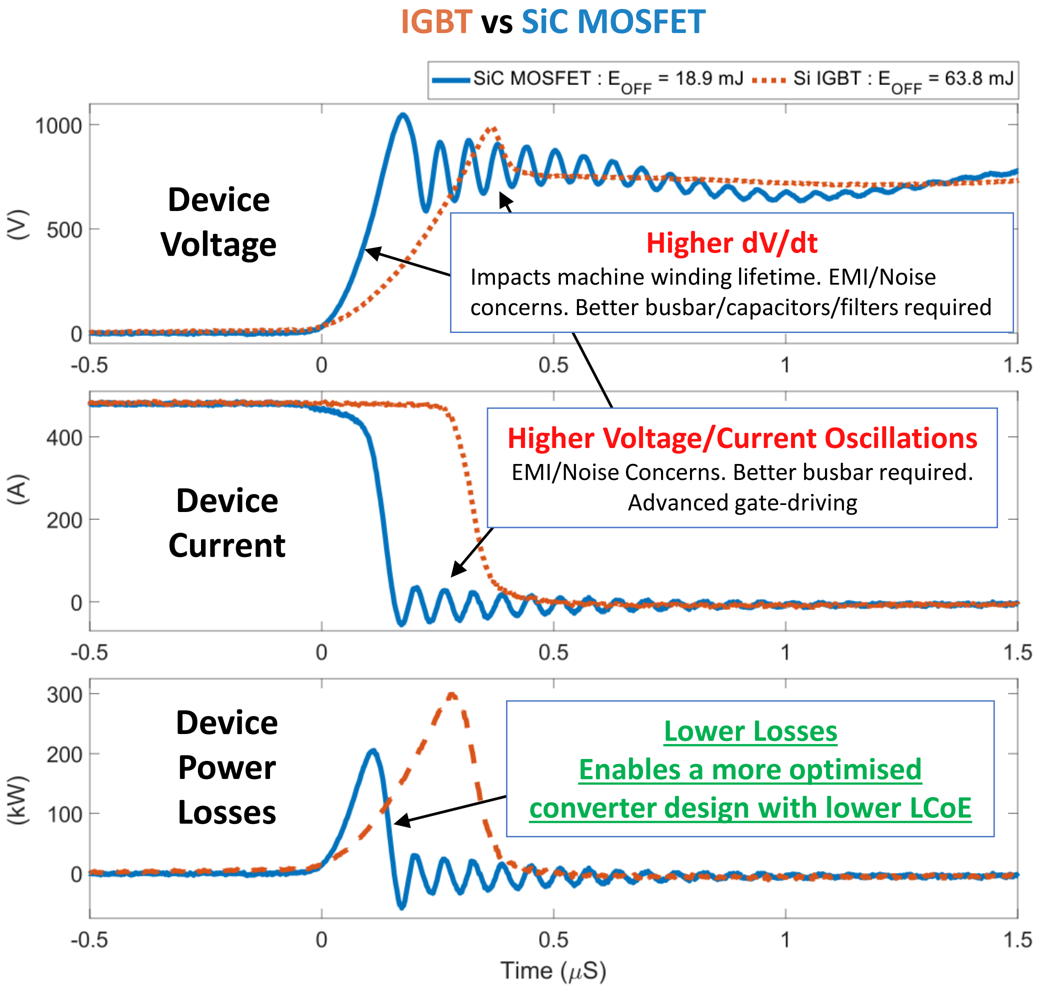
Challenges of SiC

Si-IGBT

- Very good conduction
- Poor switching
  - Slow IGBT turn off due to excess minority carriers
- Negligible oscillations
- Lower dV/dt similar dI/dt

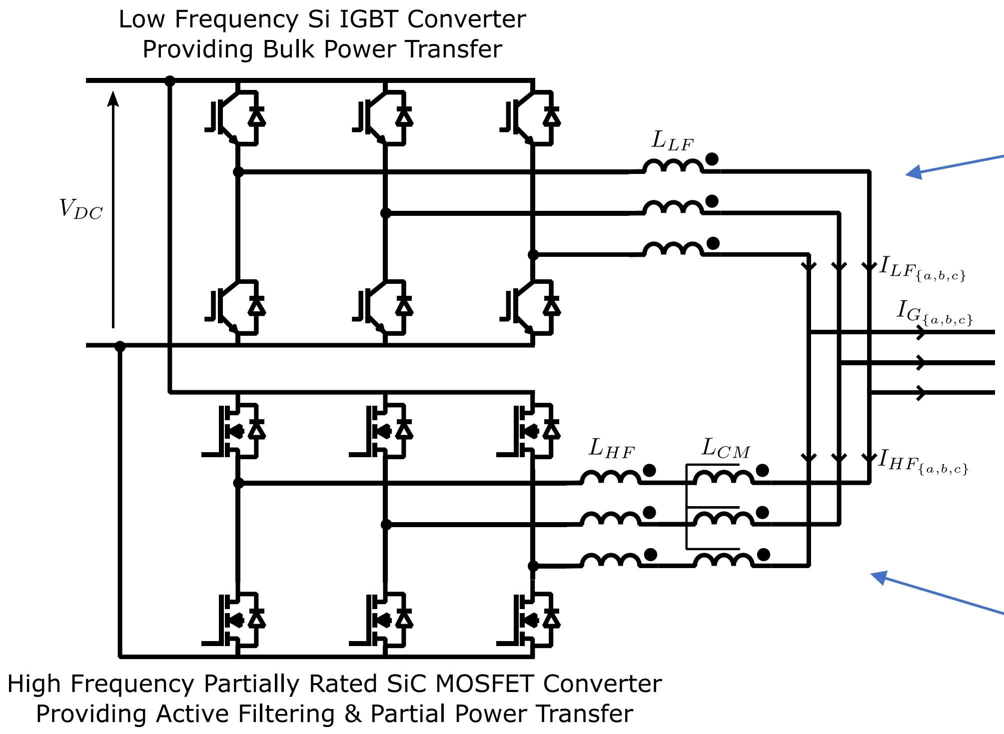
SiC-MOSFET

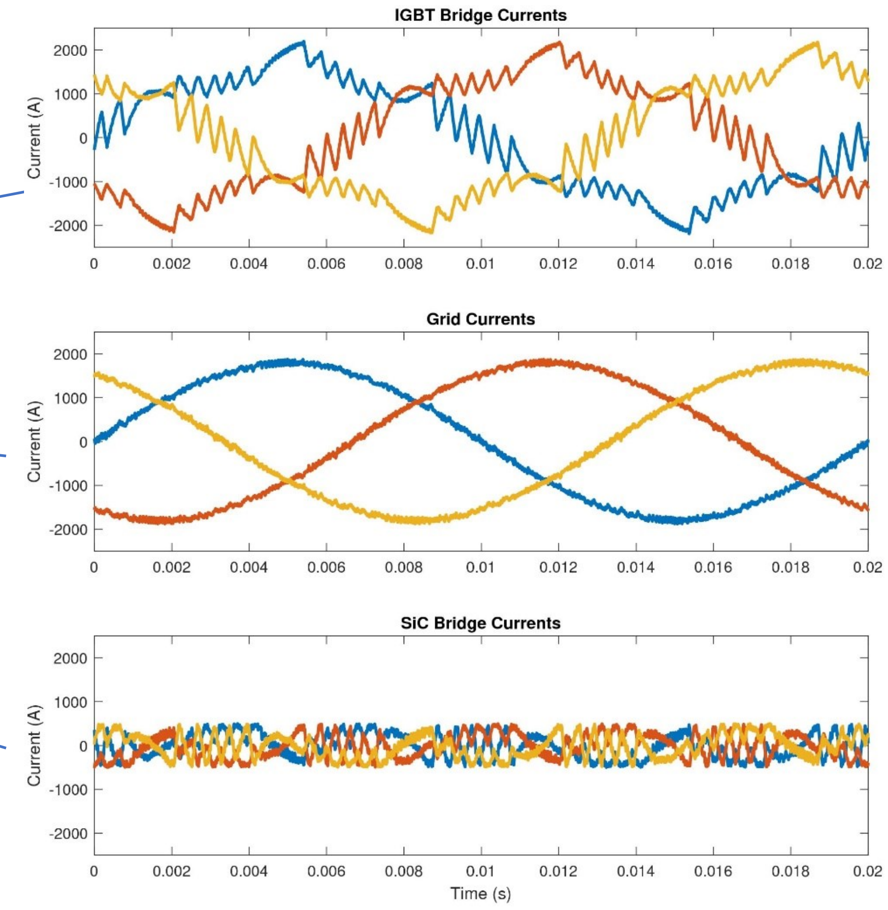
- Very good conduction & switching
- Expensive
- ~600 A is the largest production module
- Oscillations in drain-source voltage & current a major concern due to EMI generation
- **Challenges in device availability and rating**



Parallel Hybrid Converter

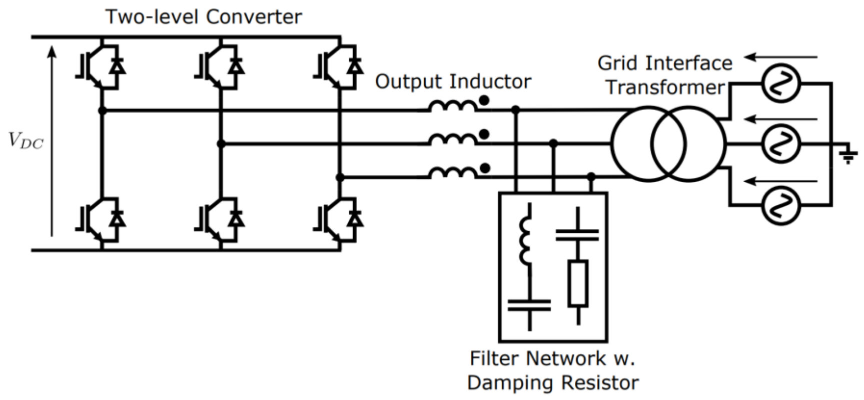
- Intermediate step to a full SiC based converter - High current (e.g 1800 A) SiC MOSFETs not commercially available yet.
- Possible using commercially available SiC MOSFETs
- Output filter purely inductive:
  - High Bandwidth Current Control

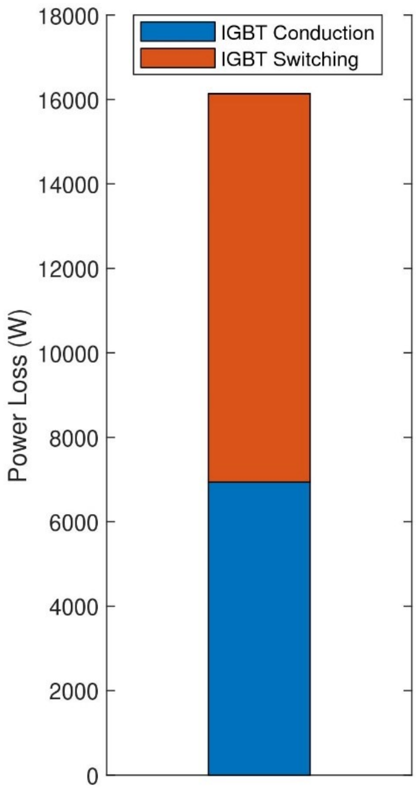




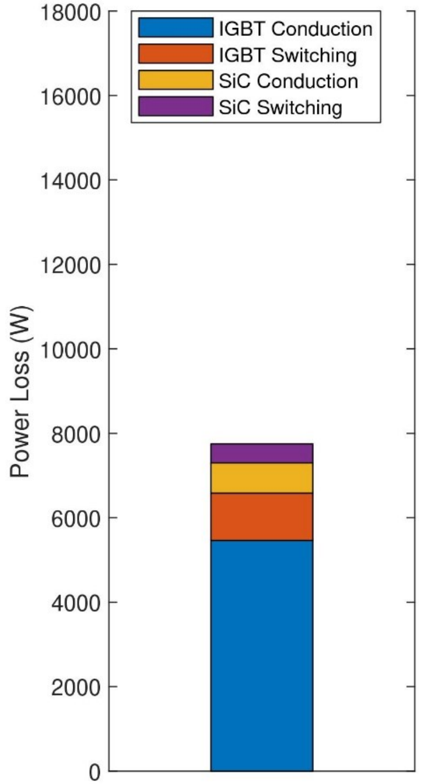
P. D. Judge and S. Finney, "2-Level Si IGBT Converter with Parallel Part-Rated SiC Converter Providing Partial Power Transfer and Active Filtering," *2019 20th Workshop on Control and Modeling for Power Electronics (COMPEL)*, Toronto, ON, Canada, 2019, pp. 1-7..

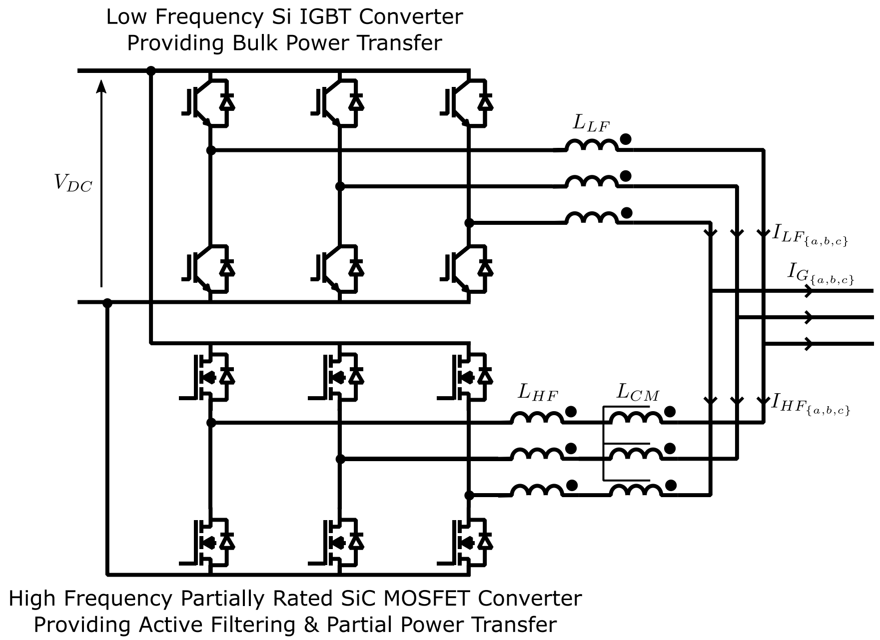
Efficiency Improvements for a 1.5 MW Module





Vs.





1.7 kV 1800 A IGBT

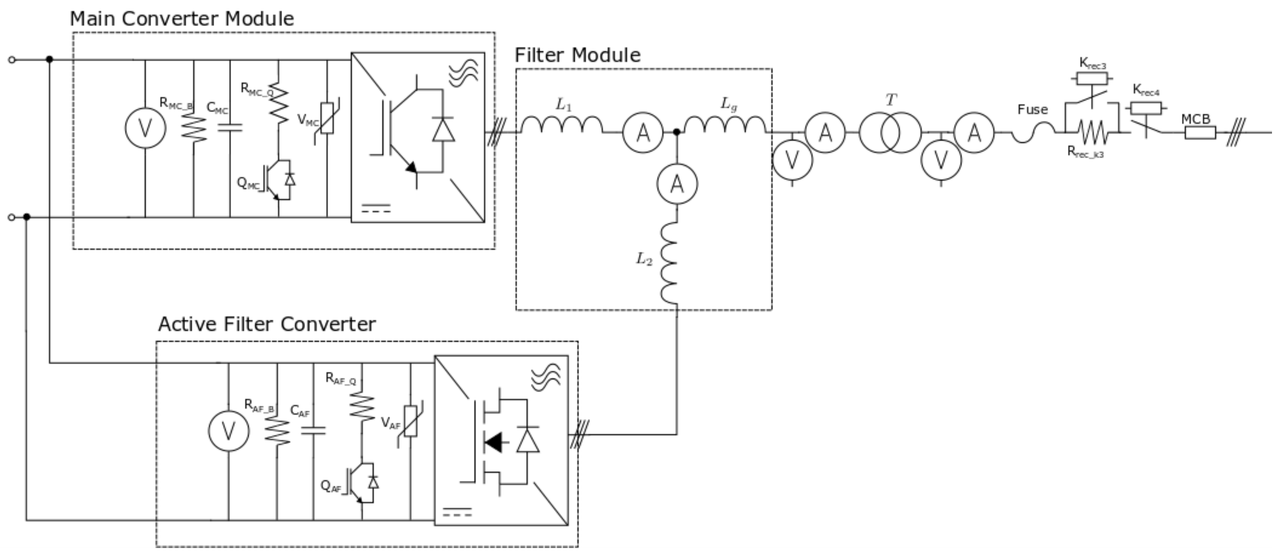
1.7 kV 1800 A IGBT

+

1.7 kV 380 SiC MOSFET

- Fully SiC based approach also a valid future option - SiC MOSFET resistive on-state characteristics would allow conduction optimised device to be used for the main bridge -> Push power semiconductor losses even further down

90 kVA Hybrid Converter Demonstrator

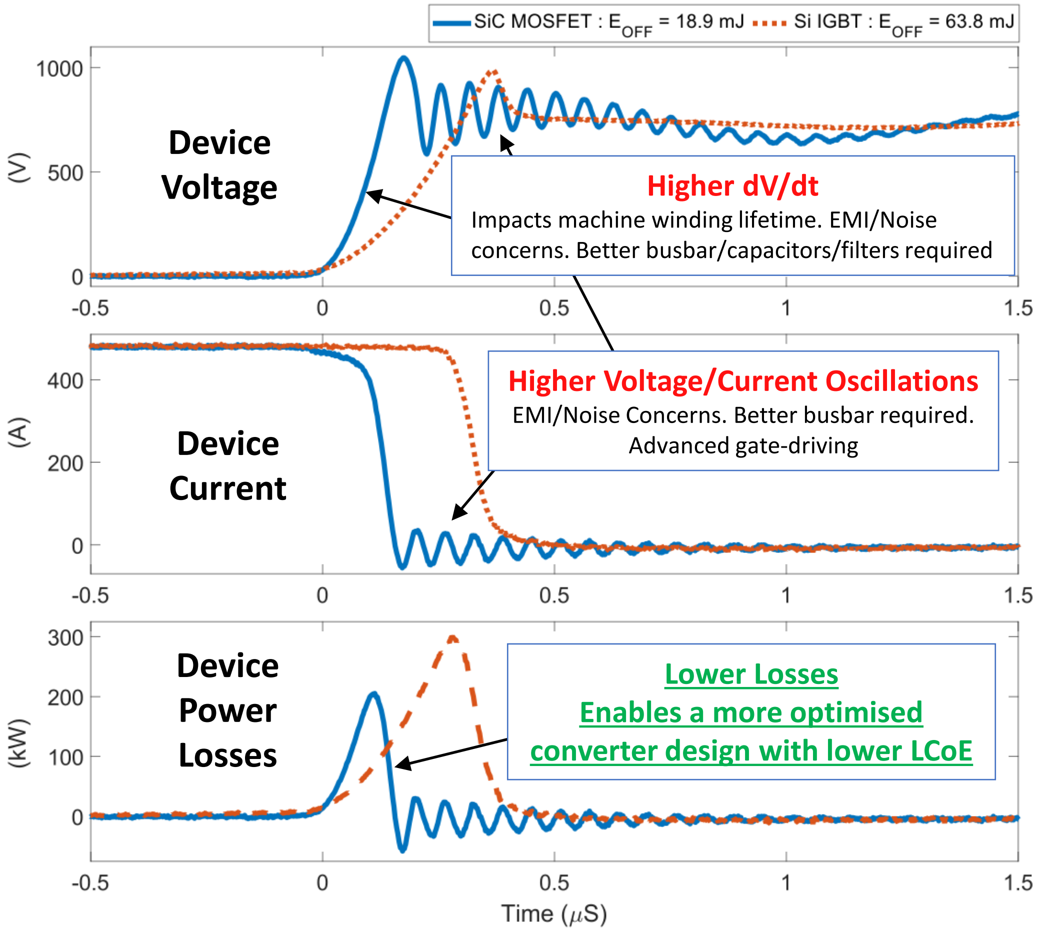


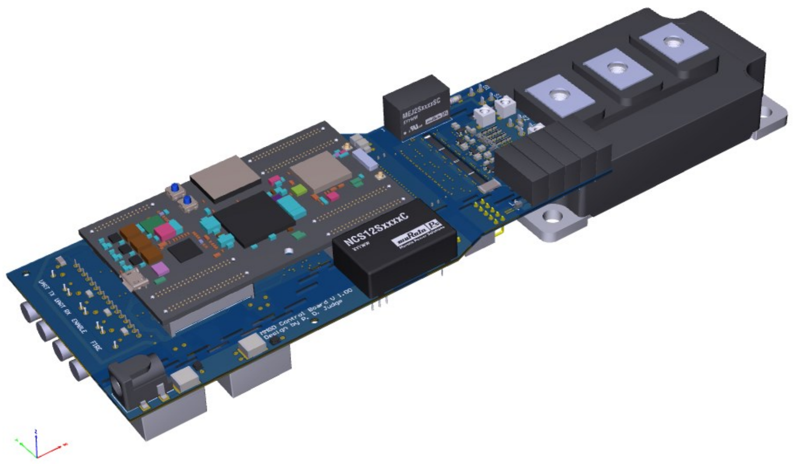
Flexible test bench that can be highly re-configurable into multiple different topologies

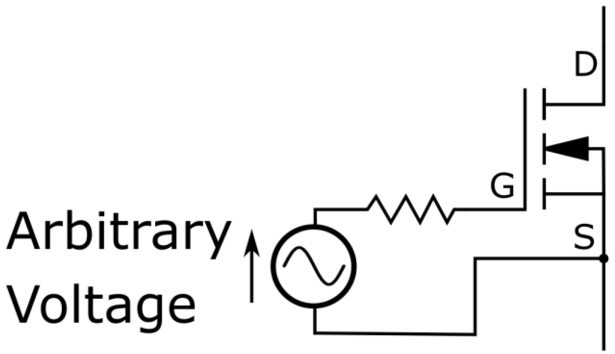
- DSpace controller with FPGA allows advanced control prototyping

The Modular Multilevel Gate Driver

IGBT vs SiC MOSFET



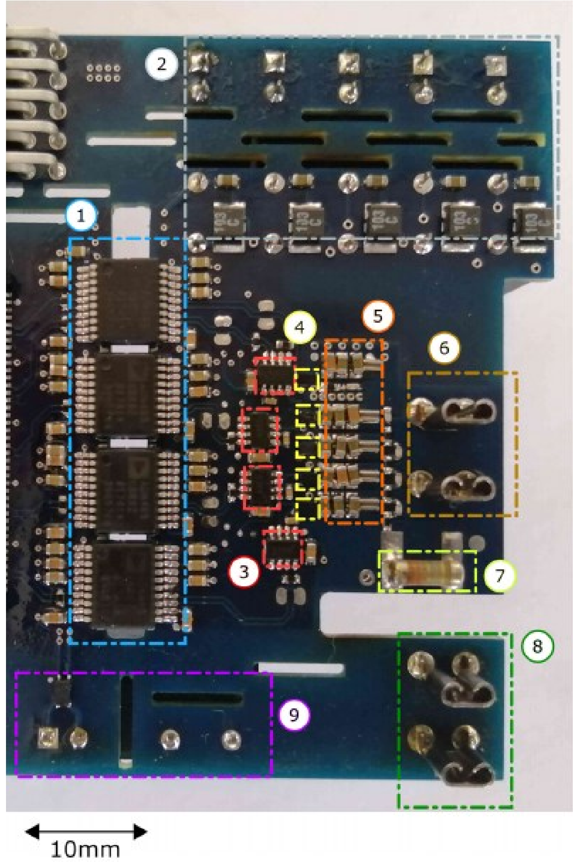




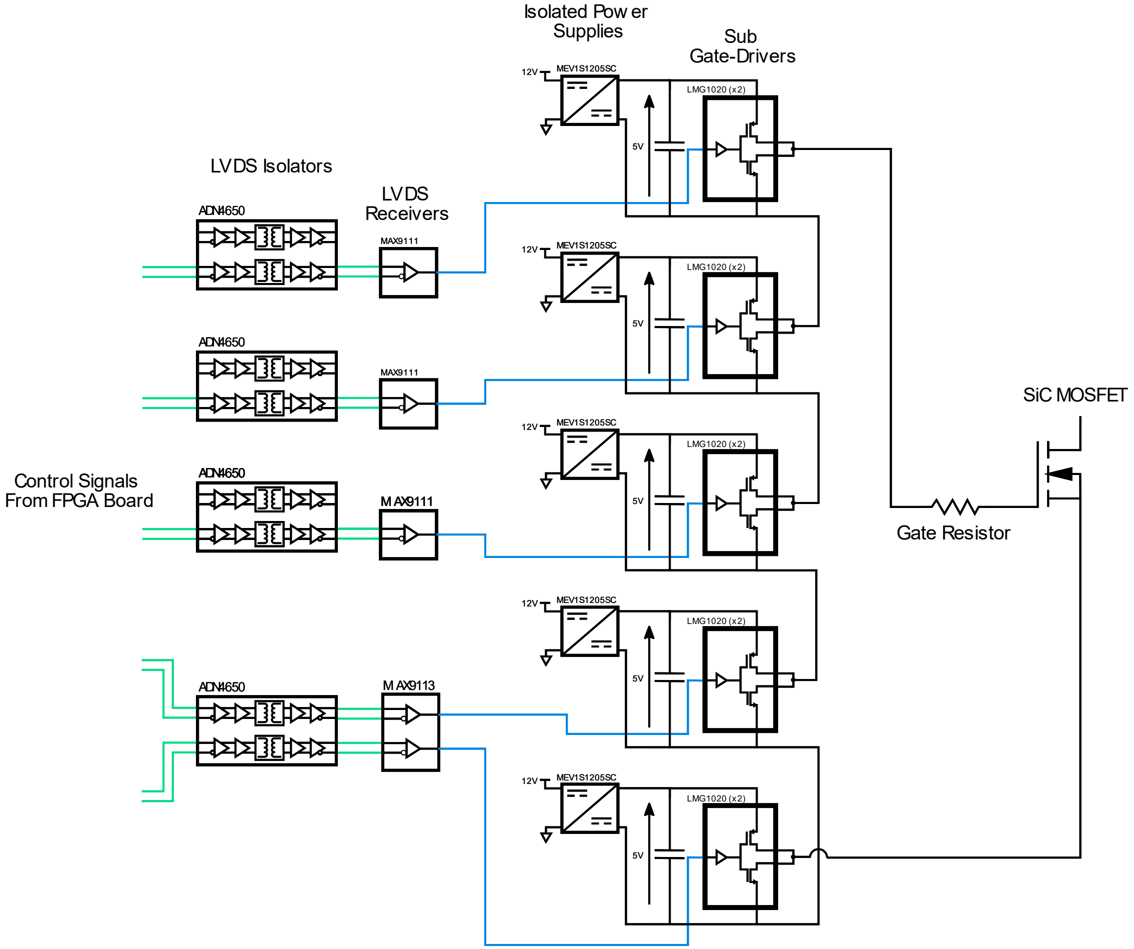
Gate Driver can modulate its output with a resolution of ~2.5 ns

- Provides 6 voltage levels in 5V steps
- New isolator chips should let us push down closer to 1 ns modulation
- Attempts to provide an 'arbitrary voltage source' as the gate-driver

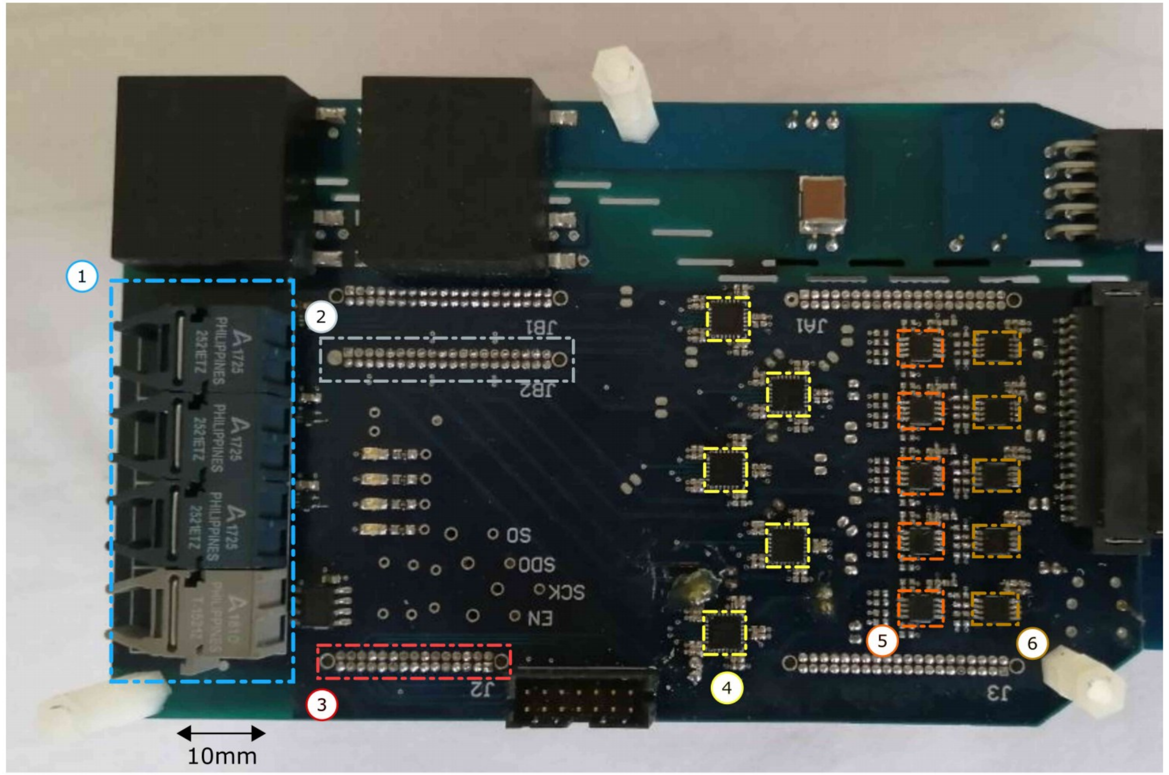
Output Stage Board



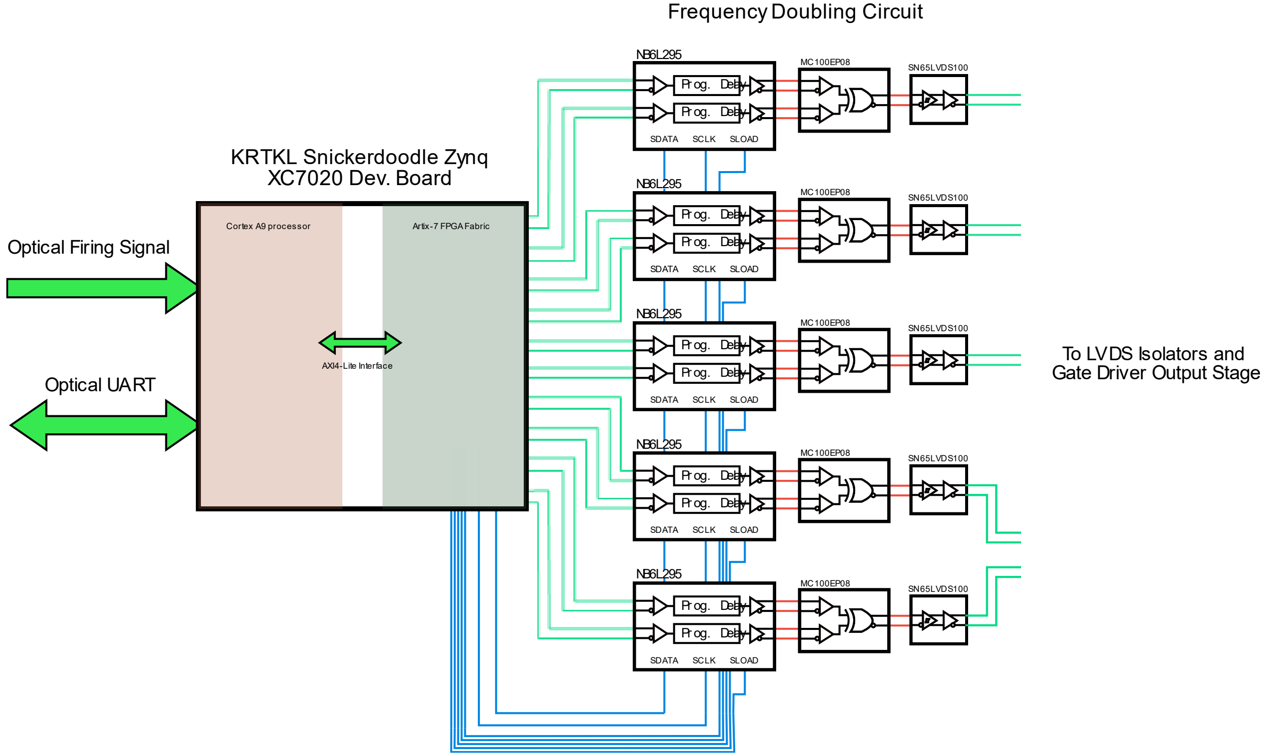
1. LVDS Isolators
2. Isolated Power Supplies
3. LVDS Receiver
4. LMG1020 Gate Drivers
5. Gate Driver Decoupling Capacitors
6. Low-Side Gate-Source Connection
7. Gate Resistor
8. High-Side Gate-Source Connection
9. High-Side -5V Isolated Power Supply



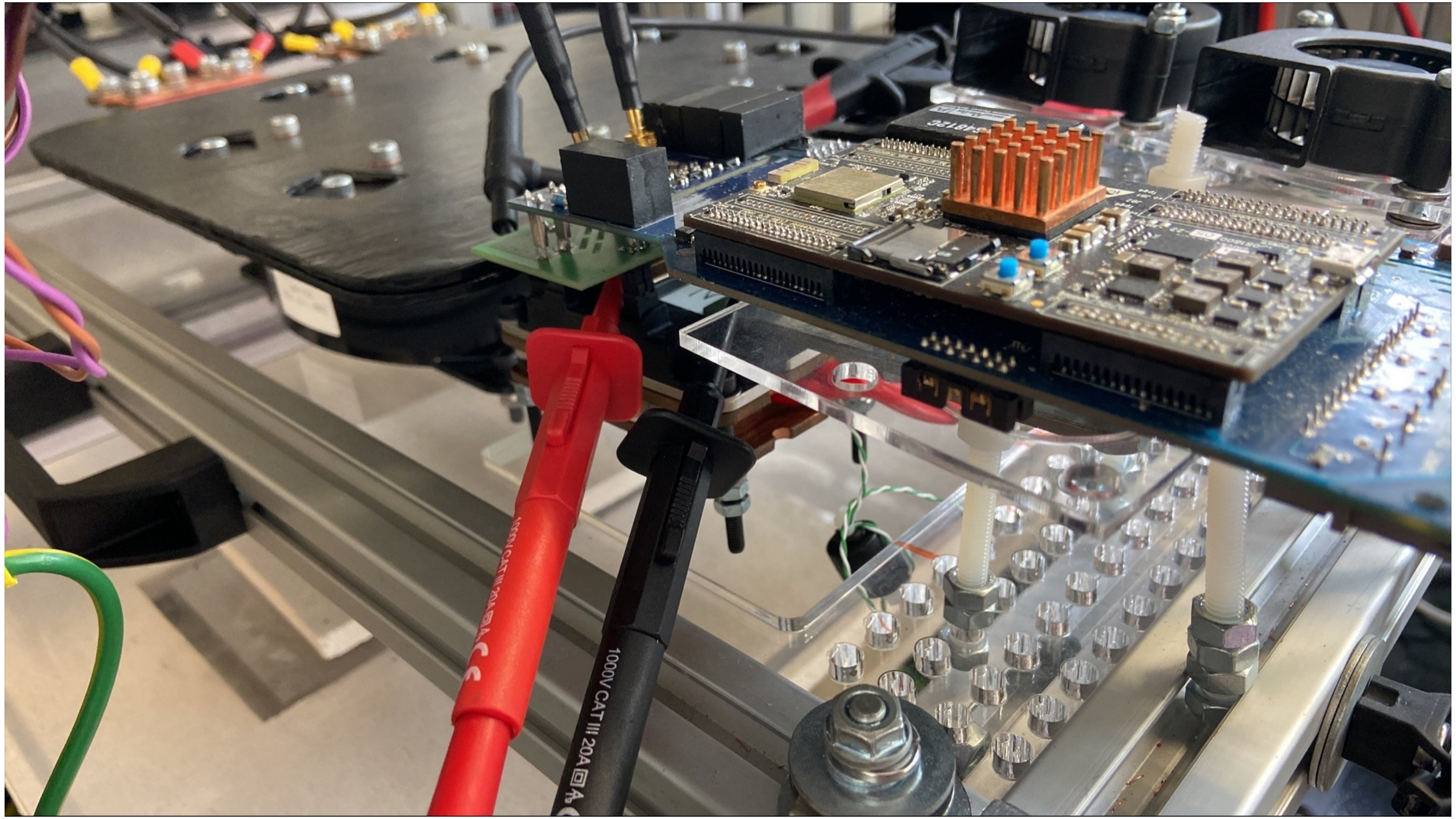
Control Board



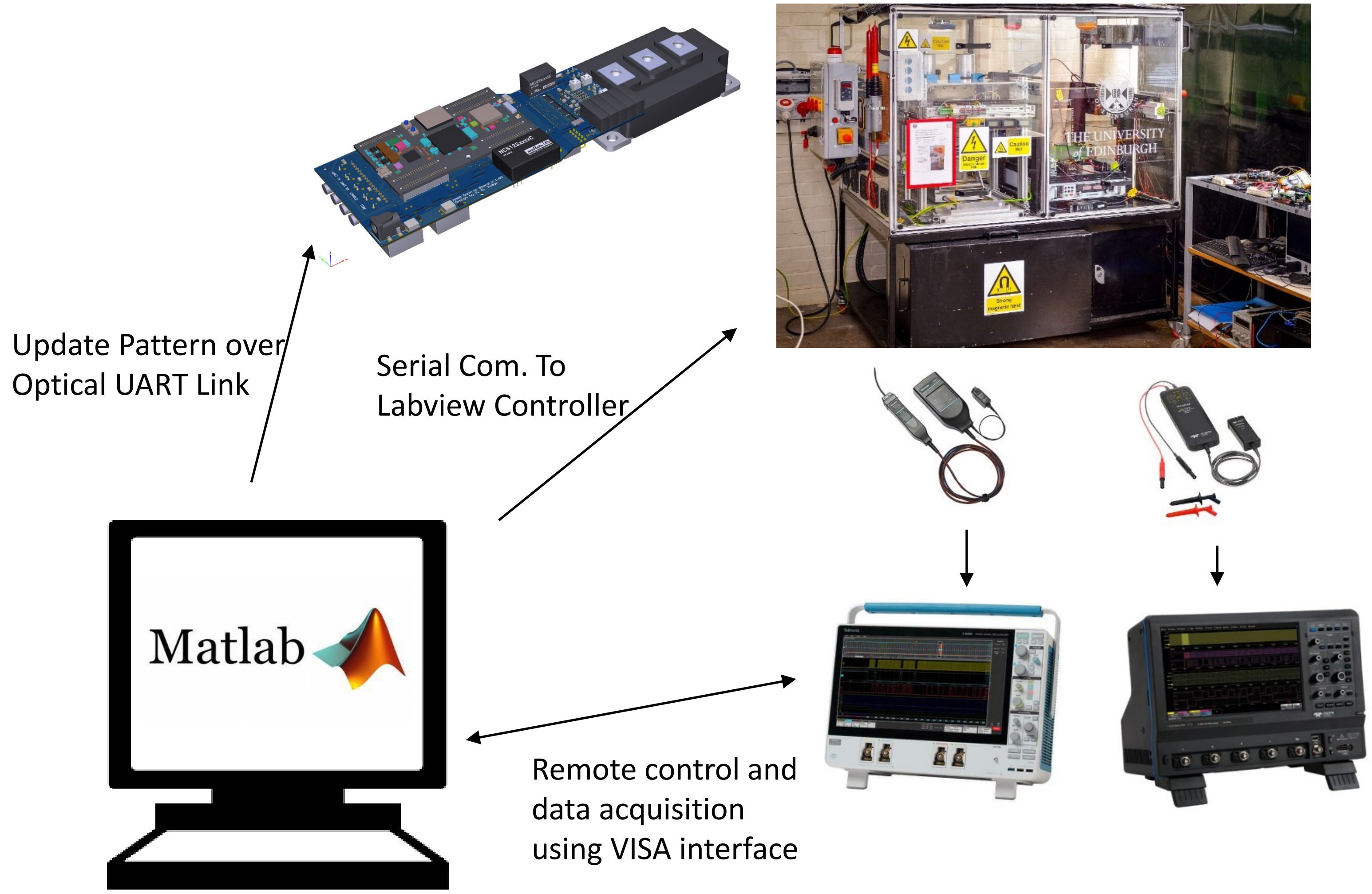
1 Optical Tx/Rx 2 LVDS Control Signals 3 SPI Signals
4 Programmable Delays 5 XOR Gates 6 ECL to LVDS Buffers



Experimental Setup

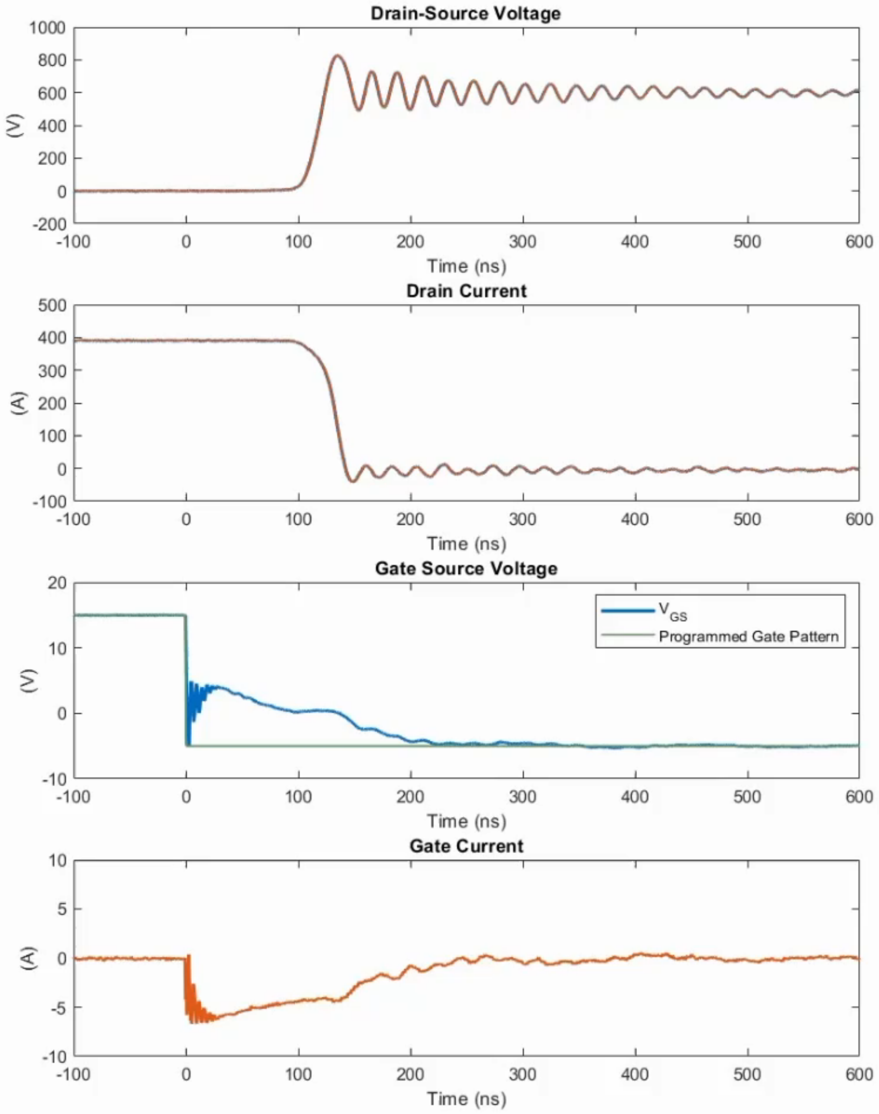


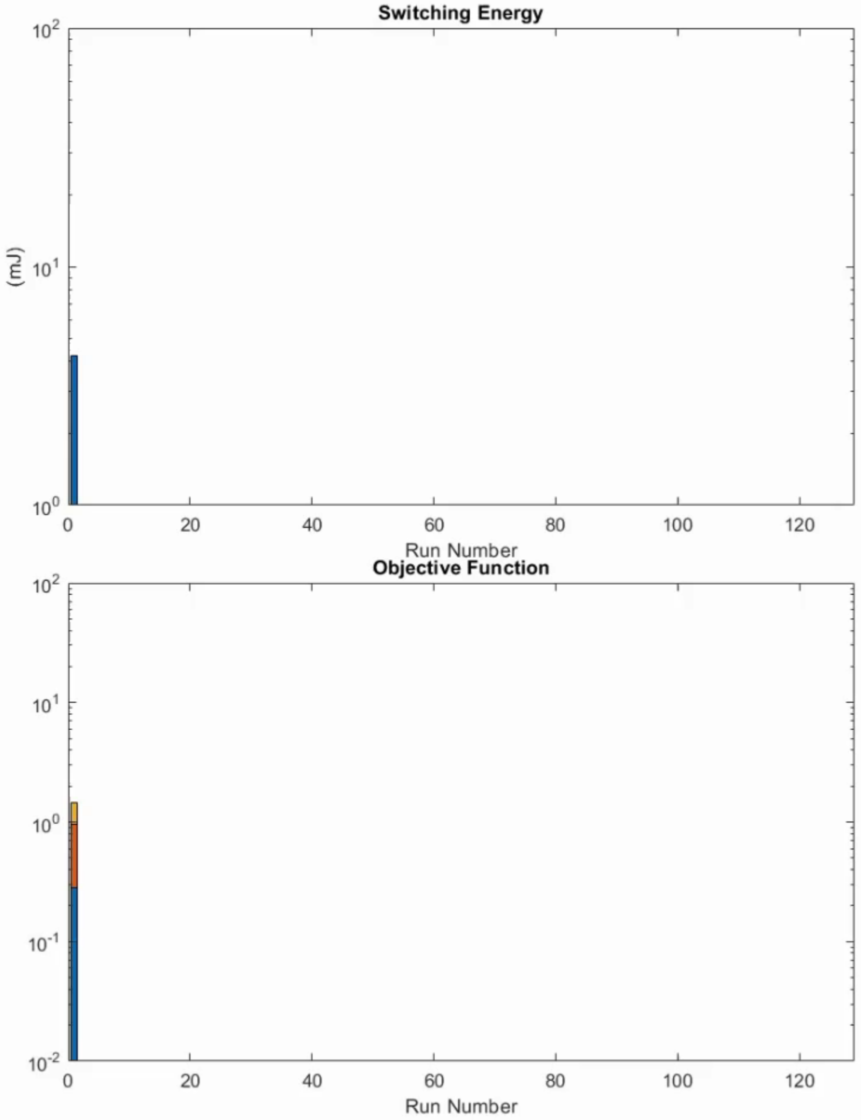
Automated Profiling

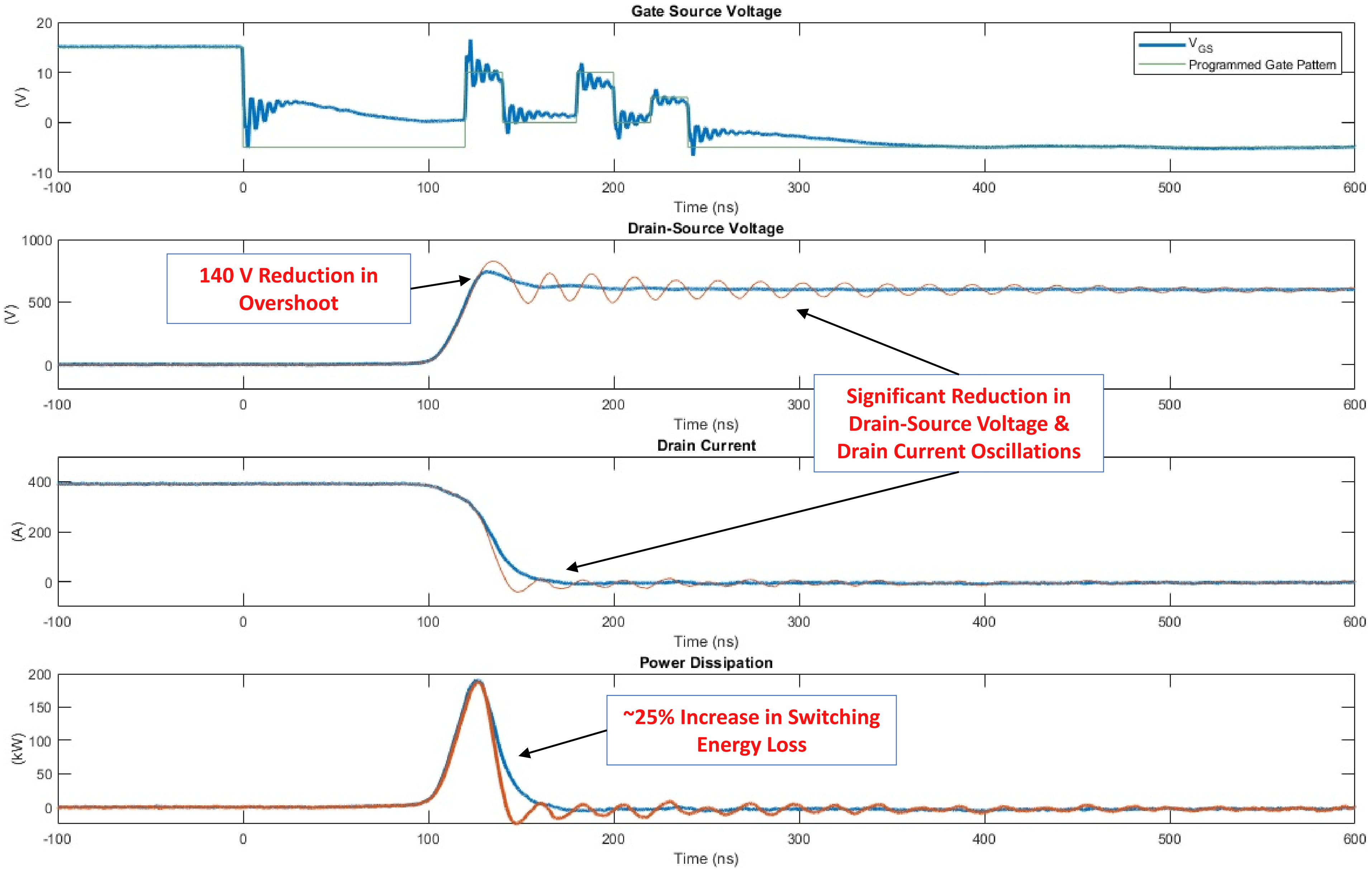


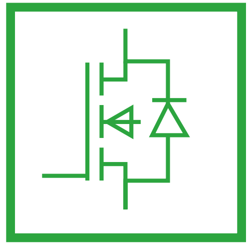
Genetic Algorithm

Wolfspeed CAB400M12XM3 1200V 400 A






Gate Source Voltage
VGS
Programmed Gate Pattern
(V)
Time (ns)
Drain-Source Voltage
140 V Reduction in Overshoot
Significant Reduction in Drain-Source Voltage & Drain Current Oscillations
Drain Current
(A)
Power Dissipation
~25% Increase in Switching Energy Loss
(kW)



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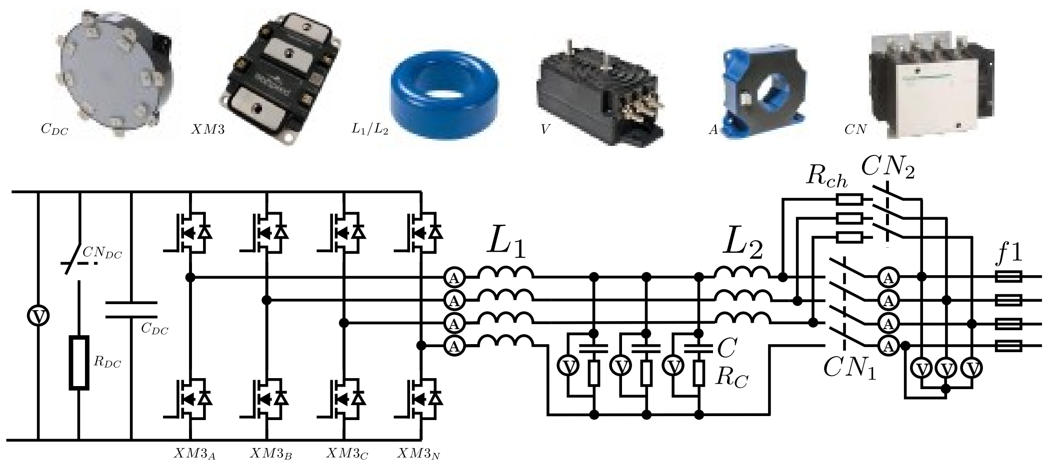
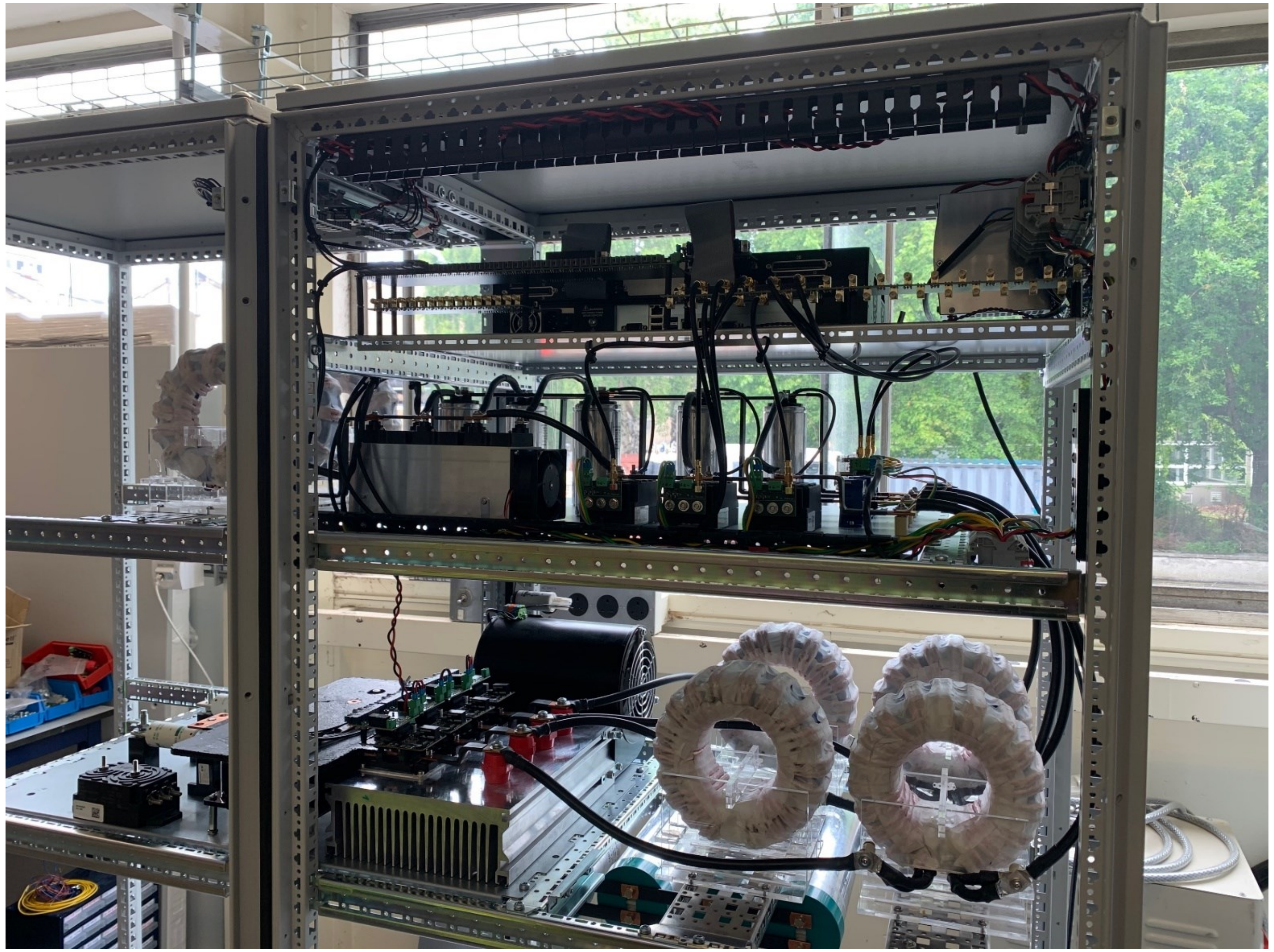
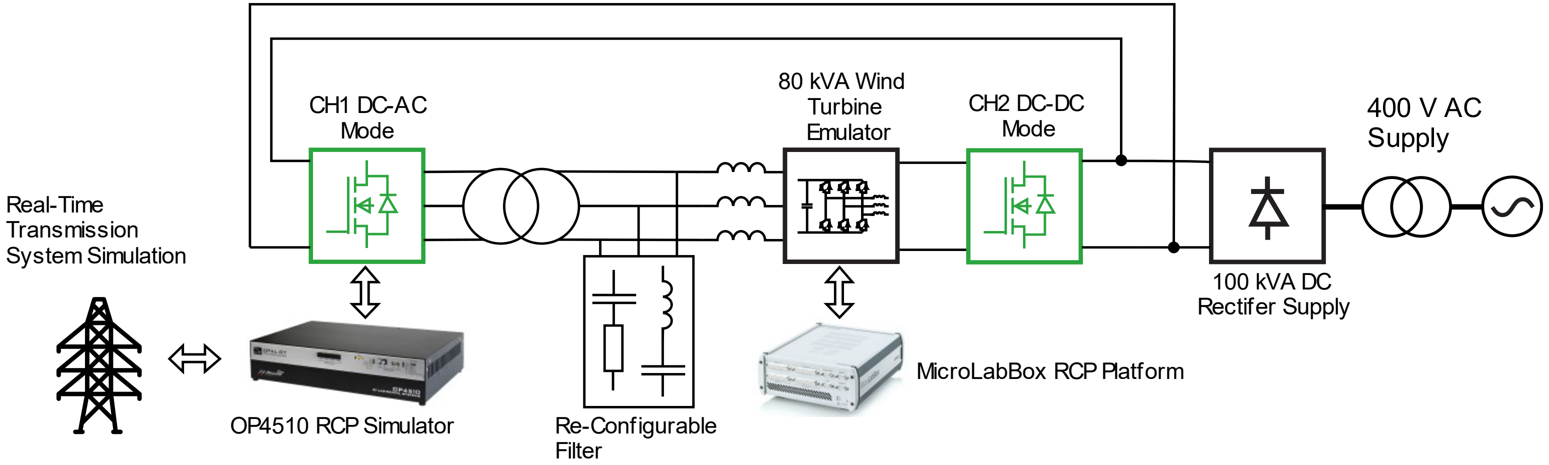


Four-leg Silicon Carbide MOSFET Bridge Design

- FPGA based Model Predictive Controller implemented on an Opal-RT Simulator
  - 200 kHz Control Frequency -> ~50 kHz Switching Frequency -> ~5 kHz Converter Bandwidth



Grid Emulator System



DC & AC Emulation for Converter Fault-Ride Through Testing

Ambition is to be capable of performing advanced experimental testing of these hybrid converter topologies:

- Grid Interaction studies.
- Fault ride through testing.
- Harmonic interaction studies.

Thank You – Any Questions?