# SiC Power Modules for More-Electric Aircraft Application

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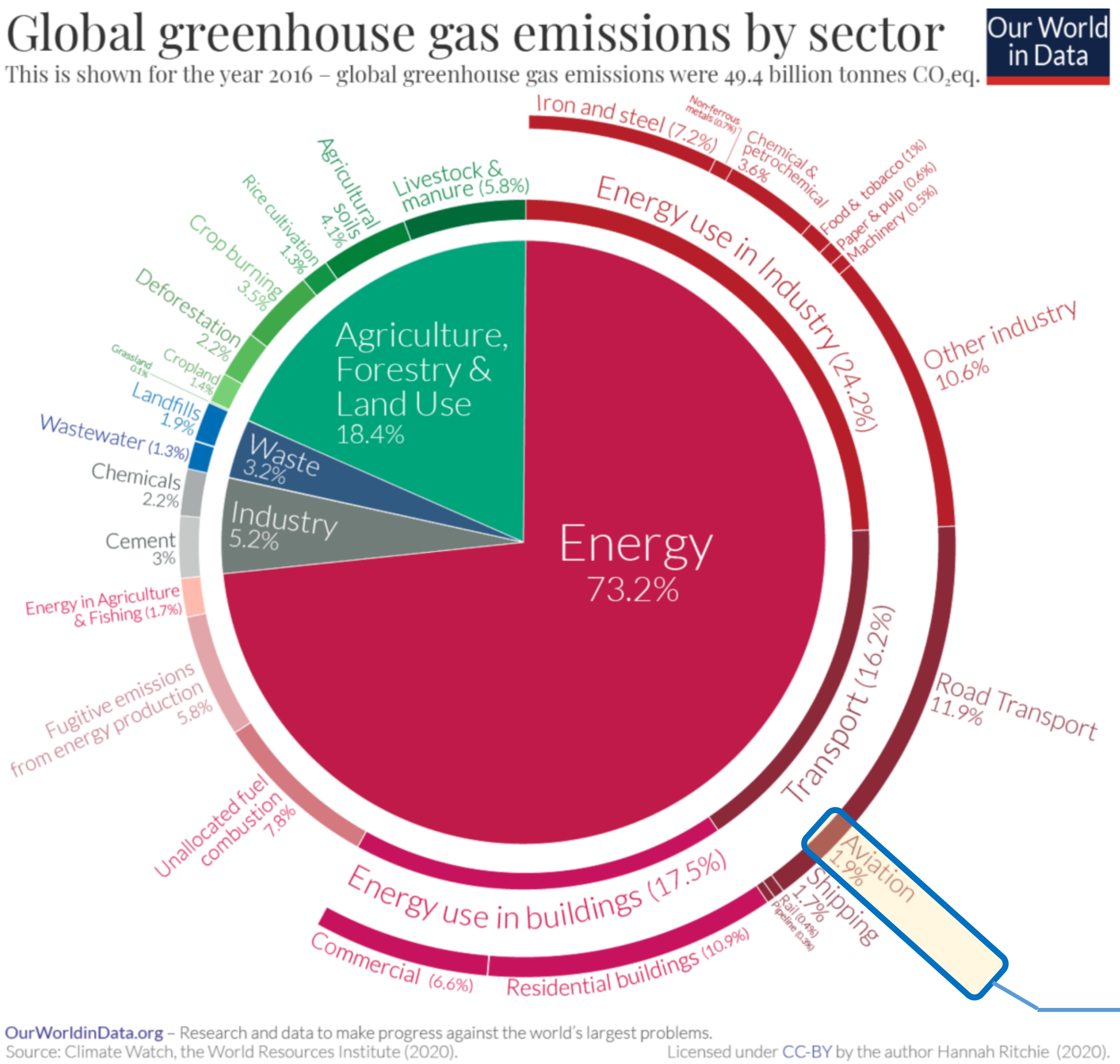
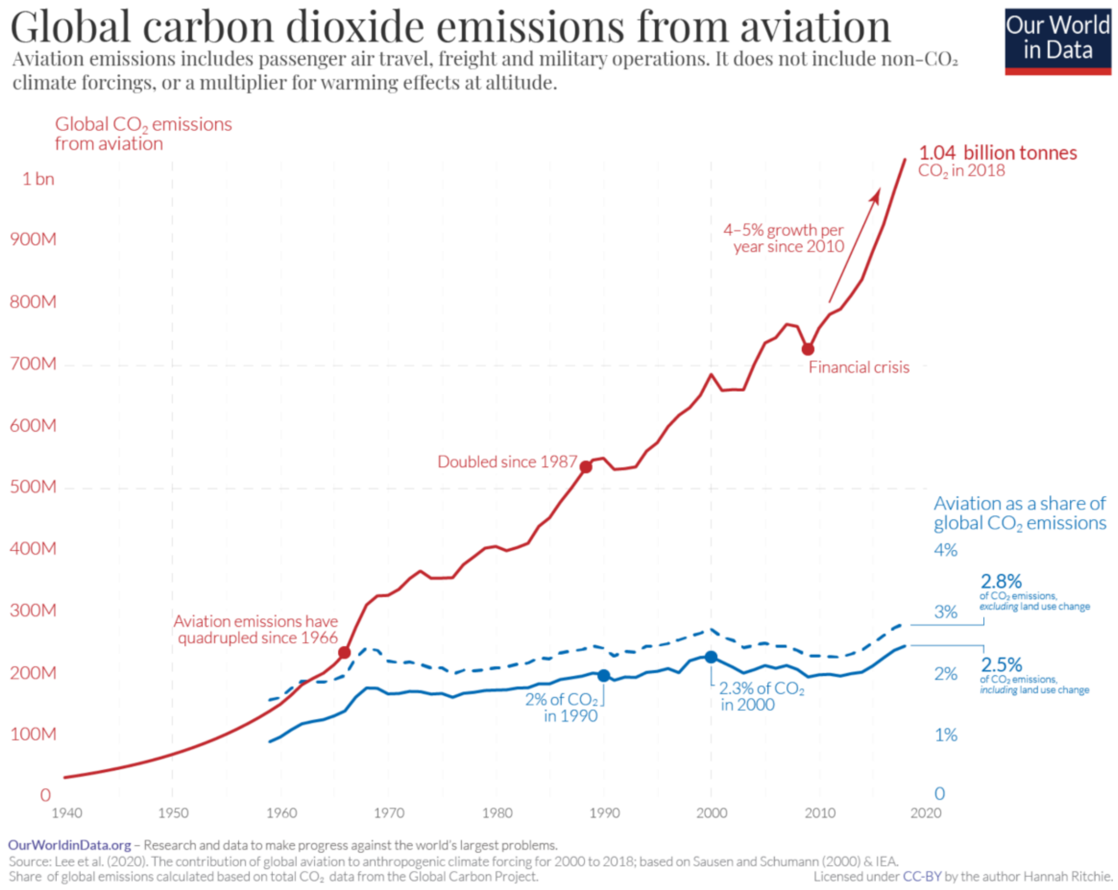
The University of Sheffield, UK

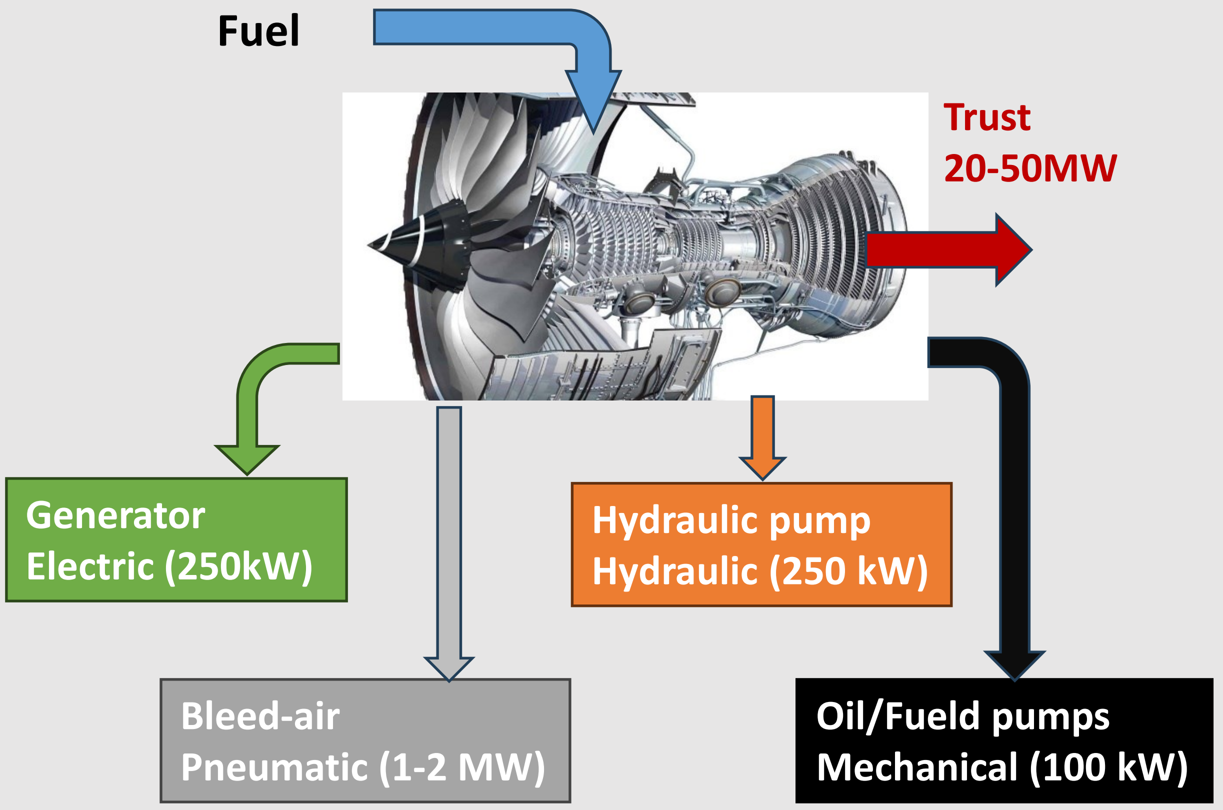
# The More-Electric Aircraft



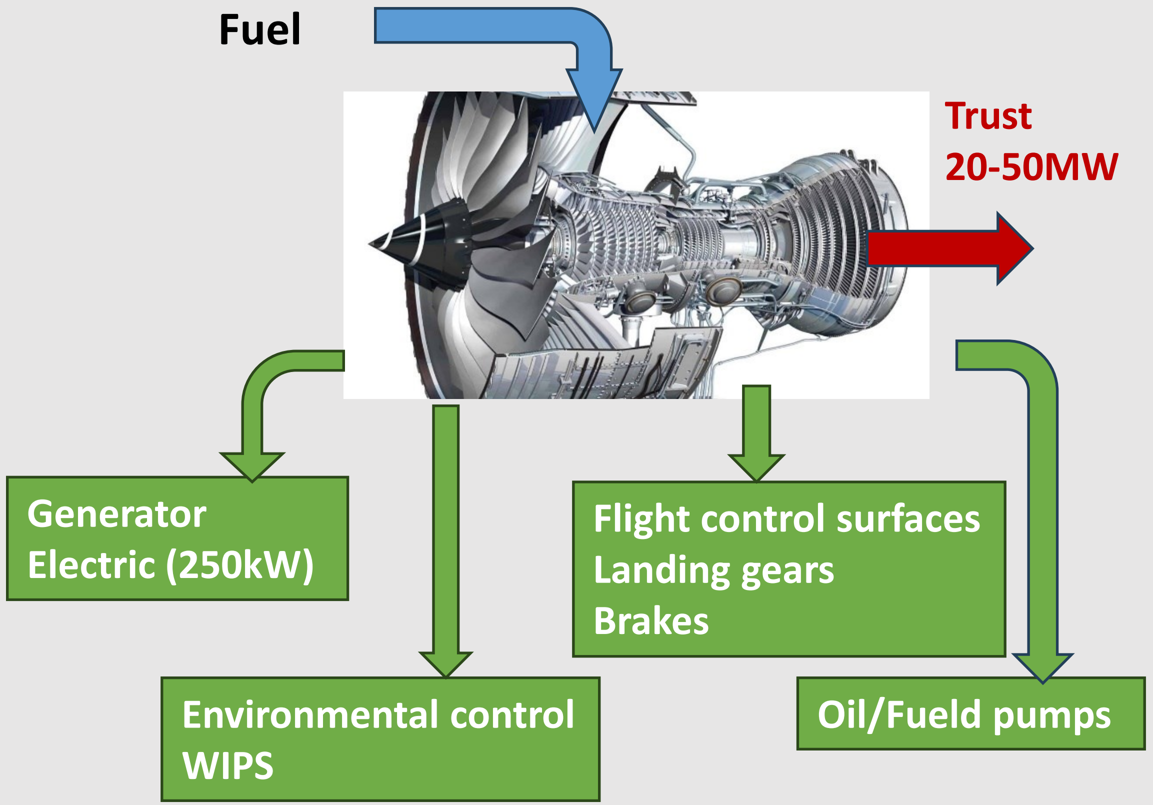




**Aviation accounts for 1.9% global CO2 emissions**

# The More-Electric Aircraft

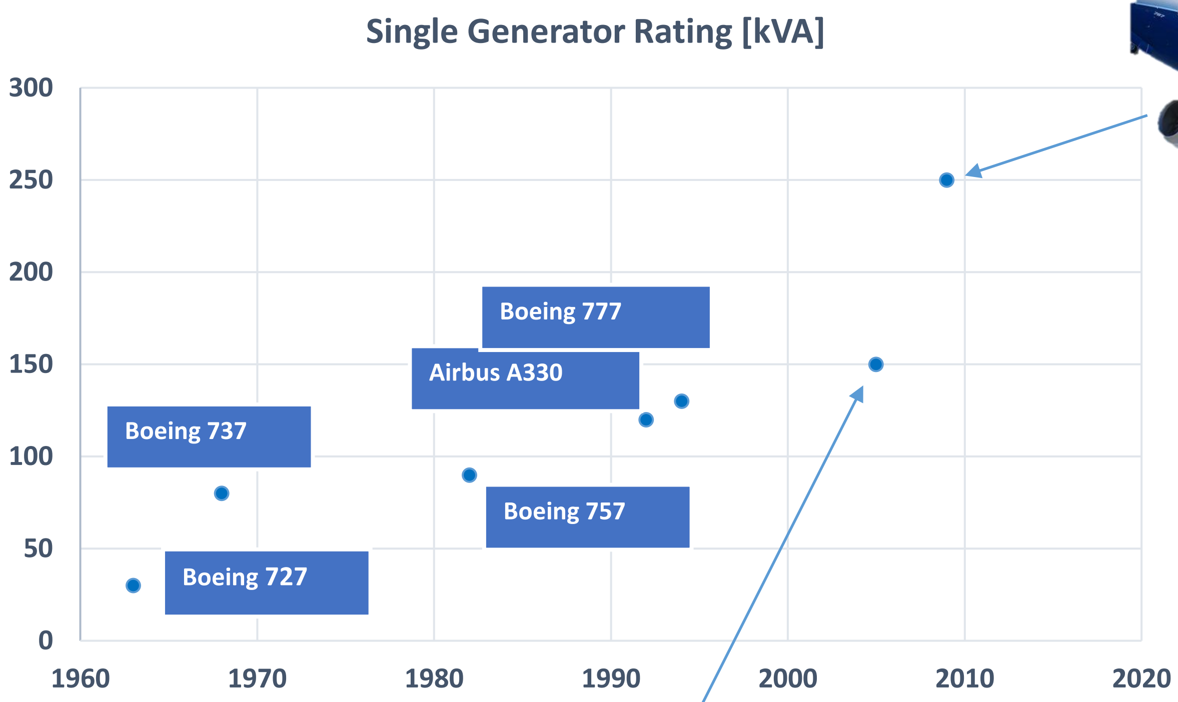



Conventional aircraft




More electric Aircraft

# The More-Electric Aircraft





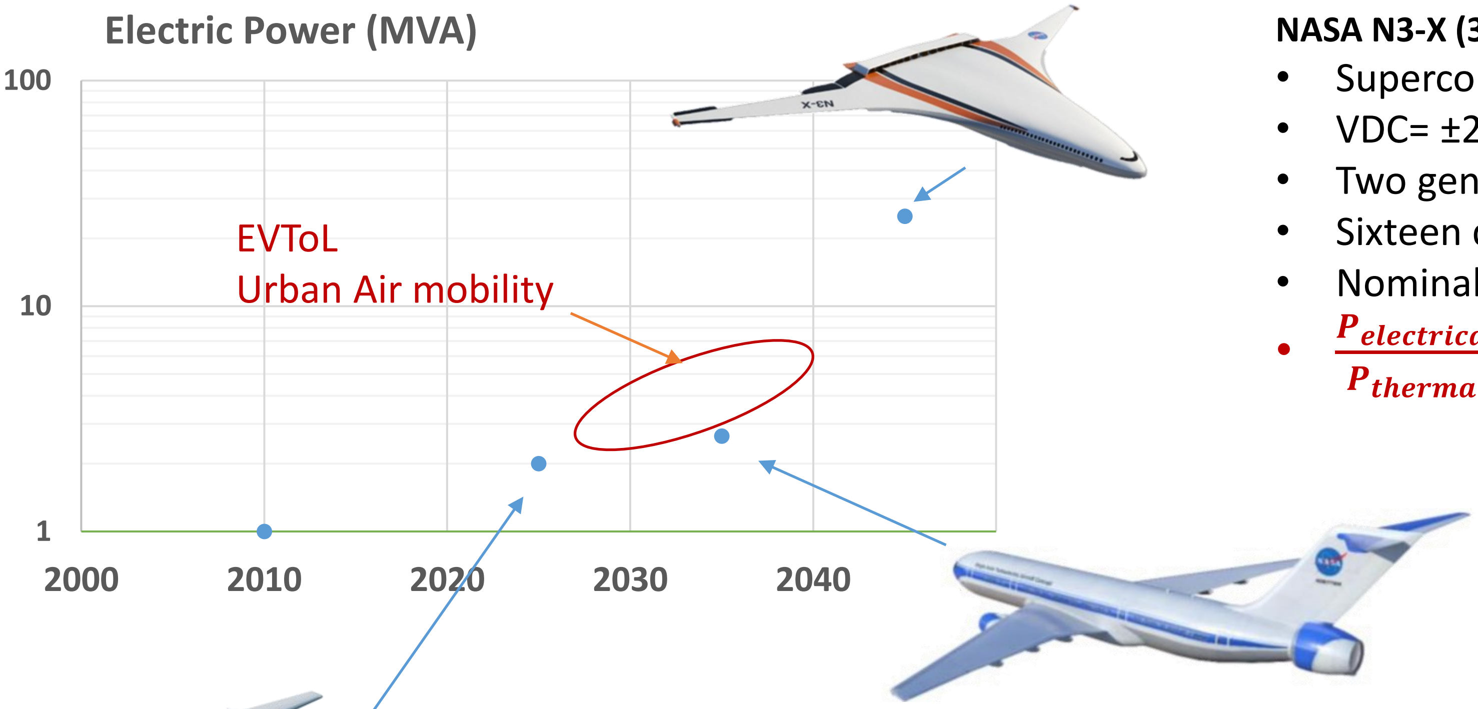
**Boeing 787** (up to 410pax)

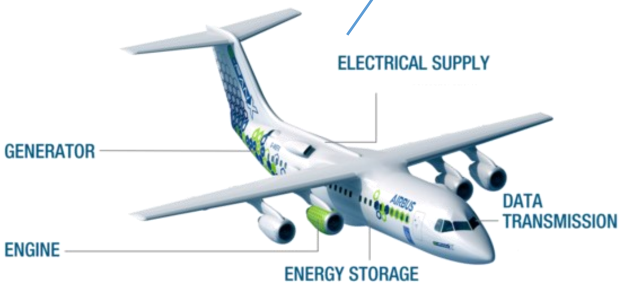
- large number of pneumatic and hydraulic systems replaced by Power electronics and electrical machines
- compressors replace pneumatic loads, such as the WIPS and the ECS.
- AC voltage 235 V
- Four generators on the two main engines generating a total electrical power of 1 MVA
- $\frac{P_{electrical}}{P_{thermal}} < 1.5\ \%$


**Airbus A380** (up to 853 seats)

- Hydraulic drives are partly electrified (flight control systems)
- AC voltage 115V
- Four generators on the main engines, total elect. 600 kVA
- $\frac{P_{electrical}}{P_{thermal}} < 0.2\ \%$

# The More-Electric Aircraft




**NASA N3-X (300 pax)**

- Superconducting machines
- VDC= ±2 kV
- Two generators, 6.5 MW each per wing.
- Sixteen distributed electric drive systems provide the thrust
- Nominal total electrical output 25 MW
- $\frac{P_{electrical}}{P_{thermal}} = \mathbf{80\ \%}$

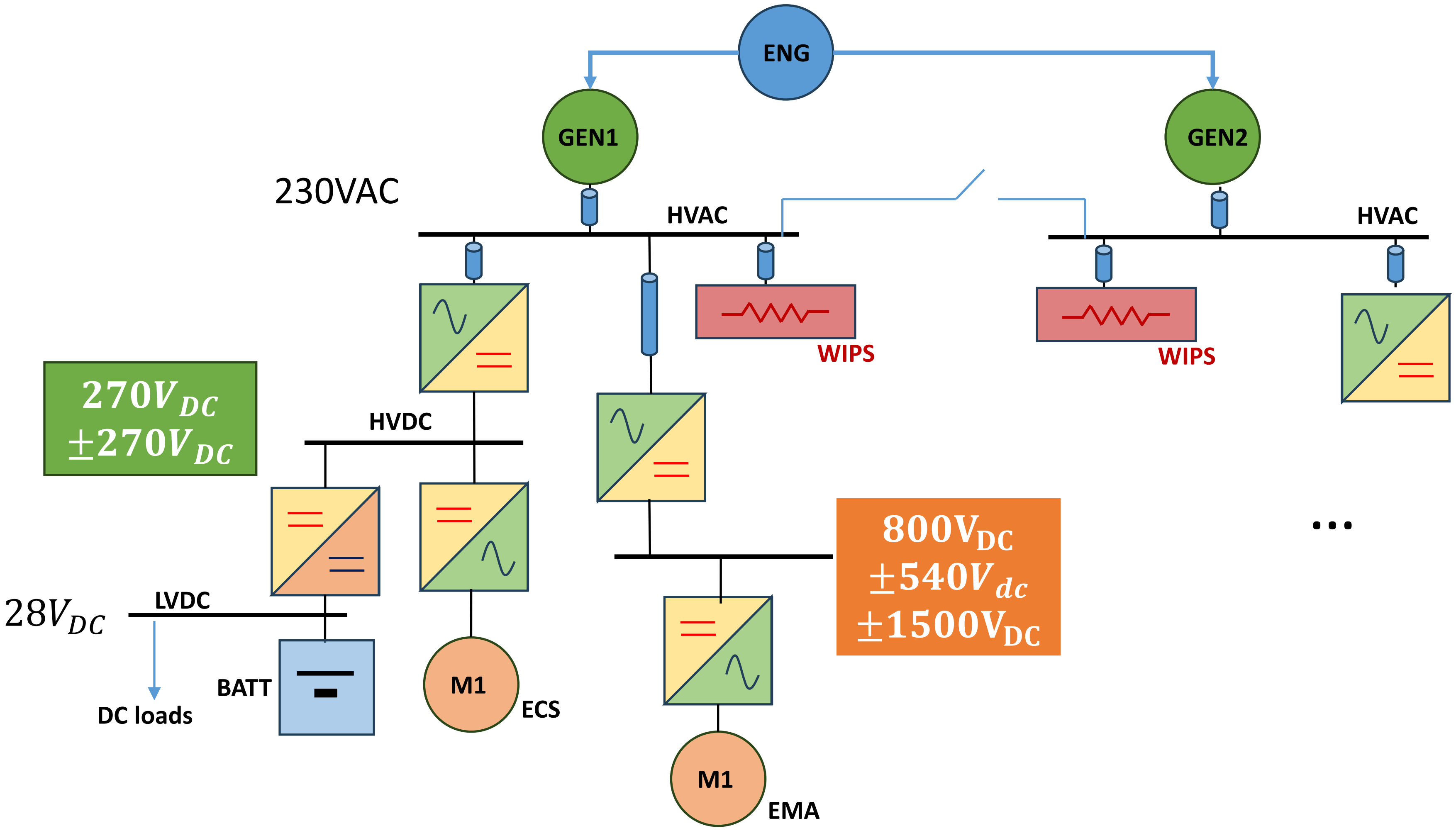
**NASA Single-Aisle Turboelectric Aircraft with Aft Boundary Layer Propulsion (STARC-ABL)** (2030-35)
154 pax

- Two engine, electrical power of 1.5 MW
- 1 kV DC on-board power supply
- boundary layer ingesting tail-one thruster
- All-electric drive, power of 2.61 MW and generates thrust
- $\frac{P_{electrical}}{P_{thermal}} = \mathbf{30\%}$

**E-FAN X**

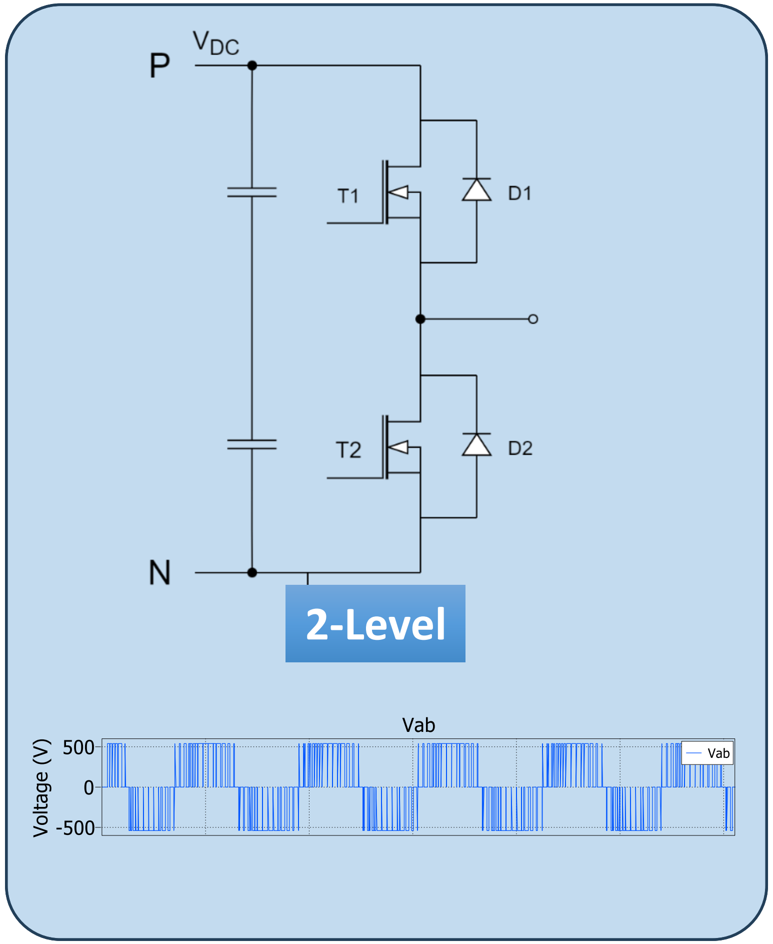
- BAe 146 powered by four engines.
- One propulsion unit powered by a 2 MW
- Vdc=3kV
- $\frac{P_{electrical}}{P_{thermal}} = \mathbf{25\%}$

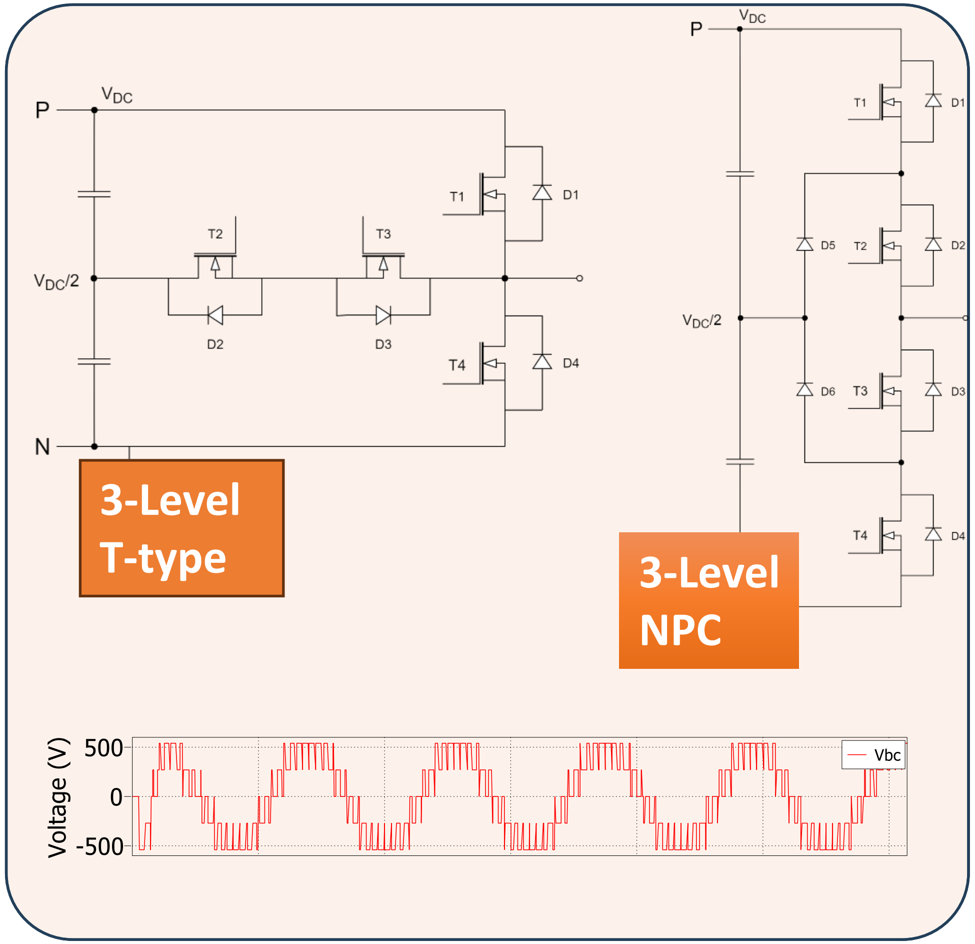
# The More-Electric Aircraft

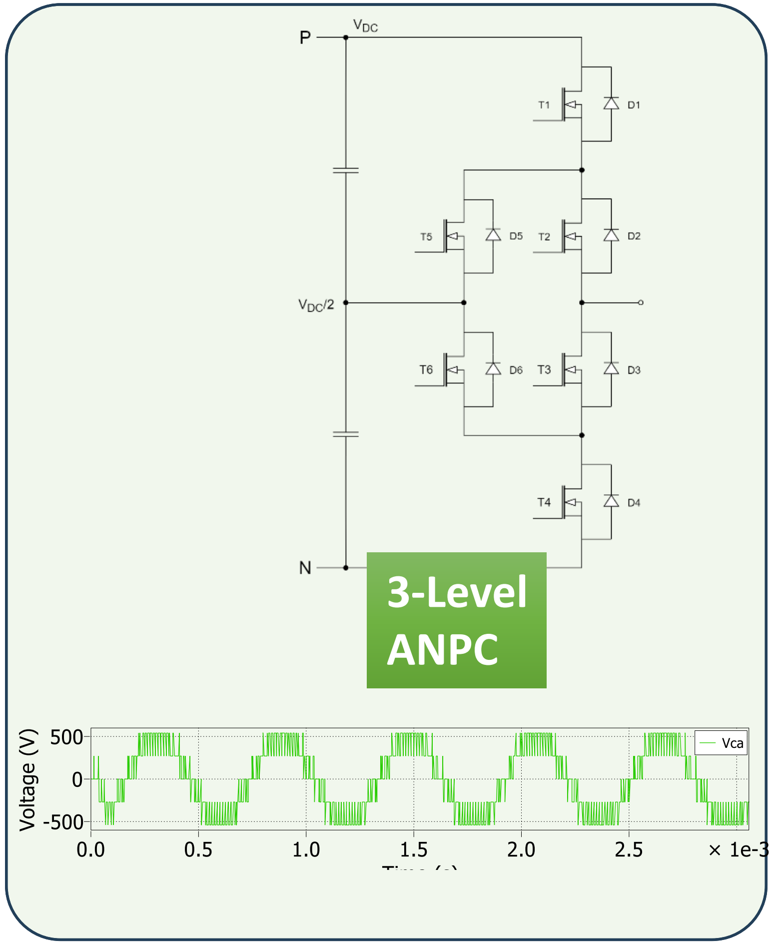


# Converters for MEA

Power electronics is a critical enabling technology for aviation electrification



# Converters for MEA

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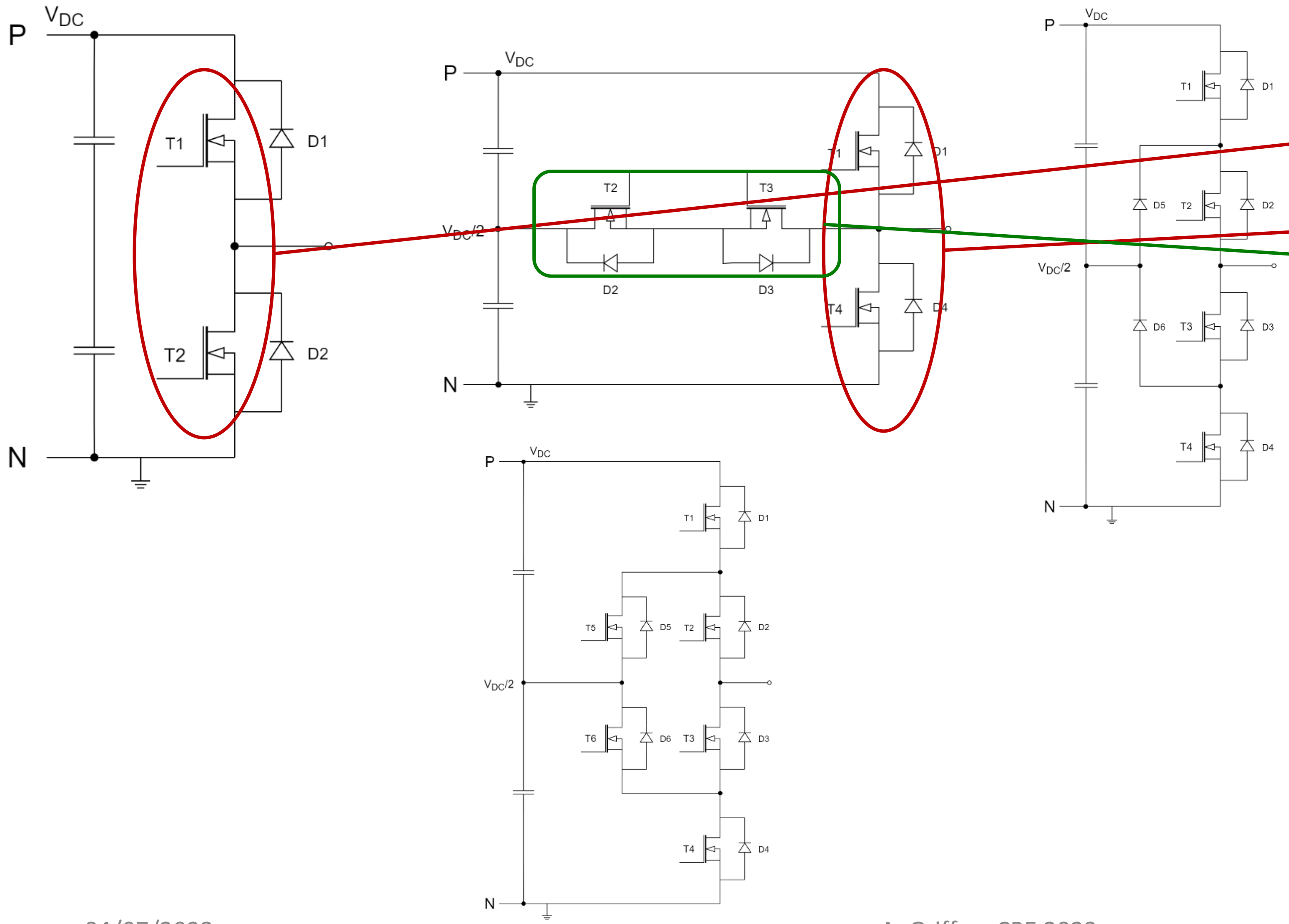
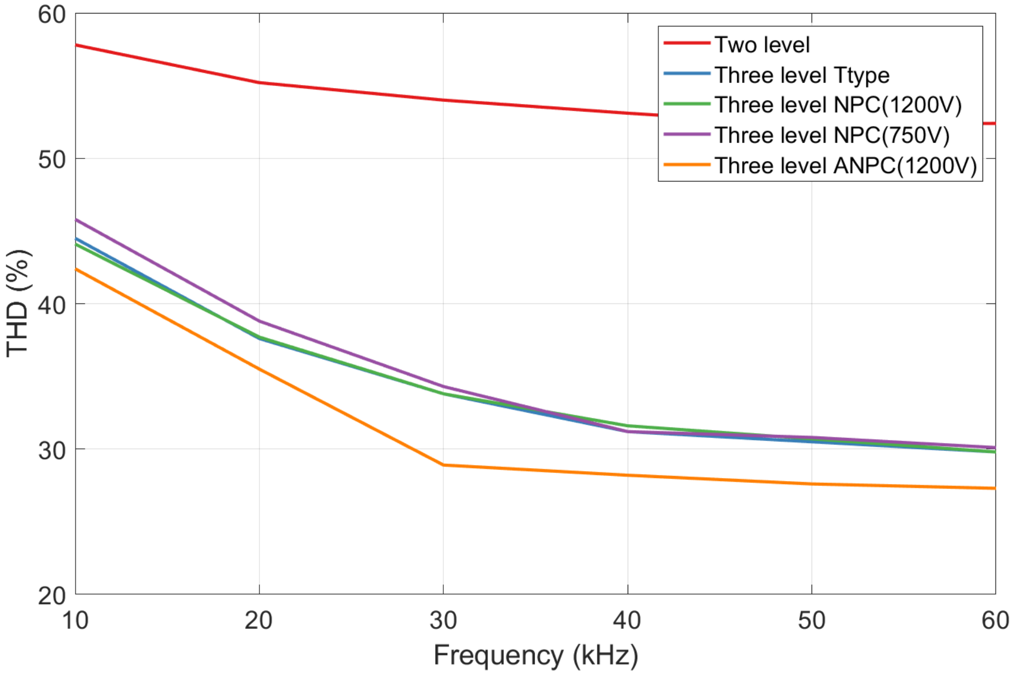
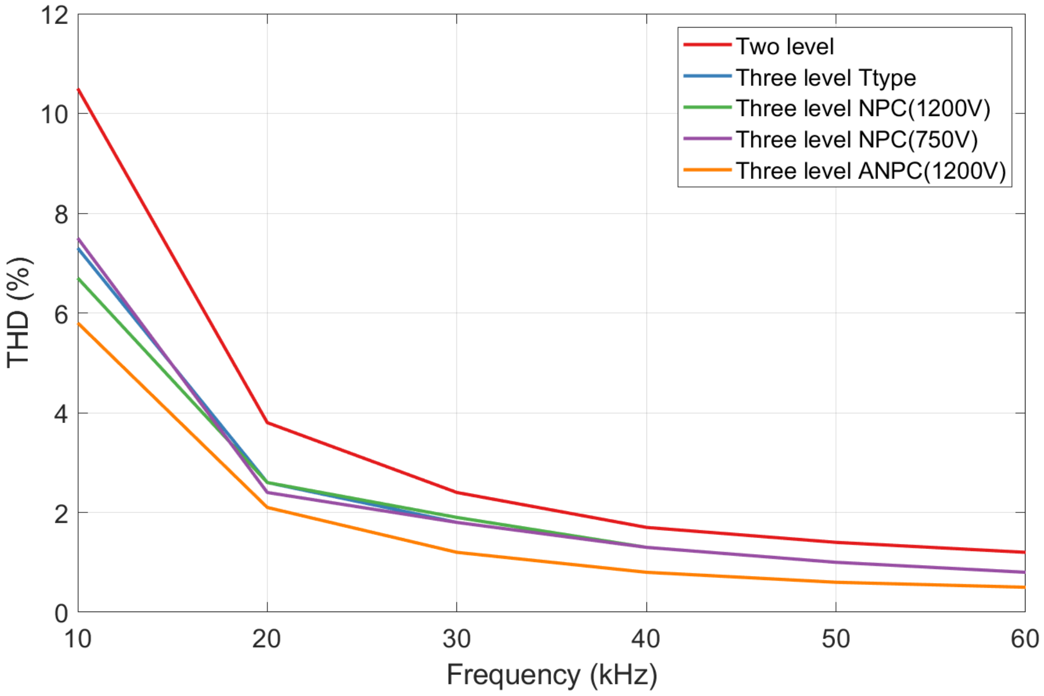
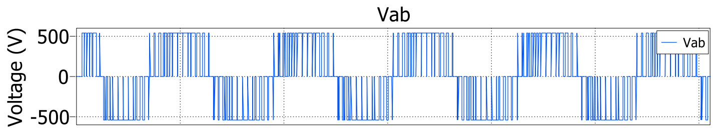



| | Switch | Blocking Voltage | Switching Voltage |
|---|---|---|---|
| 2-Level | T1 | $V_{DC}$ | $V_{DC}$ |
| | T2 | | |
| 3-Level T-Type | T1 | $V_{DC}$ | |
| | T2 | $\frac{1}{2}V_{DC}$ | $\frac{1}{2}V_{DC}$ |
| | T3 | | |
| | T4 | $V_{DC}$ | |
| 3-Level NPC | T1 | $\frac{1}{2}V_{DC}$ | $\frac{1}{2}V_{DC}$ |
| | T2 | | |
| | T3 | | |
| | T4 | | |
| | D5 | | |
| | D6 | | |
| 3-Level ANPC | T1 | $\frac{1}{2}V_{DC}$ | $\frac{1}{2}V_{DC}$ |
| | T2 | | |
| | T3 | | |
| | T4 | | |
| | T5 | | |
| | T6 | | |

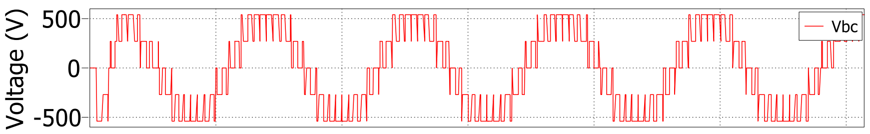
# Converters for MEA



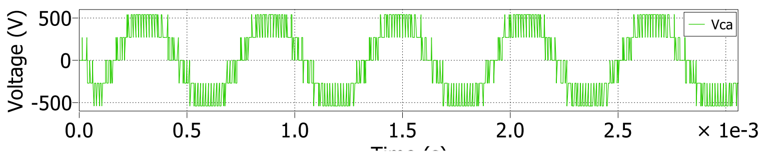




Two level




Three-level T-type & NPC




Three-level ANPC

# Converters for MEA

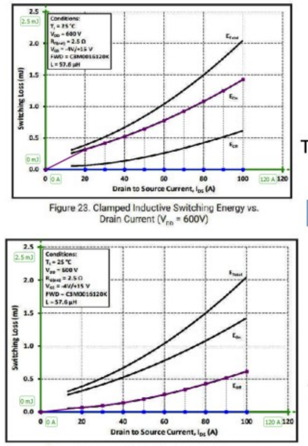


Figure 23. Clamped Inductive Switching Energy vs. Drain Current ($V_{DD}$ = 600V)

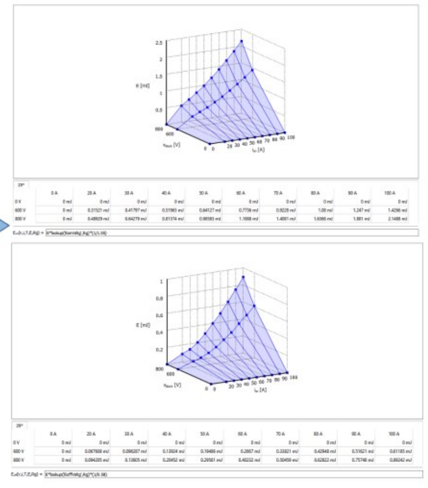
Figure 23. Clamped Inductive Switching Energy vs. Drain Current ($V_{DD}$ = 600V)

Turn-on energy vs current

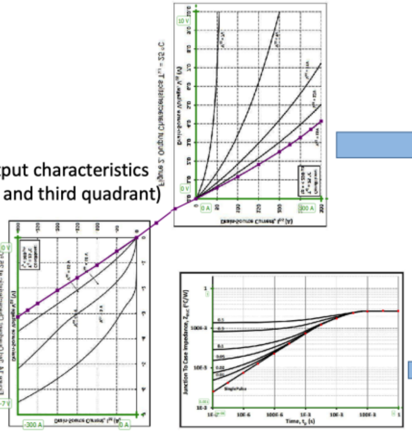
Extract from data sheet

Scalable for different gate resistance

Turn-off energy vs current



Output characteristics (First and third quadrant)



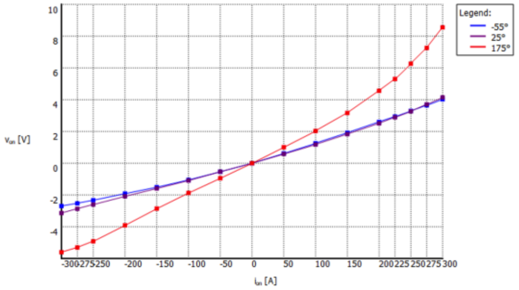


Figure 21. Transient Thermal Impedance (Junction - Case)

Thermal impedance

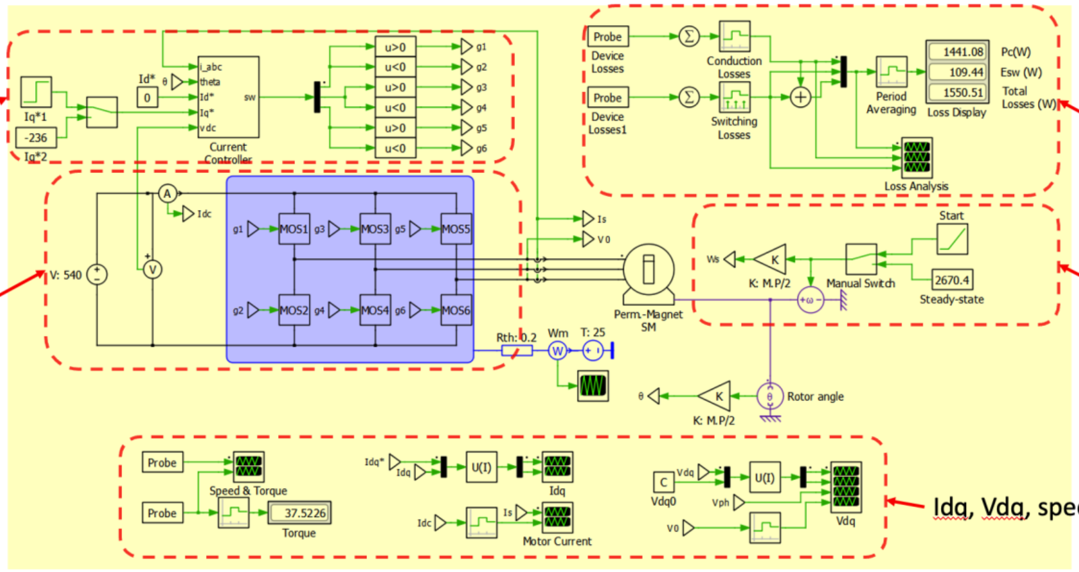
Type: Foster    Number of elements: 6

| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| R | 0.0002146 K/W | 0.001874 K/W | 0.006369 K/W | 0.02297 K/W | 0.08657 K/W | 0.1522 K/W |
| τ | 1.066e-07 s | 5.651e-07 s | 1.107e-05 s | 0.0001877 s | 0.001925 s | 0.02125 s |

Describe its physical structure in terms of thermal transitions from the junction to case.

Current control

Two-level convertor



Losses calculation

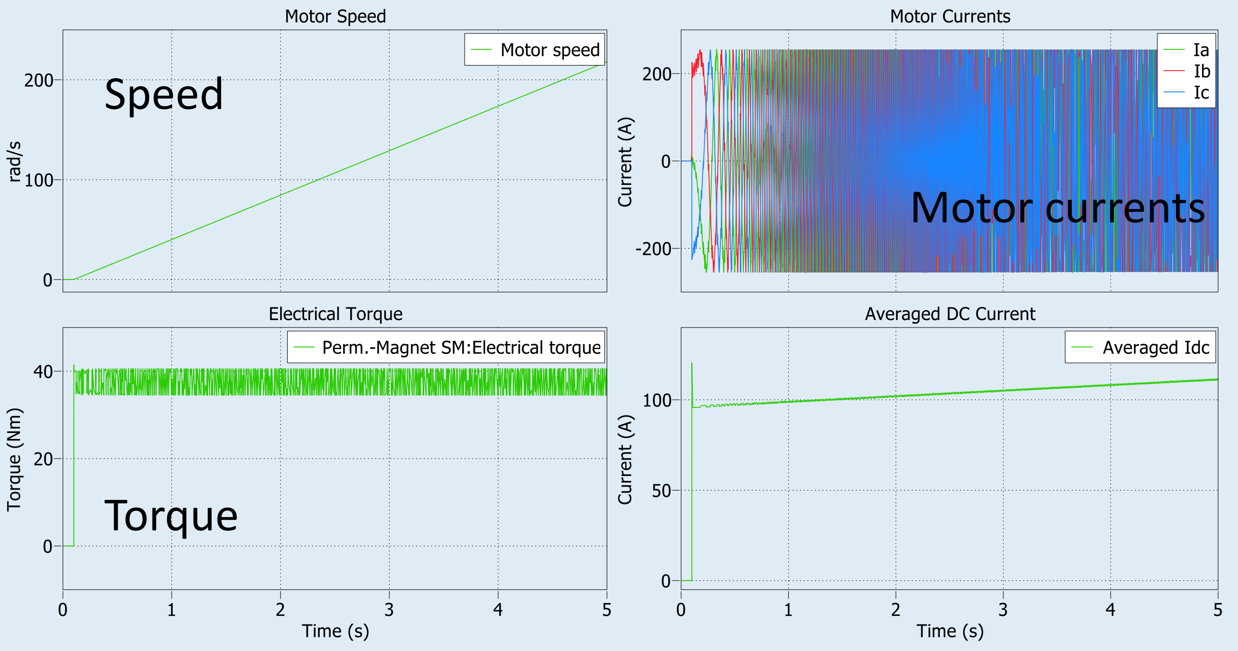
Motor mode selection

Idq, Vdq, speed & torque

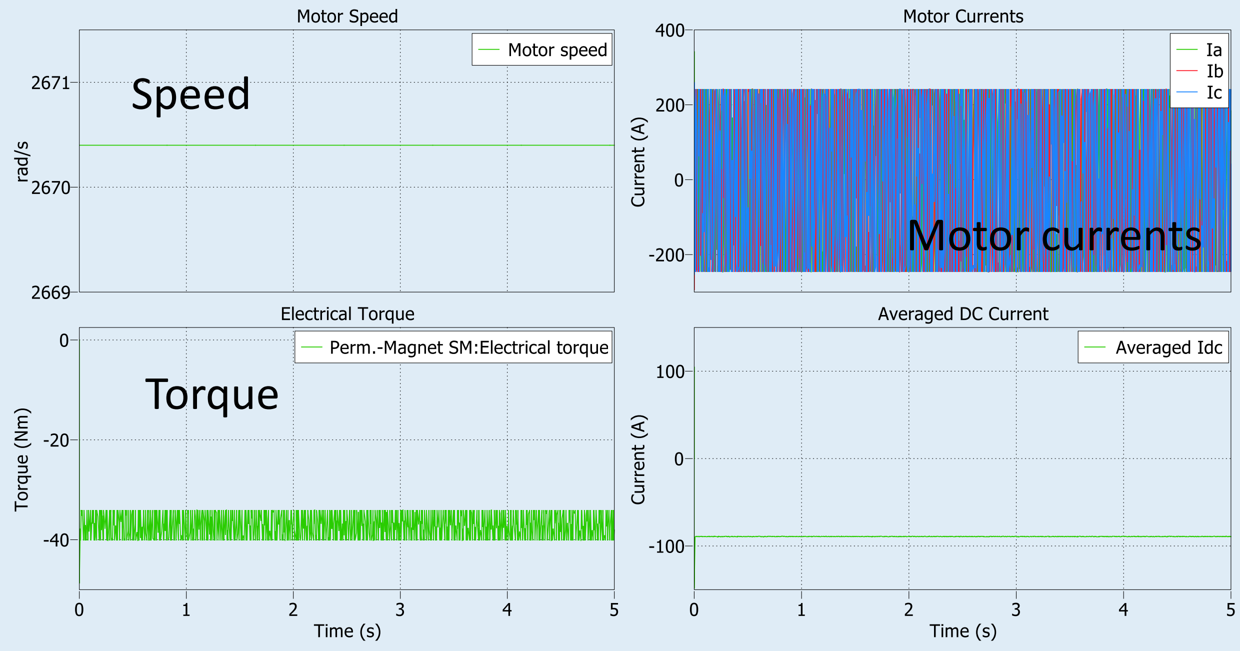
## Converter for Starter-generator

| Power factor | $\cos\varphi$ | 0-1 |
|---|---|---|
| Load frequency | $f_{load}$ | 1kHz |
| Amplitude modulation ratio | m | 0-1 |
| Output power | $P_{out}$ | 100kW / 300kW |
| Output phase current | $I_{load}$ | 166.7Arms / 282Arms |
| Vdc | | $\pm 270$<br>$\pm 540$ |

# Converters for MEA




Starting mode




Generating mode

# Converters for MEA

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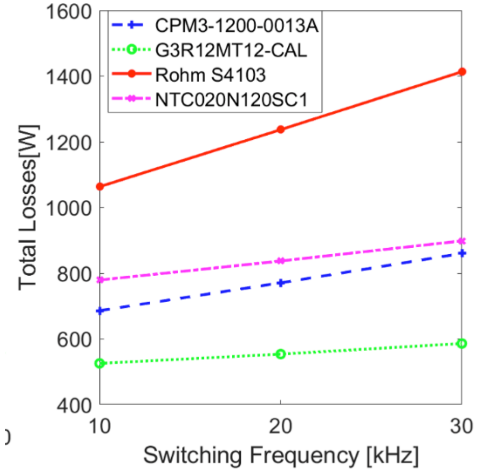
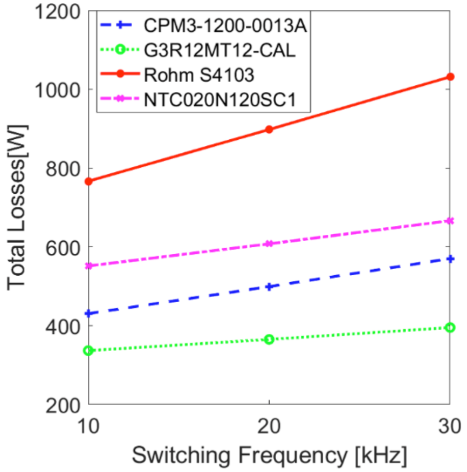
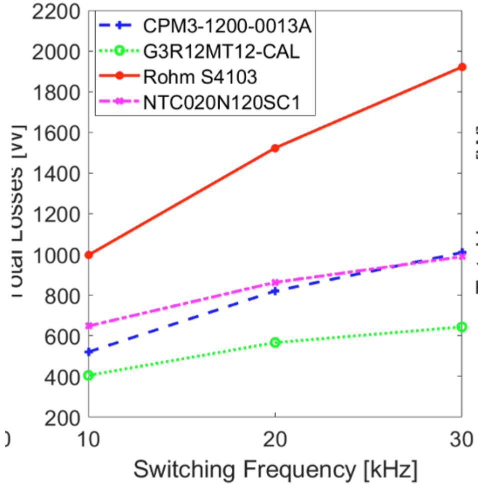



3MOSFETs

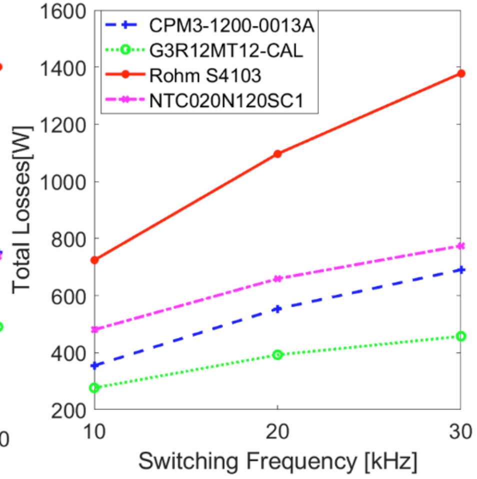



4MOSFETs

Start mode




3MOSFETs




4MOSFETs

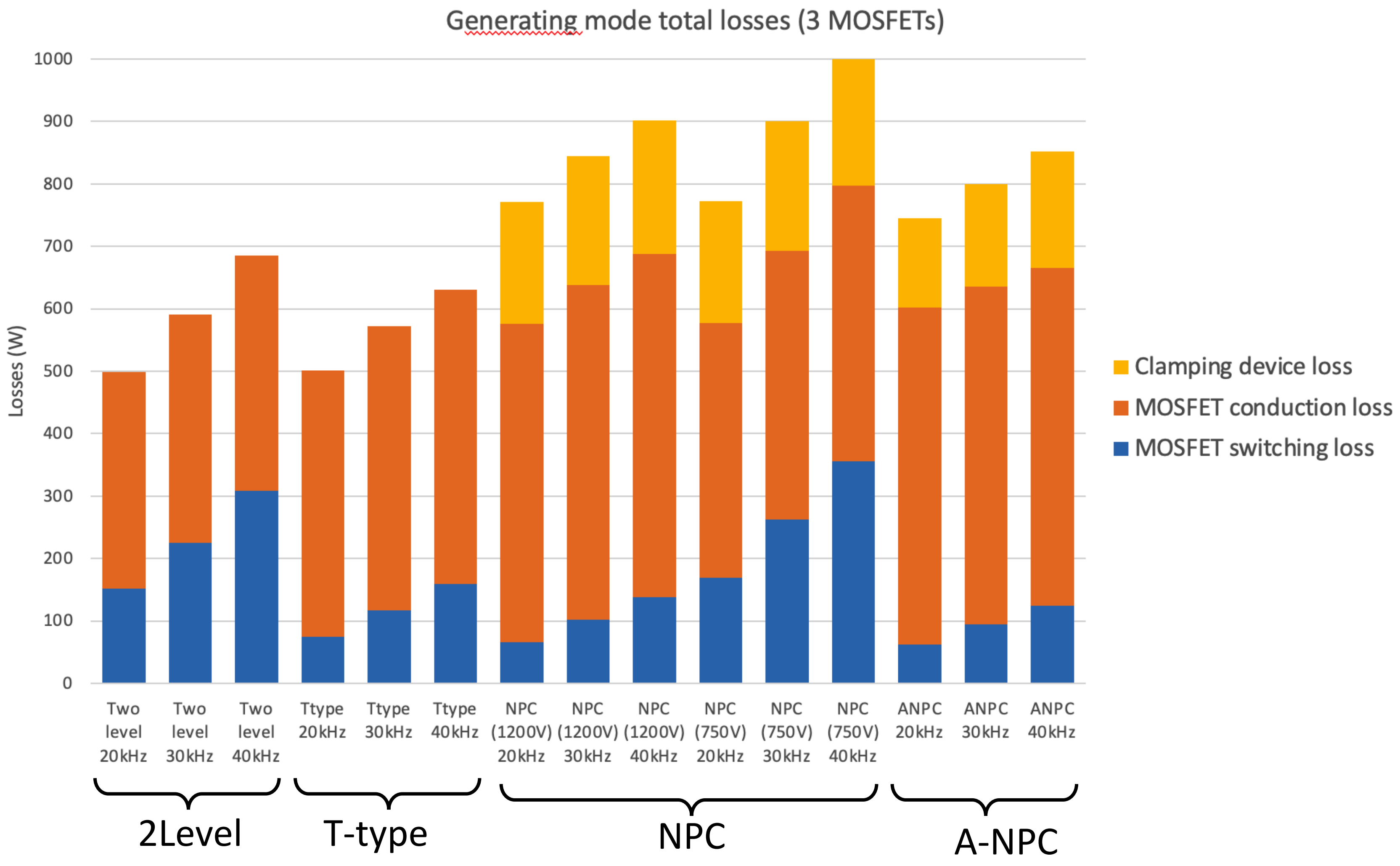
Generating mode

| Parameter | | Value |
|---|---|---|
| SiC MOSFET die | Wolfspeed<br>Rohm<br>GeneSiC<br>On-Semiconductor | CPM3-1200-0013A<br>S4103<br>G3R12MT12-CAL<br>NTC020N120SC1 |
| Switching frequency | $f_{sw}$ | 10kHz<br>20kHz<br>30kHz |
| Power factor | $\cos\varphi$ | 0-1 |
| Load frequency | $f_{load}$ | 1kHz |
| Amplitude modulation ratio | m | 0-1 |
| Output power | $P_{out}$ | 100kW |
| Output phase current | $I_{load}$ | 166.7A(RMS) |

# Converters for MEA

$V_{DC} = 540V$

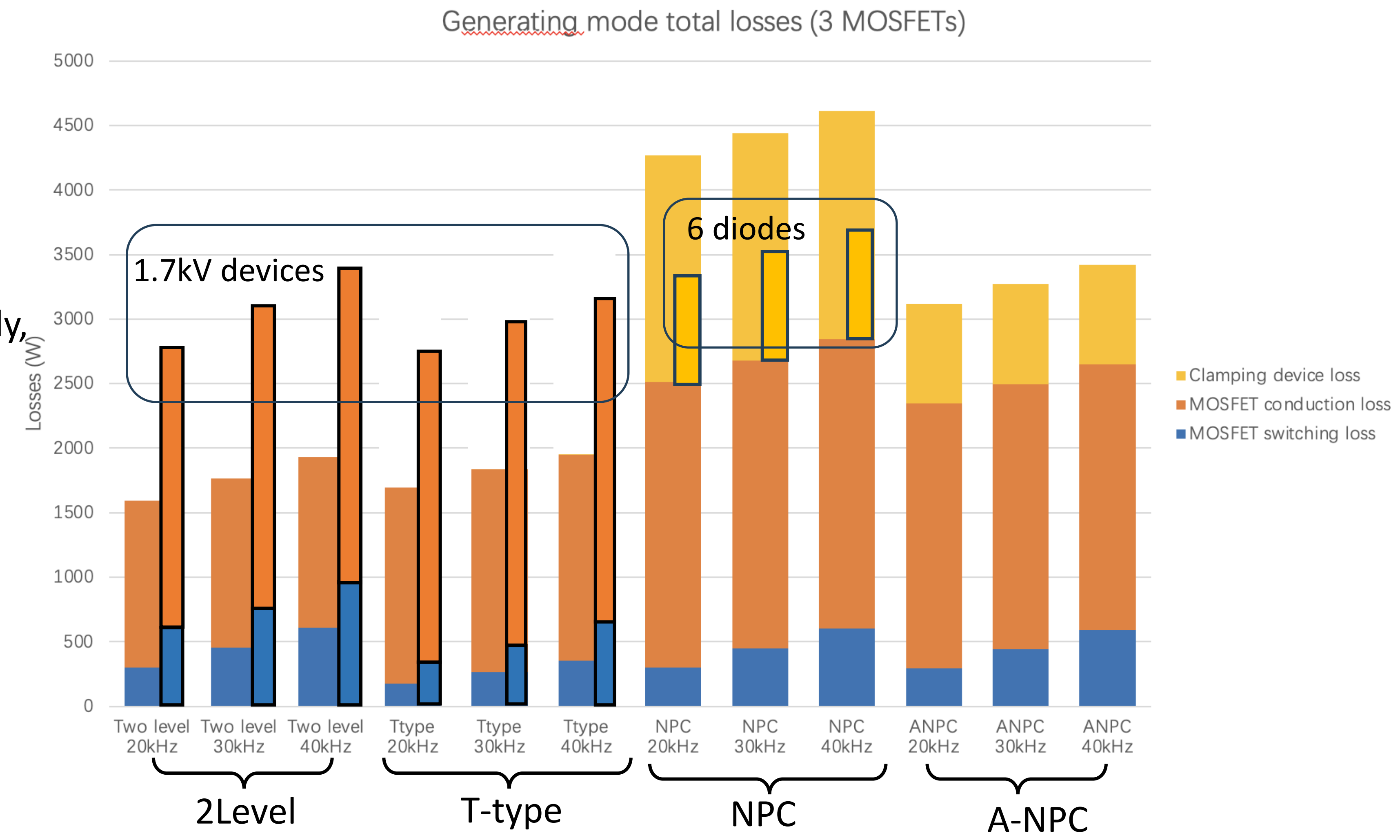
- Two-level converter has the fastest increase of losses as the switching frequency increases
- T-type has the overall highest efficiency thanks to lower switching losses (lower switching voltages)
- NPC penalised by higher conduction losses
- Availability of low $R_{DS,on}$ devices at <1.2kV



# Converters for MEA

1080V 282A rms

- 1.2kV cannot be used due to required $\approx 2x$ voltage margin
- 1.7kV increase losses considerably, making NPC competitive for

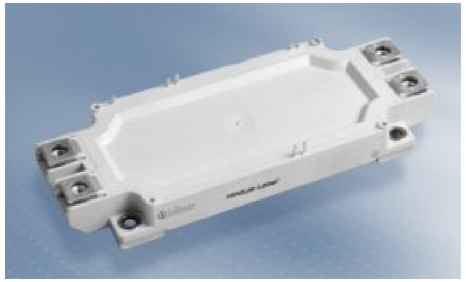


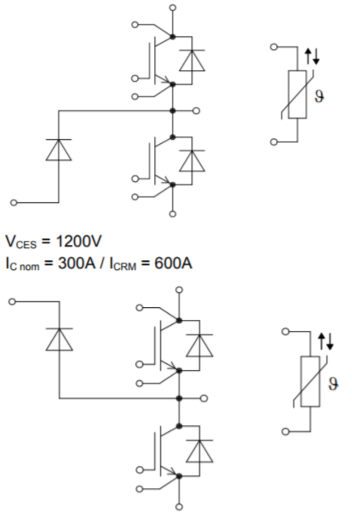
# Power modules for MEA

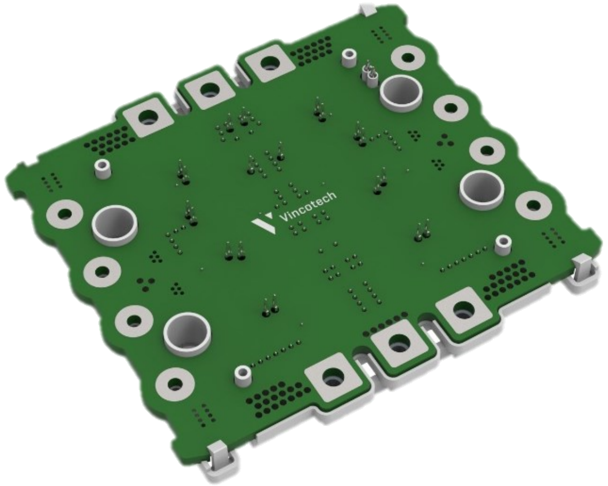
- There is no SiC multi-level module on the market beyond small (<50A) prototypes/samples
- Similarly rated Si IGBT modules have equivalent on-state resistance double of what can be achieved with SiC (5.7$m\Omega$ vs 2.6 $m\Omega$)

- MuSiCA (Multilevel SiC power modules for Aerospace applications) to enable future converters in MEA with DC voltage above 1000V
    - Modularity
    - MRL

- MuSiCA will enable converters at 20kW/kg compared with 10kW/kg of the Si-IGBT state of the art





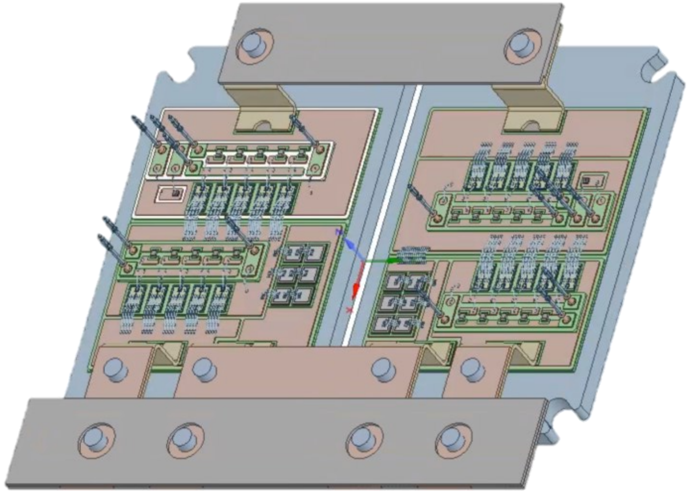
# Power modules for MEA

| Specifications | | Notes |
|---|---|---|
| Topology | 3-Level NPC | 3-Level I-type NPC Converter |
| DC-link voltage | 540V/1080V | 1080V (±540V) max DC-link voltage |
| Power | 100kVA per phase | power factor between 1 and 0 |
| Current | 280A/400A | Steady State current >280A(rms)<br>Peak AC current of 400A<br>400A(maximum) peak of AC current under highest load condition. |
| Switching frequency | >10kHz | No maximum |
| Thermal monitoring | required | NTC/PTC |
| Passives | | DC-link capacitor. |
| Cooling method | Air cooling | The modules are mounted on an Aluminium heat sink.<br>Assume base plate temperature up to 80°C, worst case scenario.<br>Air 'coolant' temperature according to airplane requirements.<br>Max air temp. 50°C. |

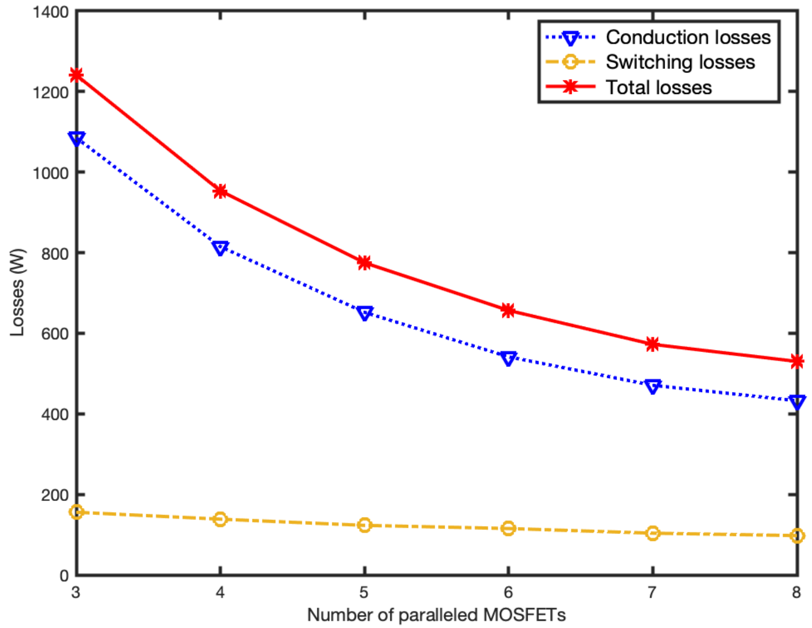
# Power modules for MEA: Electro-thermal optimisation

## Electro-thermal simulations

- Scalable design for different power levels/applications
- 5 dies per switch → >99% efficiency
- 6 SiC diodes

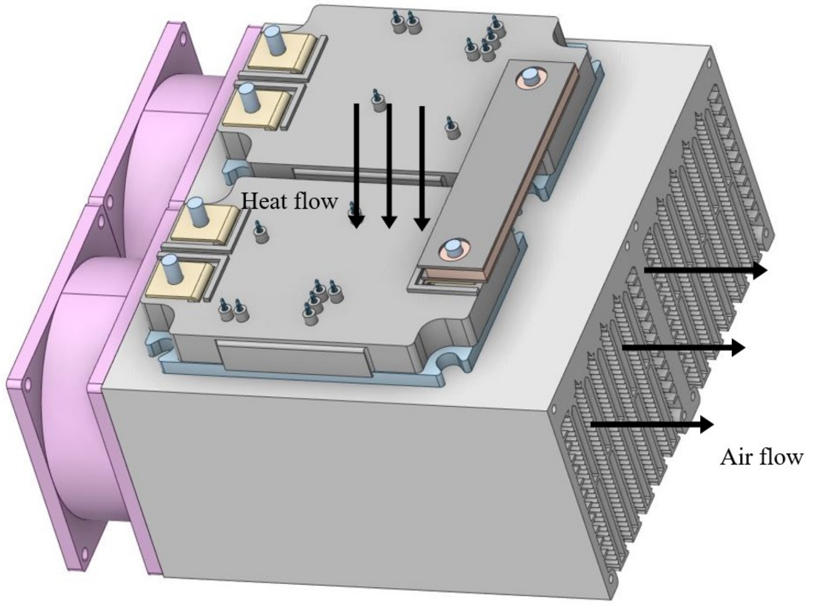


*Losses for different number of MOSFETs in parallel (Devices characteristic at Temp.=125℃)*




| Losses per phase Leg [W] | Conduction losses | Switching losses | Total losses | Efficiency |
|---|---|---|---|---|
| 3 MOSFETs per Switch | 1085.4 | 155.6 | 1241.0 | 98.74% |
| 4 MOSFETs per Switch | 815.1 | 138.4 | 953.5 | 98.98% |
| 5 MOSFETs per Switch | 652.1 | 123.0 | 775.1 | 99.21% |
| 6 MOSFETs per Switch | 541.4 | 115.2 | 656.6 | 99.33% |

# Power modules for MEA: Electro-thermal optimisation




*3D view of forced air-cooled system*

### *Three MOSFETs per switch*

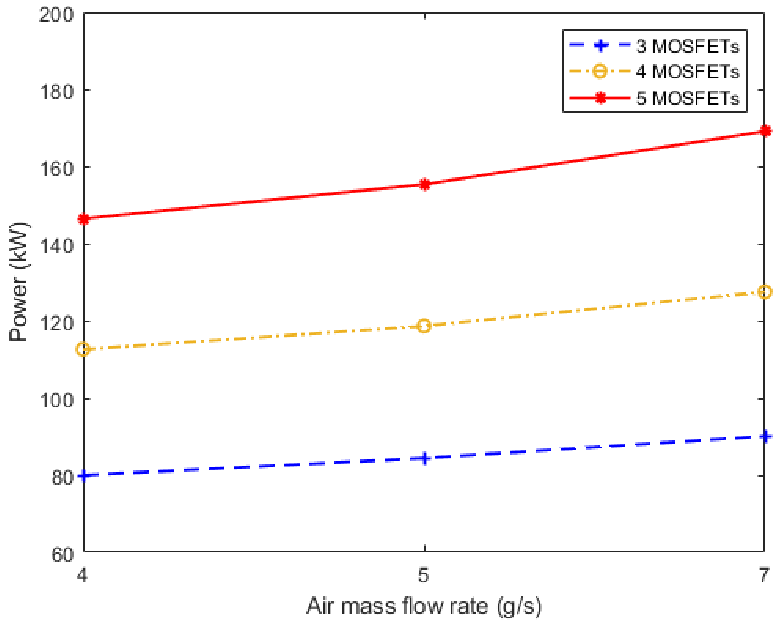
| Temperature (°C) | 4g/s | 5g/s |
|---|---|---|
| Top MOSFETs | 197.4 | 188.9 |
| Bottom MOSFETs | 175.4 | 166.8 |
| Middle MOSFETs | 223.5 | 213.1 |
| Clamping diodes | 150.3 | 141.9 |

### *Four MOSFETs per switch*

| Temperature (°C) | 4g/s | 5g/s |
|---|---|---|
| Top MOSFETs | 152.7 | 146.1 |
| Bottom MOSFETs | 139.5 | 132.5 |
| Middle MOSFETs | 166.0 | 158.8 |
| Clamping diodes | 142.4 | 135.1 |

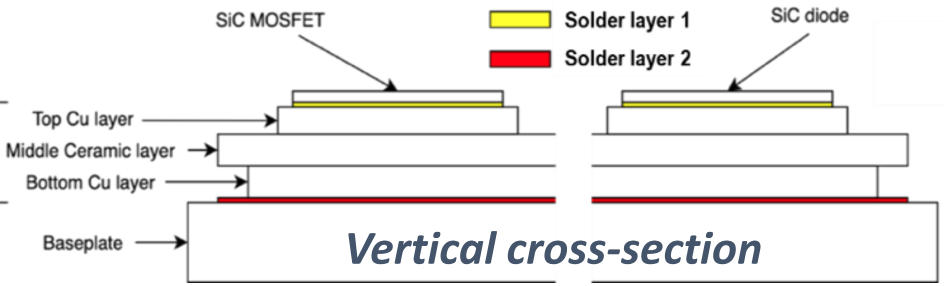
### *Five MOSFETs per switch*

| Temperature (°C) | 4g/s | 5g/s | 7g/s |
|---|---|---|---|
| Top MOSFETs | 124.4 | 118.4 | 110.6 |
| Bottom MOSFETs | 115.9 | 110.0 | 101.9 |
| Middle MOSFETs | 133.0 | 126.8 | 118.9 |
| Clamping diodes | 133.4 | 127.2 | 118.7 |



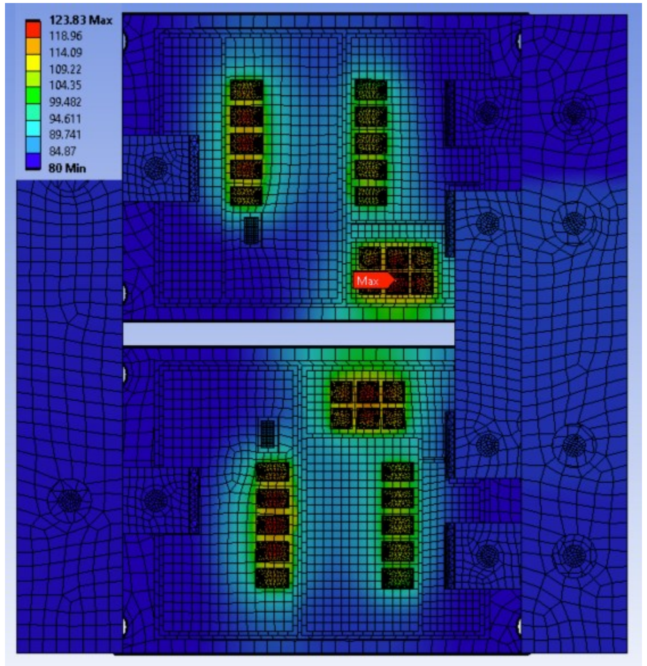

*Achievable power at different flow rates*

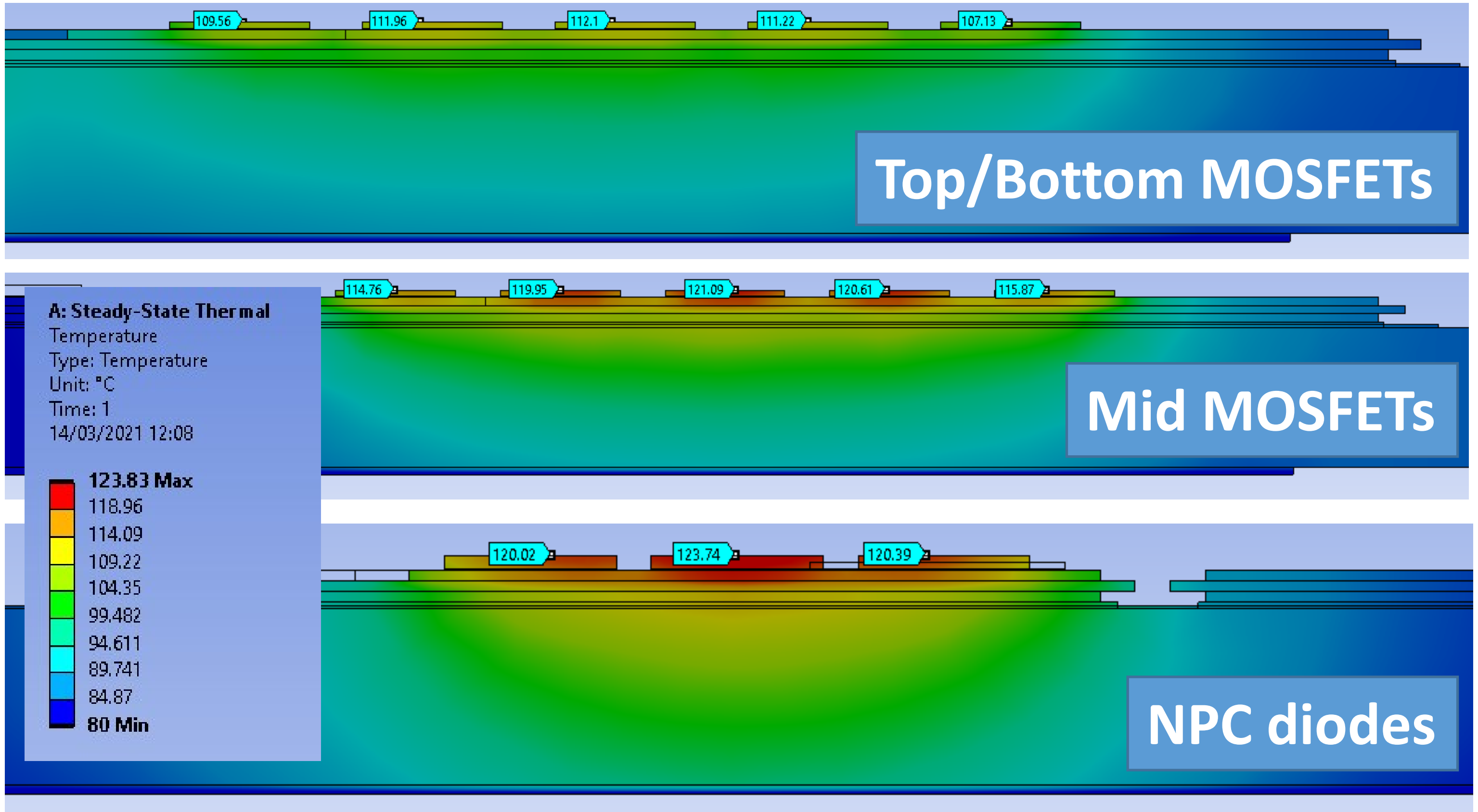
# Power modules for MEA: Electro-thermal optimisation




*Vertical cross-section*

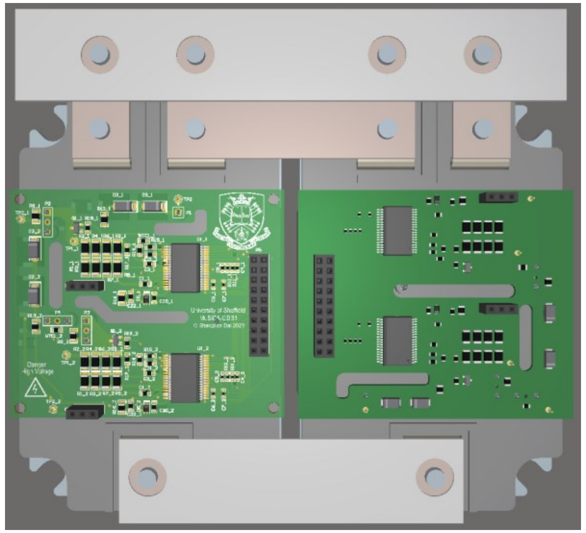
Max temperature increase at full load = 44°C



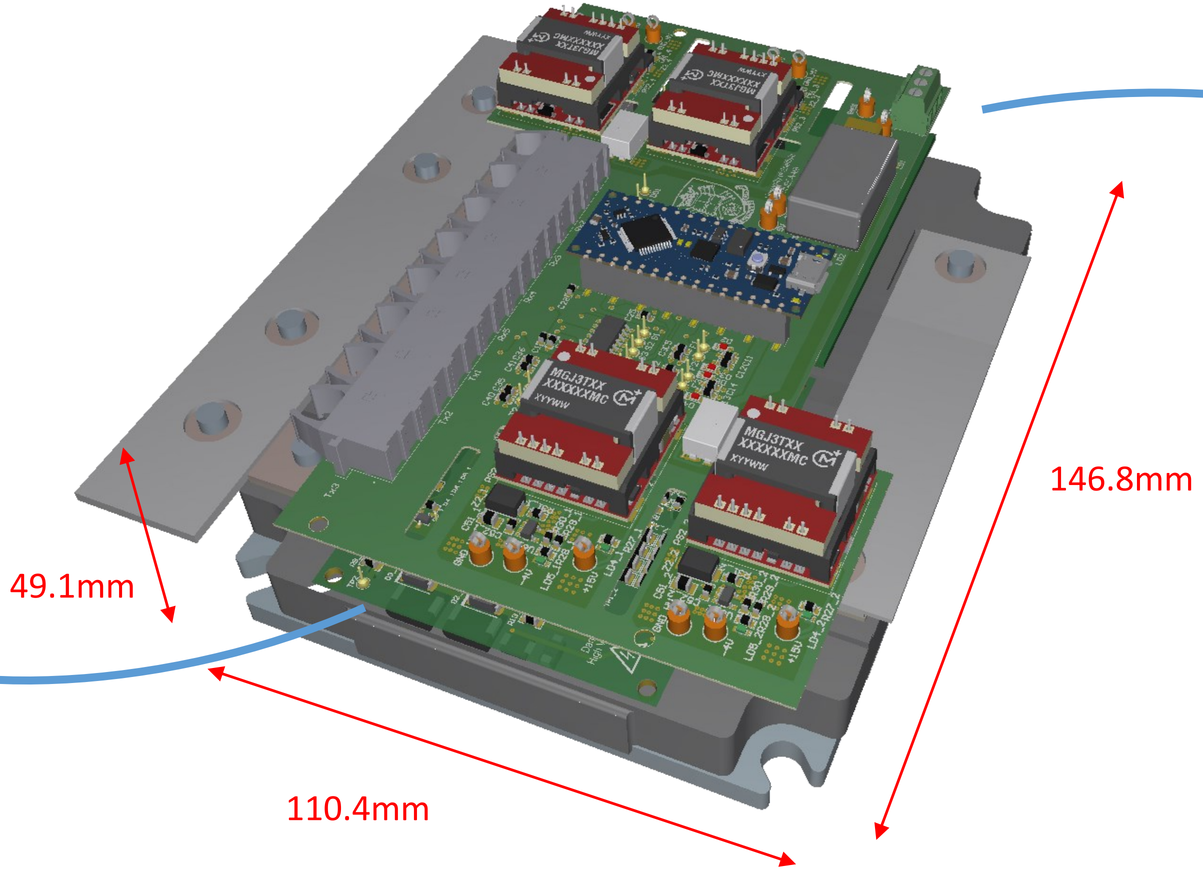




*temperature distribution*

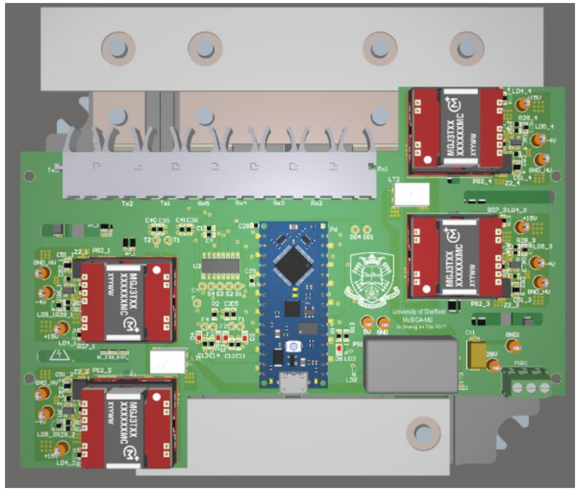
# Power modules for MEA: Gate drives



Sub-gate drive boards

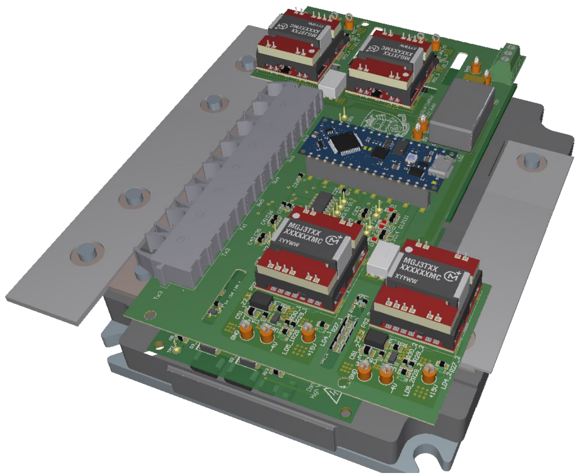



Master board

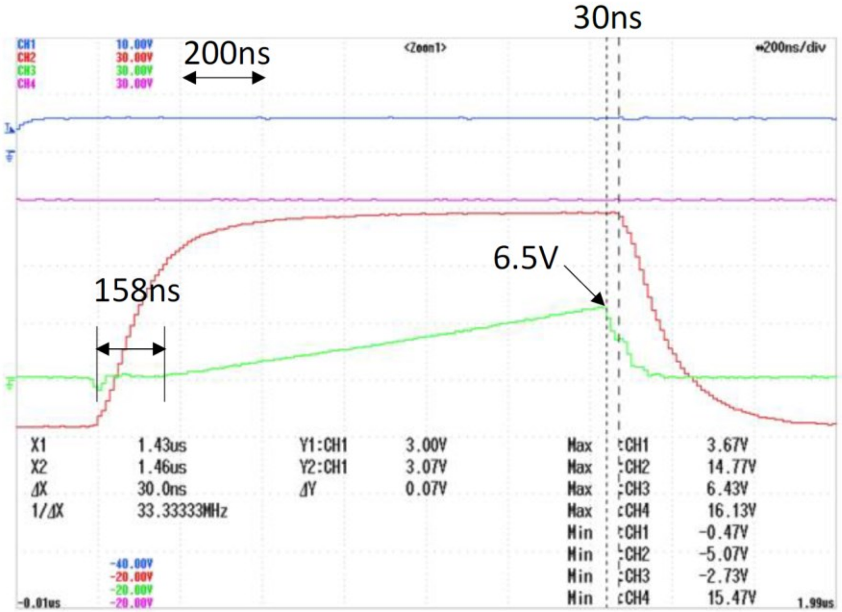


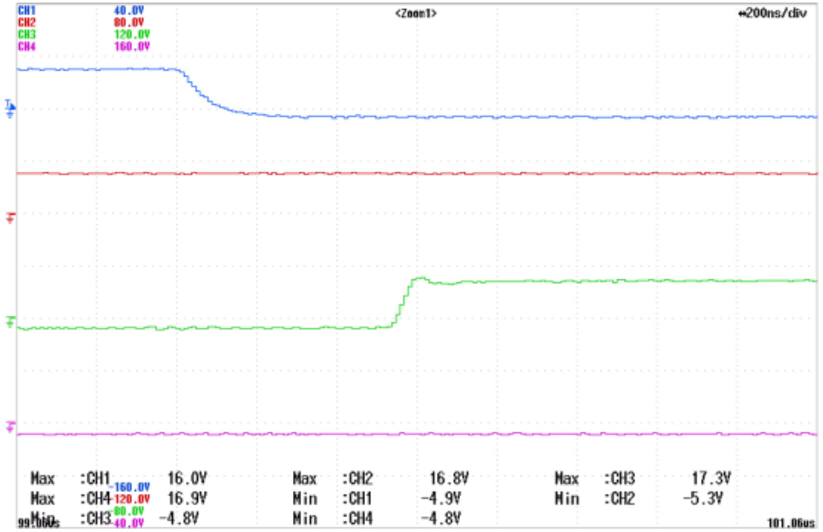
Total cuboid volume=0.8L

# Power modules for MEA: Gate drives

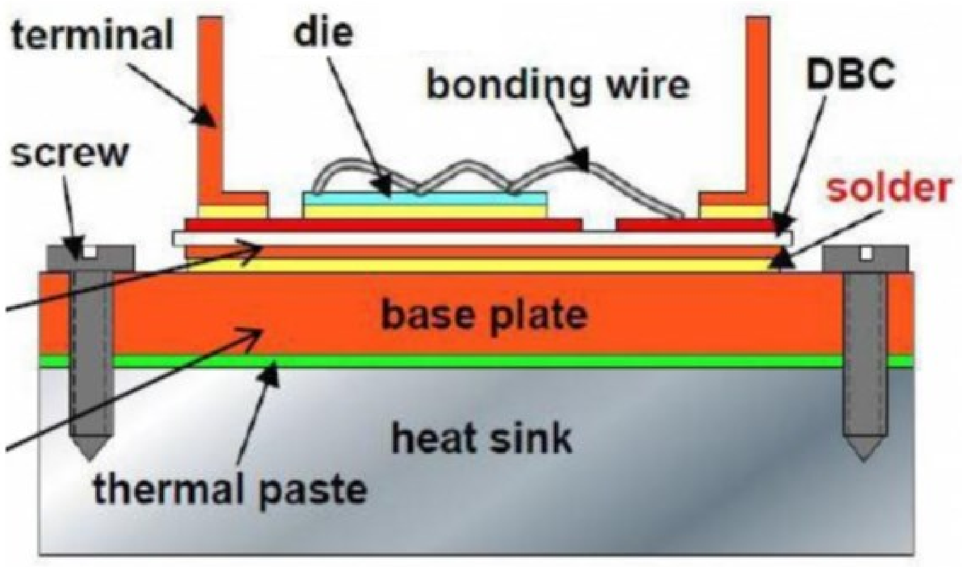


- Programmable gate drive
- $-4, +15V$
- 30A peak at 50kHz
- Programmable short circuit protection, desaturation detection $V_{ds,th} = 6.5V \ (I_{sc} = 1346A); \ 400 - 1000ns$
- Hardware deadtime $105ns$ – 4445ns with the step of 70ns

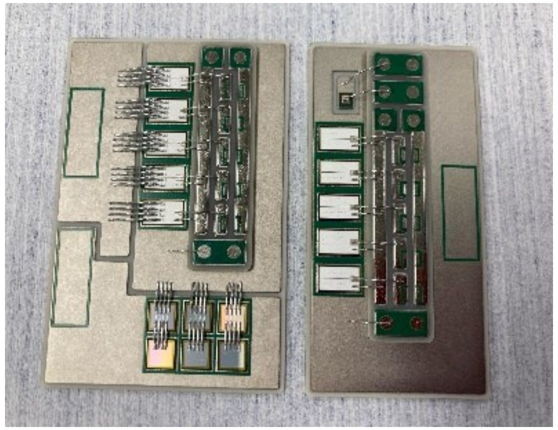


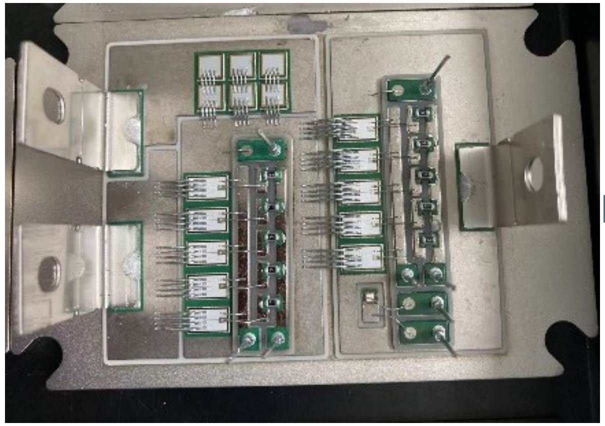
# Power modules for MEA: packaging



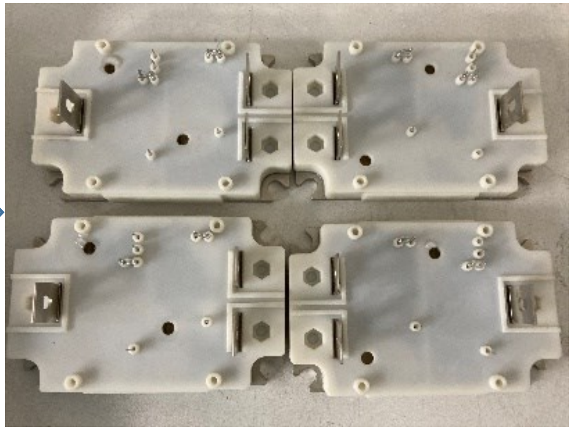

- Gen3 SiC MOSFET from Wolfspeed
- Si3N4 active metal brazed (AMB) substrate
- AlSiC baseplate (air cooling)
- High temperature grade silicon gel (-50 to 150 °C)
- Vacuum solder reflowing for die attach & sub attach
- Wire bonding & soldered terminals



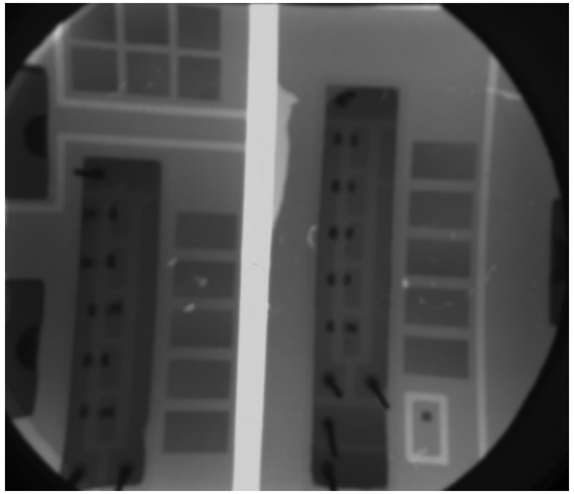
Die attach & wire bonding



Substrate attach & terminal bonding

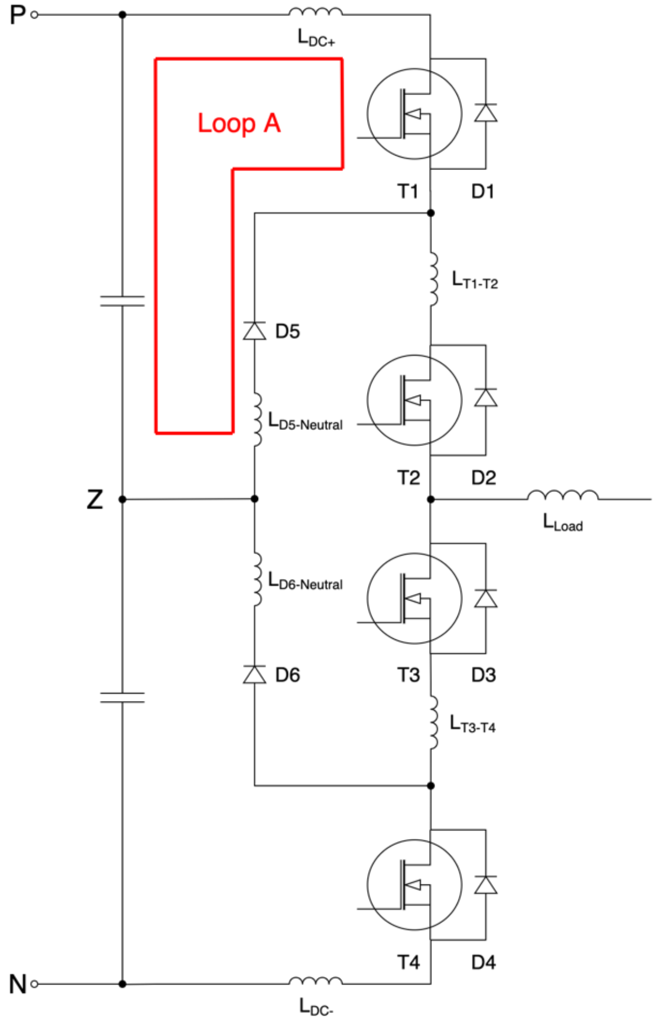


Housing & encapsulation



X-ray transmission image

# Power modules for MEA: parasitics

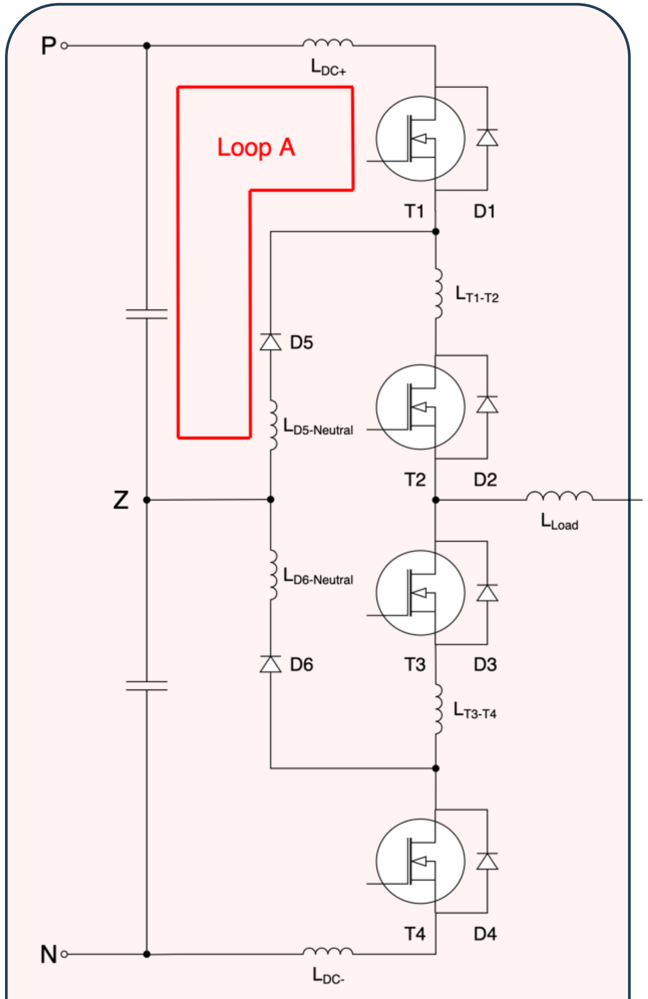



Fast-switching transients of SiC devices result in high current gradients $di/dt$, which can be over an order of magnitude higher than those of conventional Si devices.

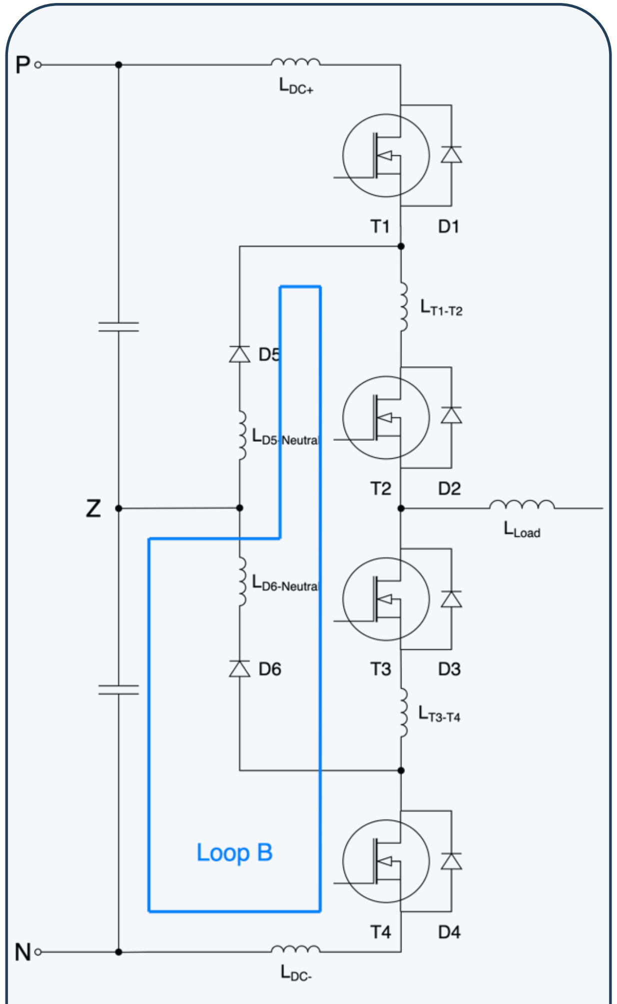
Fast current transients during switch commutation result in over-voltages $L \cdot di/dt$ due to parasitic inductances

- electrical stress and potential reduction in the safe operating area of devices,
- reduced reliability
- increased electromagnetic interference (EMI) emissions

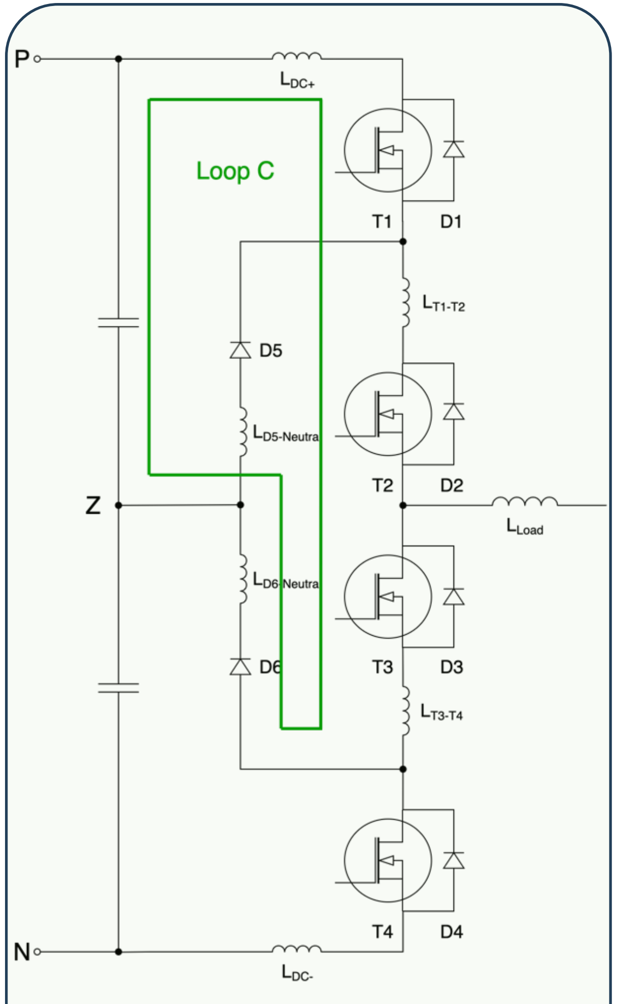
# Power modules for MEA: parasitics



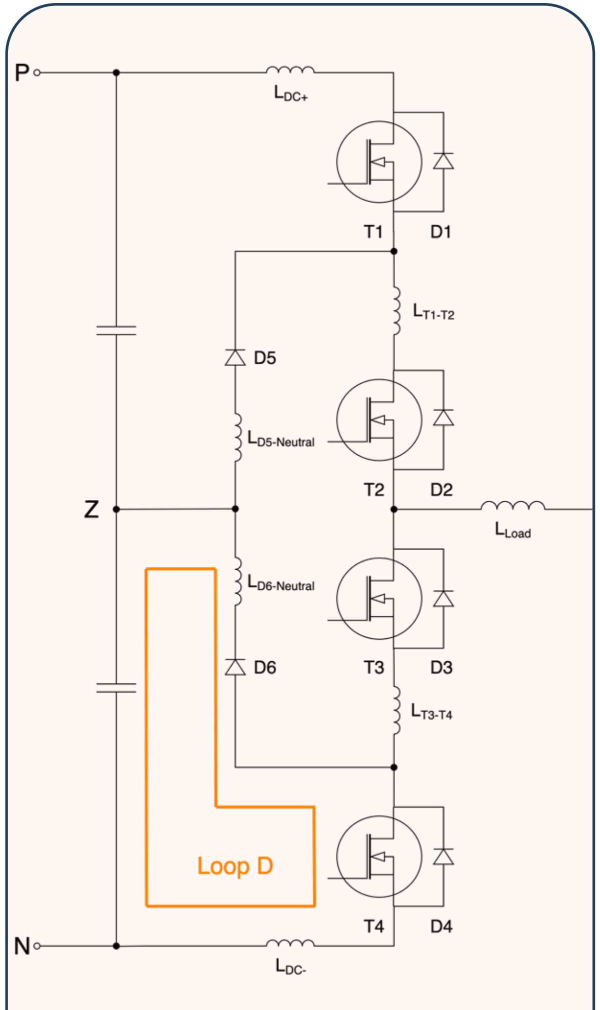

Small loop A




Large loop B

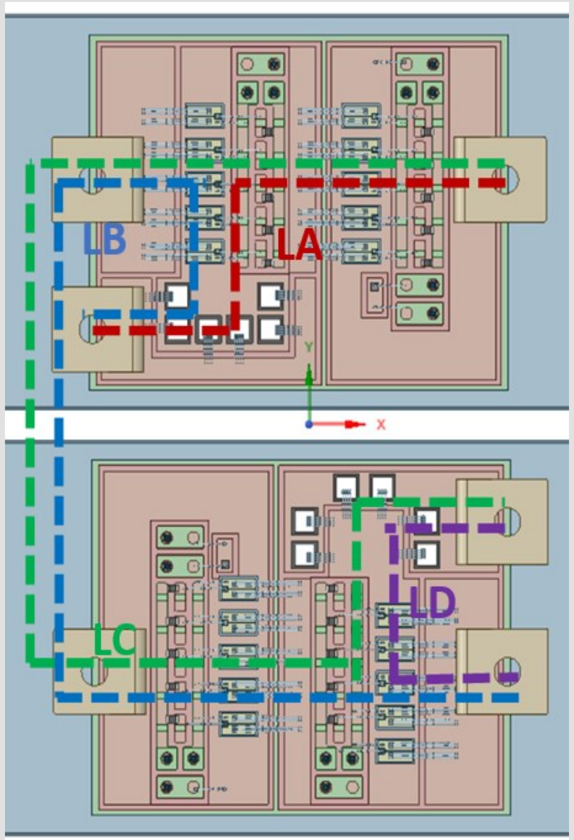



Large loop C

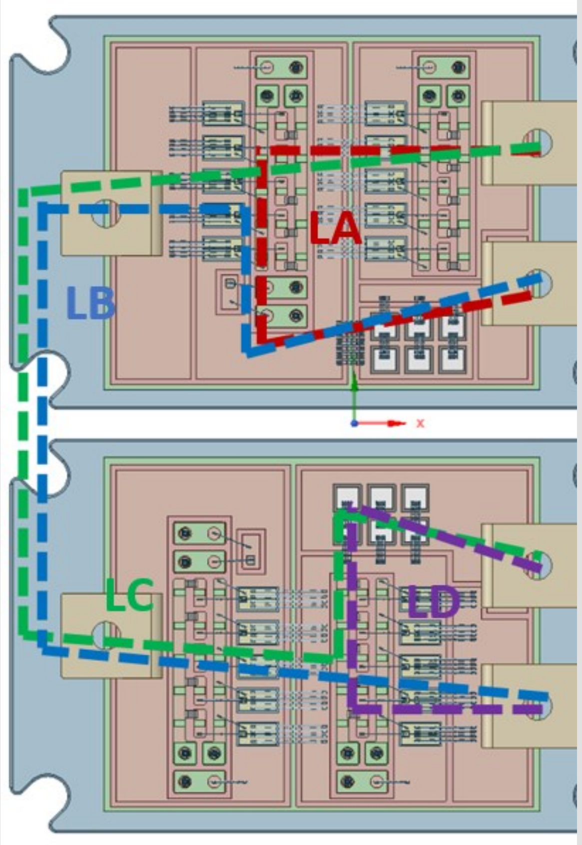



Small loop D

# Power modules for MEA: parasitics

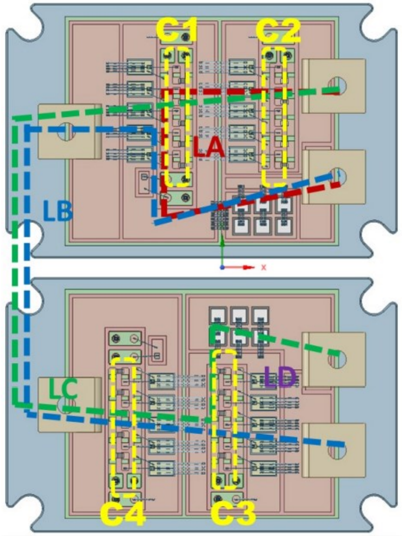



Asymmetrical




Symmetrical

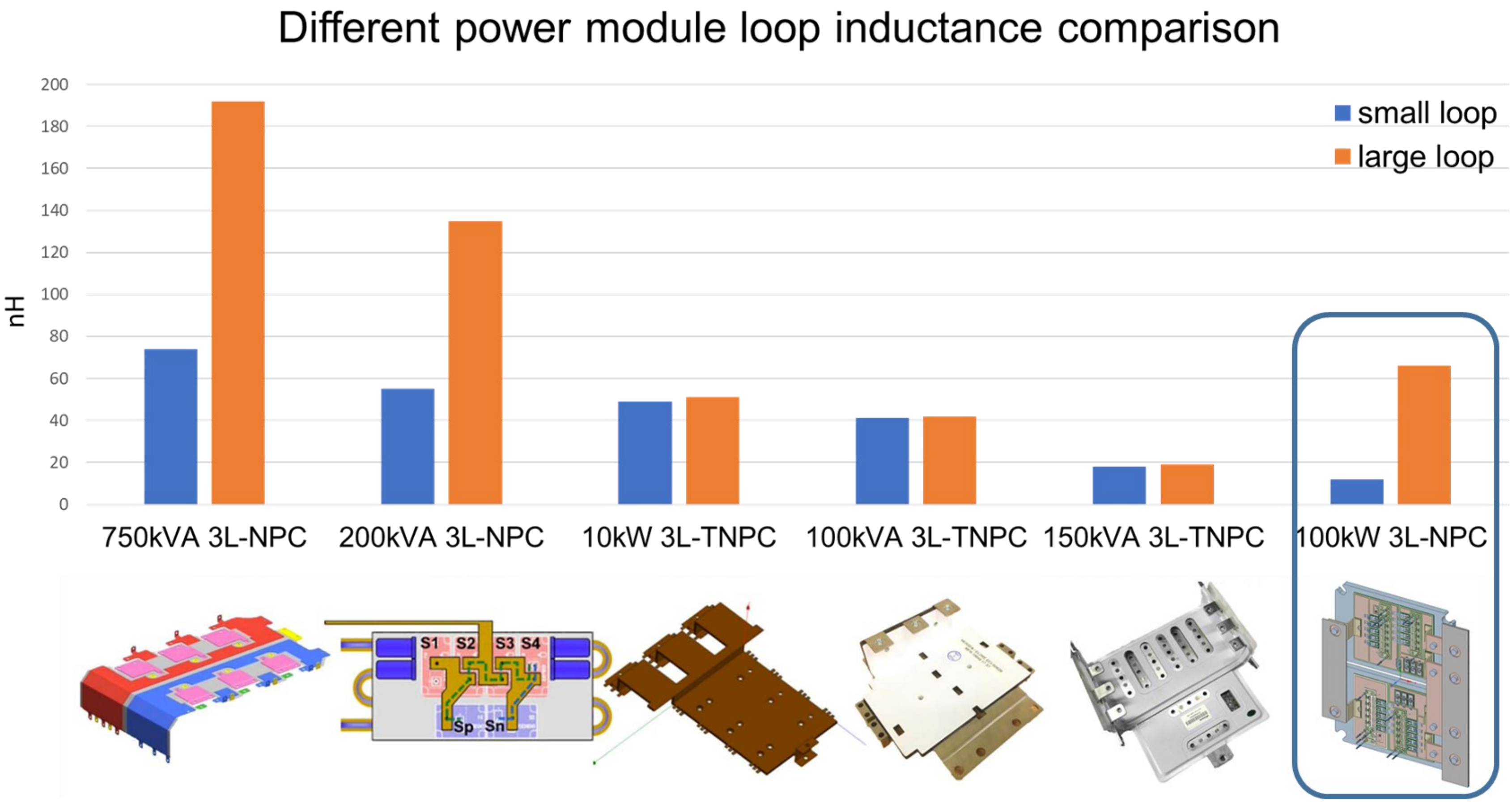
| Design | Loop A | Loop B | Loop C | Loop D |
|---|---|---|---|---|
| Asymmetrical | 22.2nH | 68.5nH | 76.9nH | 9.3nH |
| Symmetrical | 11.1nH | 75.3nH | 74.6nH | 9.9nH |



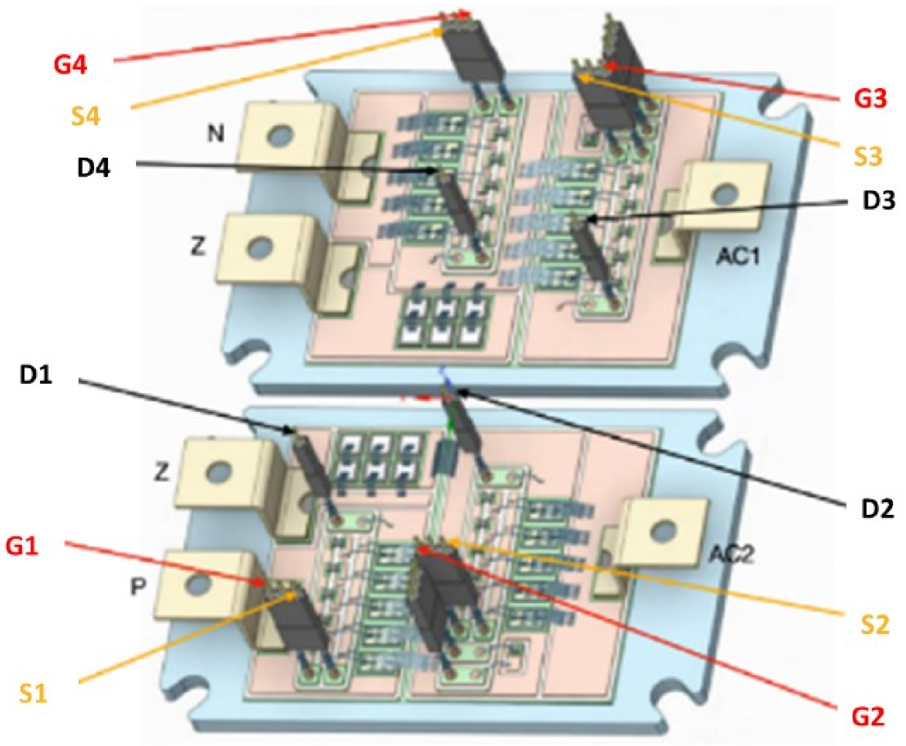

Minimization of coupling between current and control loops

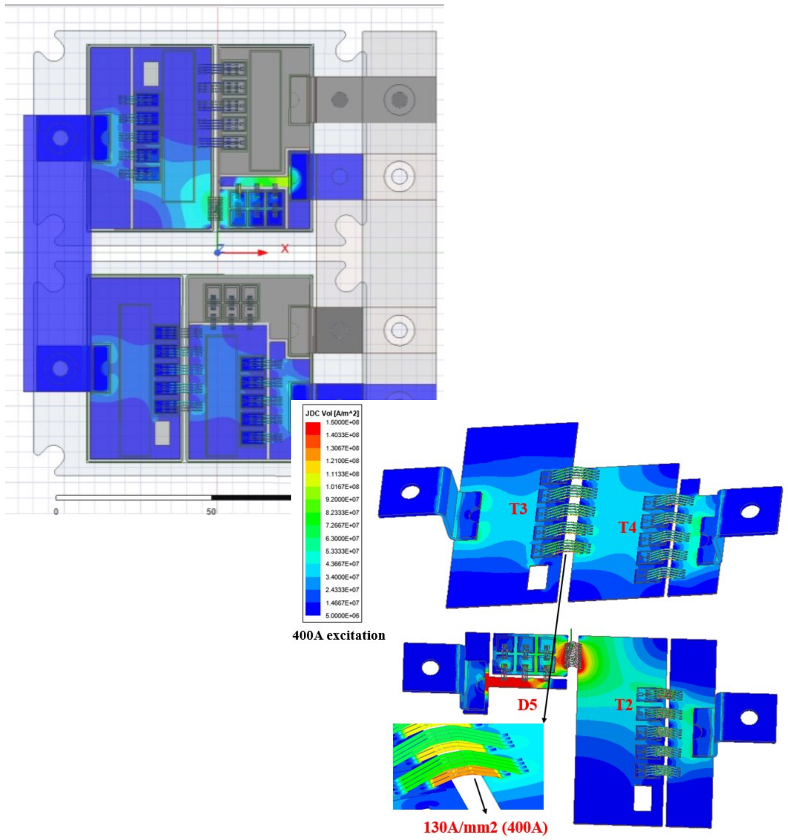
| Control Loops | Self-inductance | Mutual inductance | |
|---|---|---|---|
| C1 | 17.09nH | LA | 0.16 |
| | | LC | 0.93 |
| C2 | 16.95nH | LA | 0.48 |
| | | LC | 0.97 |
| C3 | 17.15nH | LA | 0.03 |
| | | LC | 0.70 |
| C4 | 17.06nH | LA | 0.03 |
| | | LC | 0.78 |

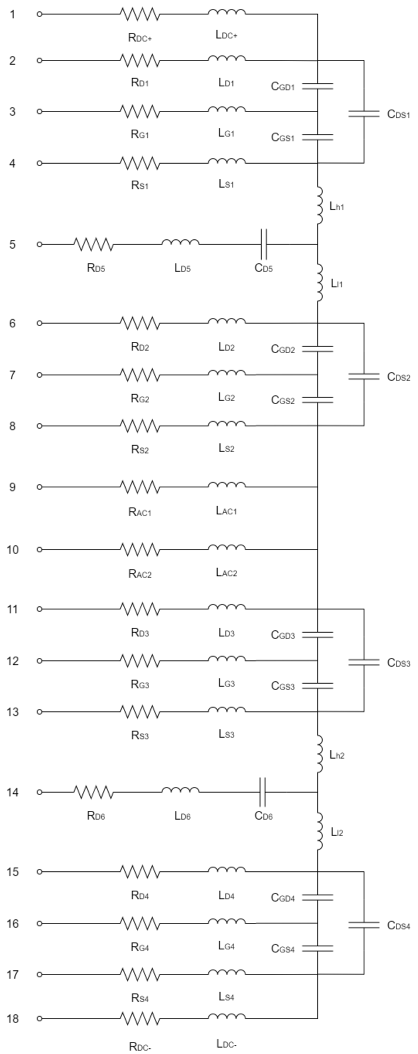
# Power modules for MEA: parasitics



# Power modules for MEA: parasitics




Power module commutation inductances can be calculated using analytical tools

- method of moments e.g. Ansys Q3D
- Direct measurement is difficult in complex structure e.g. multi-level modules and is not possible in assembled modules

# Power modules for MEA: parasitics

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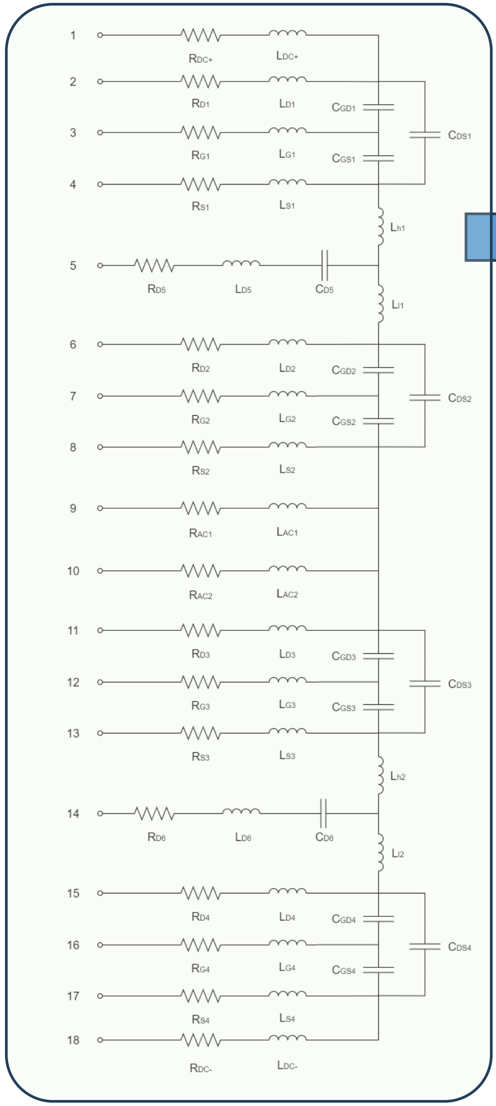
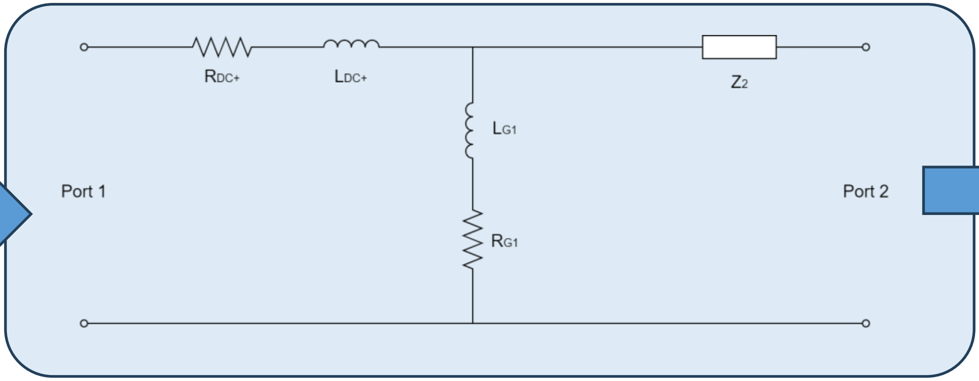
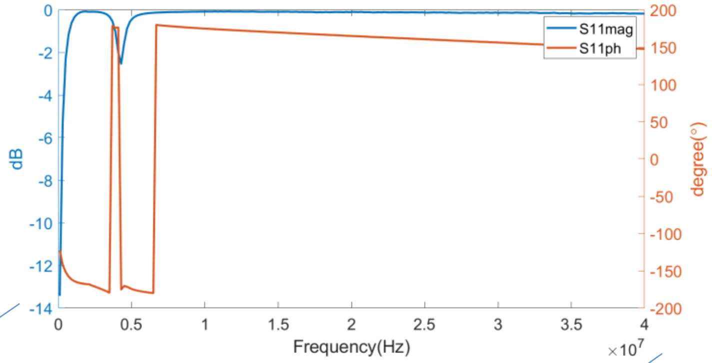
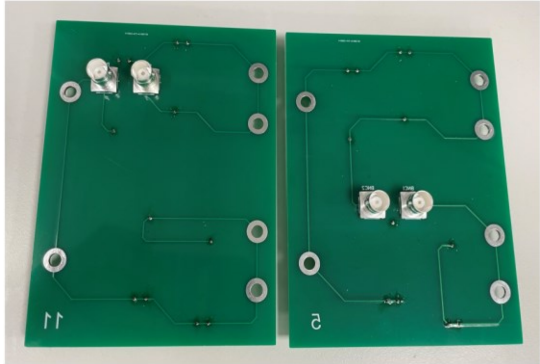


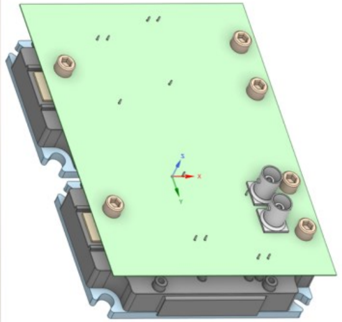




to measure all the parasitic inductances of each branch, the small signal model can be subdivided in **16 two-port networks**

Measure S-parameters with VNA





- two-port 'Short-Open-Load-Thru' calibration to eliminate the effects caused by the cable
- decoupling PCBs for the measurement of the PCB parasitics

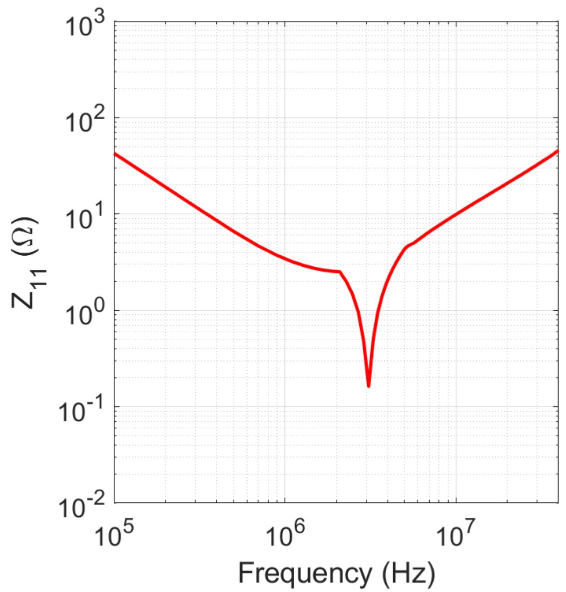
# Power modules for MEA: parasitics

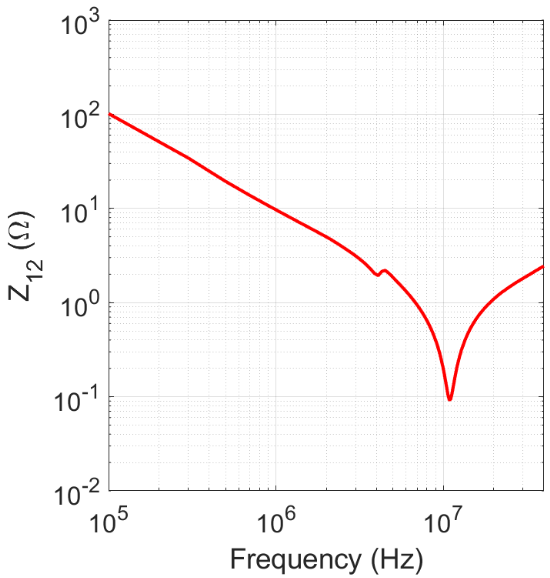
S parameters → 

$$Z_{11} = \left[\frac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{(1-S_{11})(1-S_{22})-S_{12}S_{21}}\right]Z_0$$

$$Z_{12} = \left[\frac{2S_{12}}{(1-S_{11})(1-S_{22})-S_{12}S_{21}}\right]Z_0$$

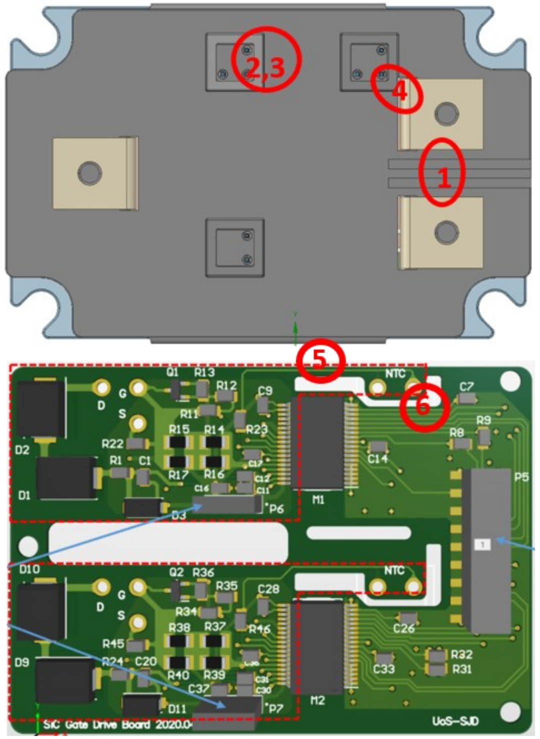
→ R,L,C

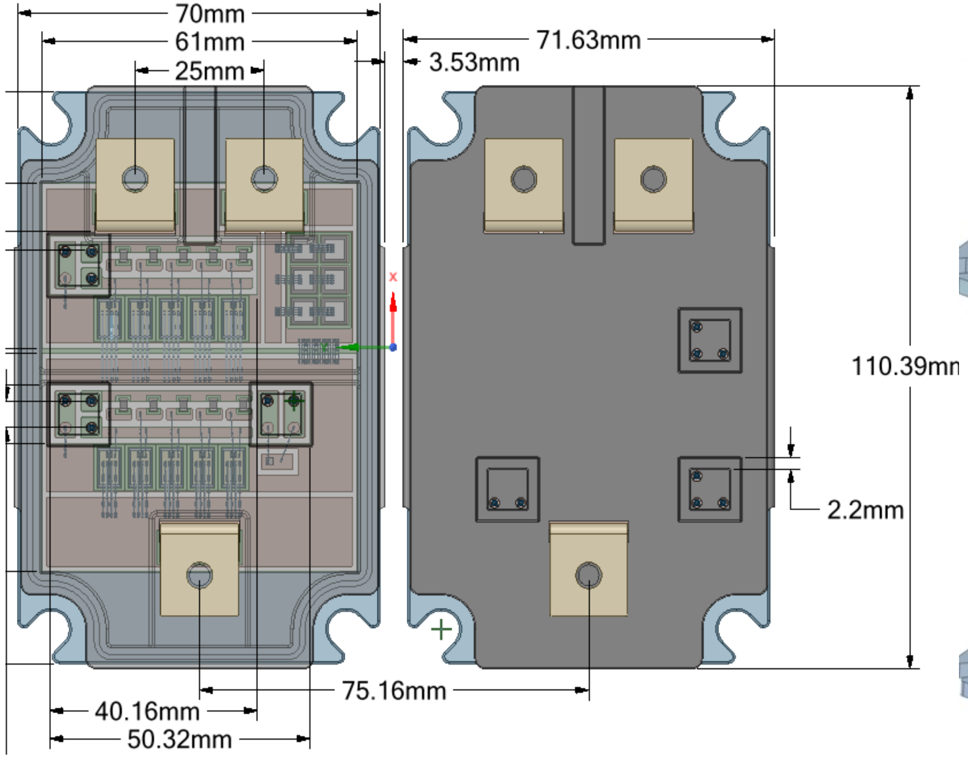


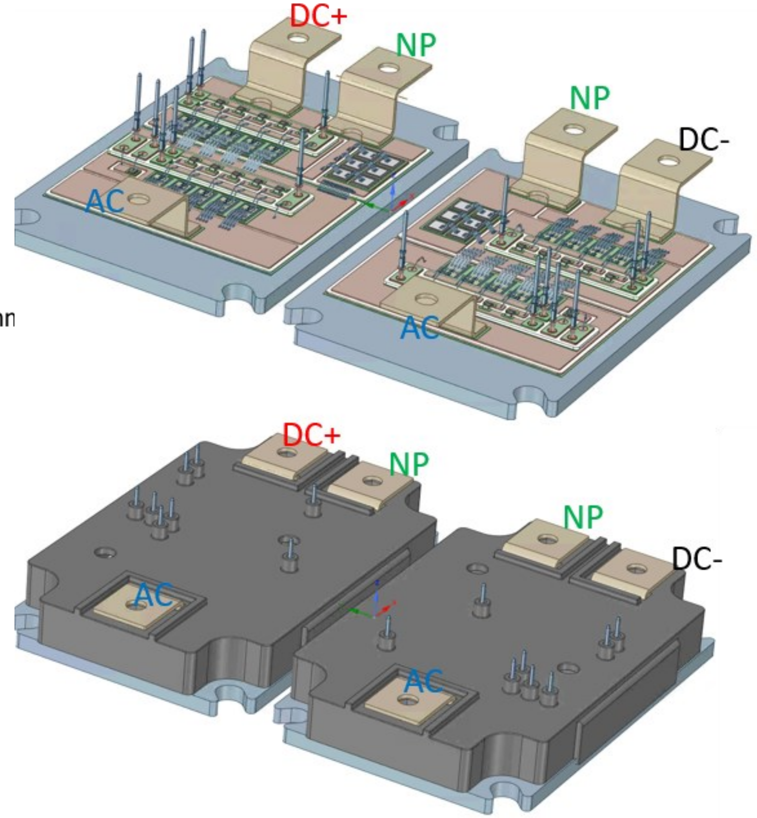




| Parasitic inductance | Simulation (nH) | Measurement (nH) | %difference |
|---|---|---|---|
| D1 (T1 MOSFET) | 20.61 | 22.49 | 8.7% |
| G1 (T1 MOSFET) | 22.64 | 20.97 | 7.6% |
| S1 (T1 MOSFET) | 20.71 | 20.53 | 0.9% |
| D2 (T2 MOSFET) | 20.74 | 20.78 | 0.2% |
| G2 (T2 MOSFET) | 21.92 | 19.94 | 9.5% |
| S2 (T2 MOSFET) | 20.72 | 21.28 | 2.7% |
| D3 (T3 MOSFET) | 21.27 | 23.11 | 8.3% |
| G3 (T3 MOSFET) | 22.64 | 23.31 | 2.9% |
| S3 (T3 MOSFET) | 20.67 | 20.72 | 0.2% |
| D4 (T4 MOSFET) | 20.62 | 21.88 | 5.9% |
| G4 (T4 MOSFET) | 22.59 | 22.95 | 1.6% |
| S4 (T4 MOSFET) | 20.72 | 21.08 | 1.7% |
| DC+ | 9.58 | 10.16 | 5.9% |
| DC- | 7.75 | 8.25 | 6.3% |
| AC1 | 7.72 | 8.46 | 9.1% |
| AC2 | 9.11 | 9.74 | 6.7% |
| D5 (Clamping diode) | 11.82 | 10.99 | 7.3% |
| D6 (Clamping diode) | 11.89 | 12.87 | 7.9% |

# Power modules for MEA: packaging



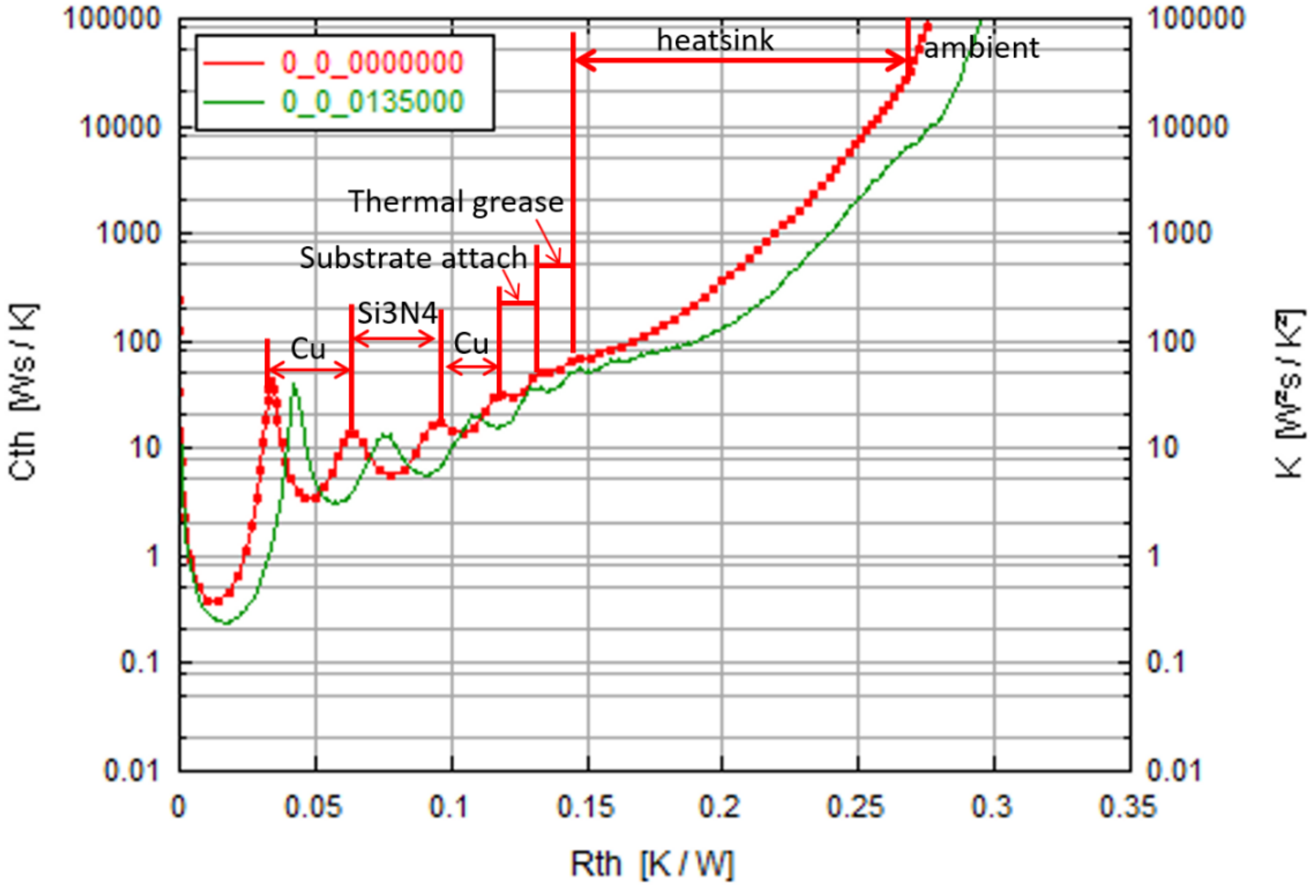




- clearance and creepage for high altitude
  - IEC 60664 derating factors x3.02 for 10,000m

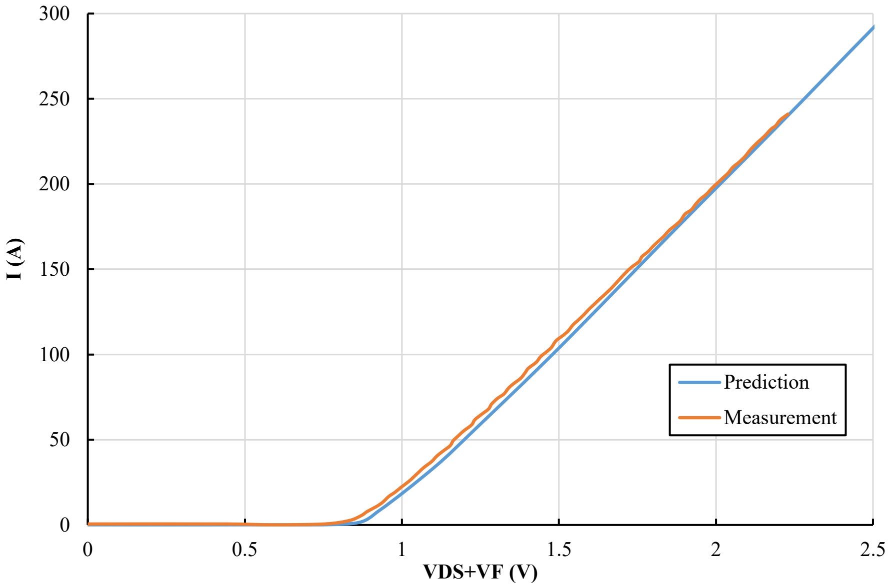
**final power module design**

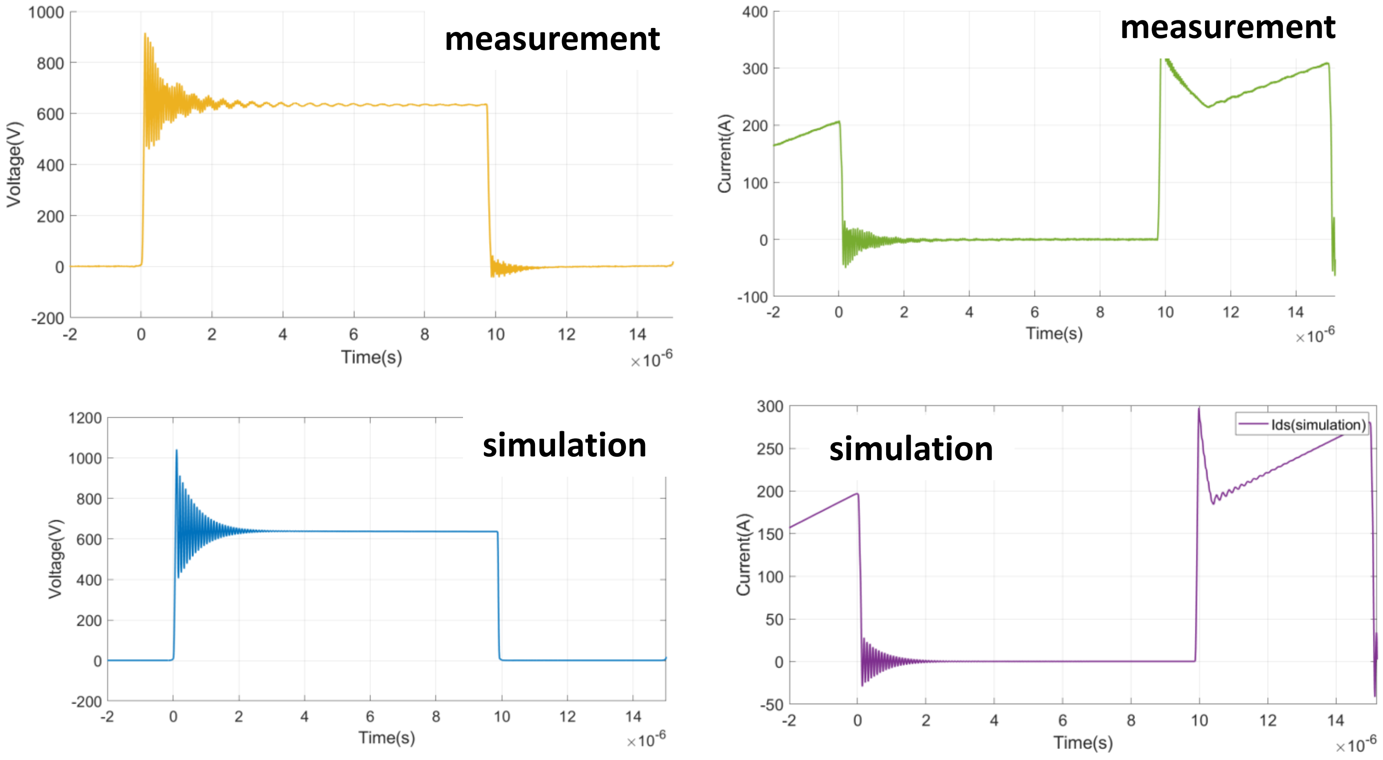
# Power modules for MEA: reliability




- High reliability demonstrated
- >135000 power cycles
- >100 cycles of thermal shock
- No obvious changes in the output characteristics of dies after 100cycles

# Power modules for MEA: measurements

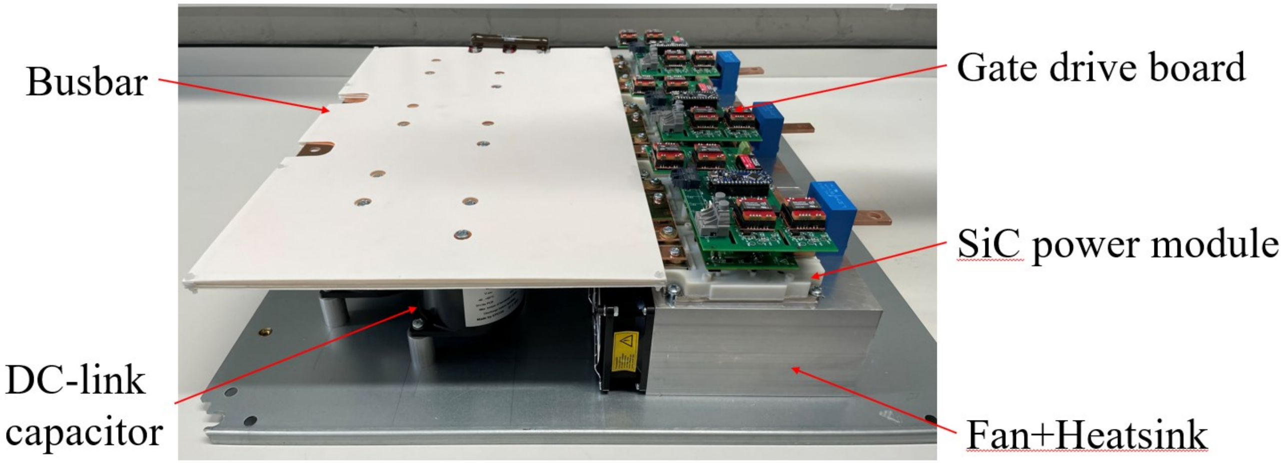



| | Oscillation frequency (MHz) | Maximum voltage (V) |
|---|---|---|
| T1(experiment) | 15.8 | 807 |
| T1(simulation) | 15.6 | 812 |
| T2(experiment) | 12.7 | 920 |
| T2(simulation) | 11.2 | 1020 |
| T3(experiment) | 13.0 | 960 |
| T3(simulation) | 11.5 | 1063 |
| T4(experiment) | 16.4 | 779 |
| T4(simulation) | 17.2 | 785 |

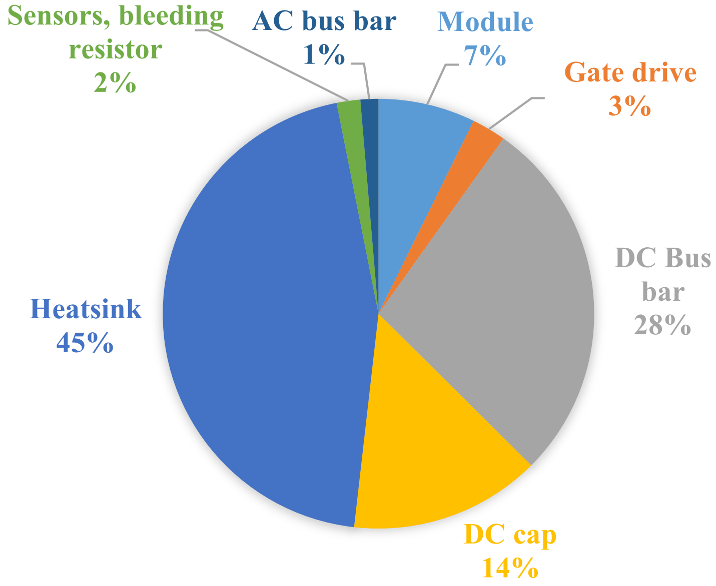
Models predict both static and dynamic characteristics accurately

# Power modules for MEA: converter



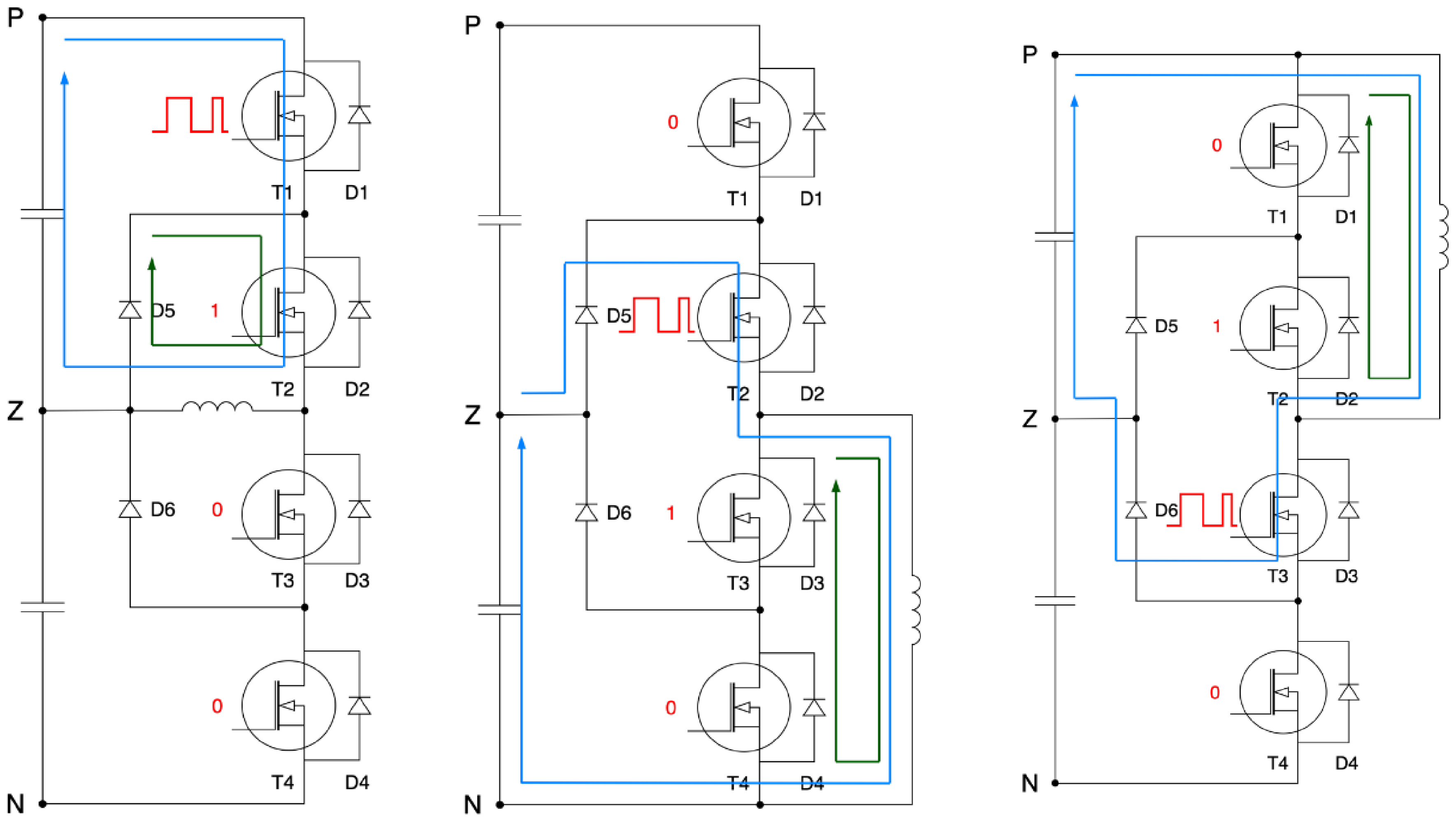

- Total weight 18.6kg.
- Assuming a nominal power of 350kW → power density of 18.8kW/kg.

- Over 45% of the total mass is due to the cooling system and a further 42% due to DC busbars and Caps.
  - Since these were not the main focus of the project, no particular optimisation of the cooling system and DC link has been performed




Weight breakdown of the converter prototype (the total weight is 18.6kg, excluding the enclosure and cables).

# Power modules for MEA: converter tests



# Power modules for MEA: converter tests

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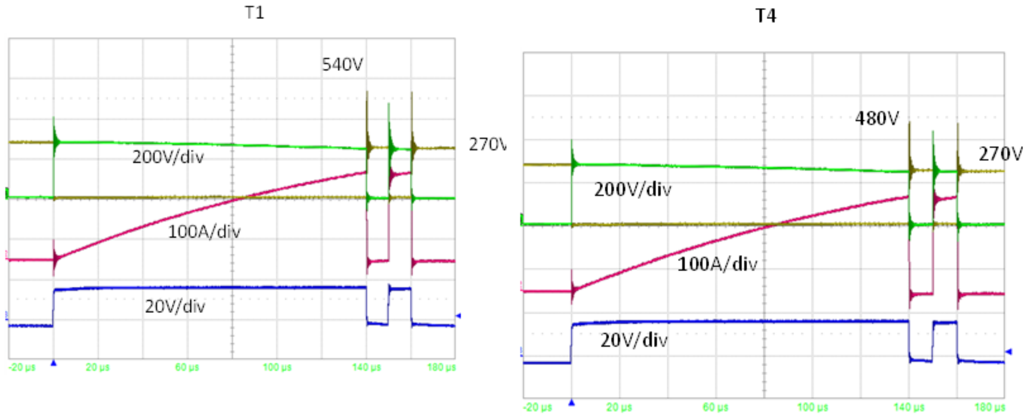



Fig. 20 Double pulse test for the outer switches T1 (left) and T4 (right)
Yellow: Vds of switch, Green: voltage of complimentary diode, Purple: drain current, Blue: Vgs

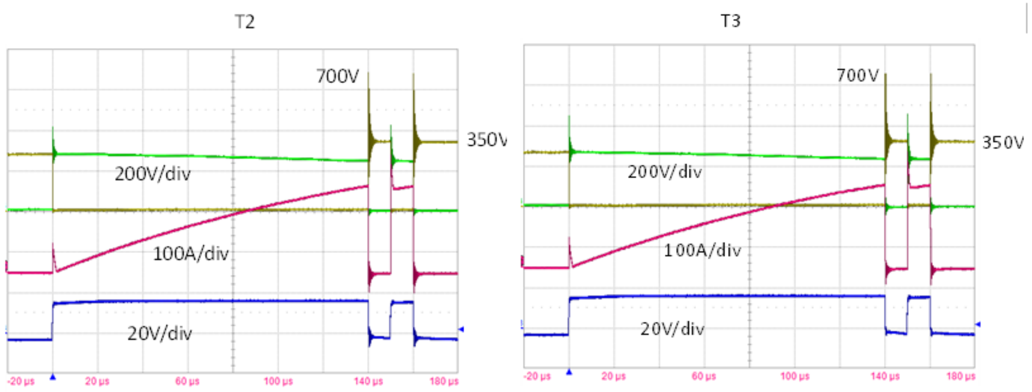
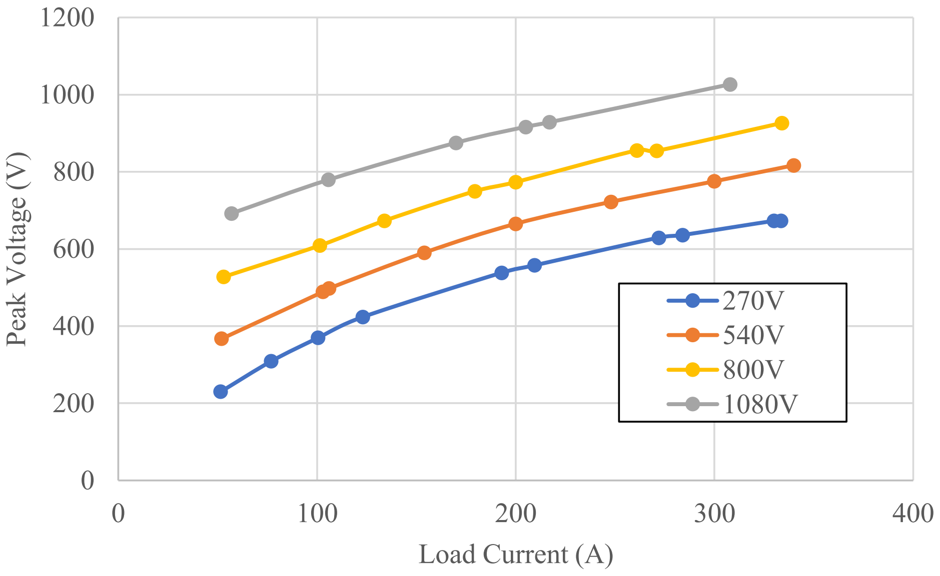


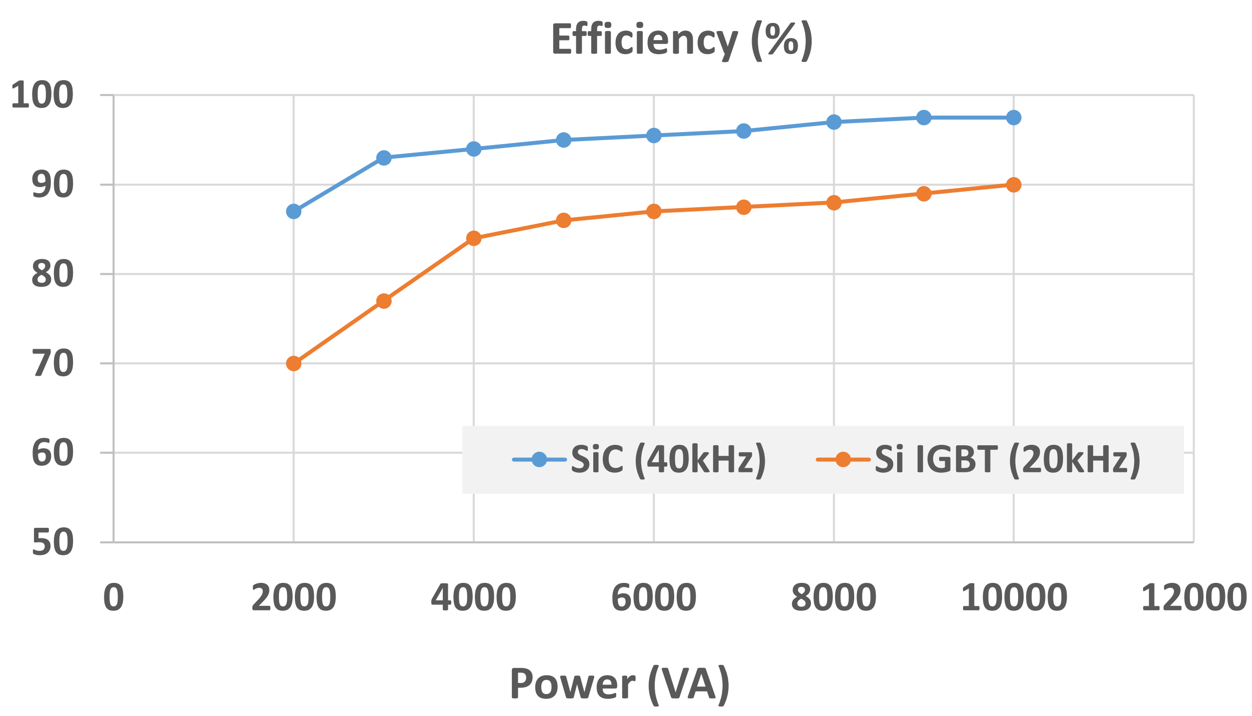

Fig. 21 Double pulse test for the inner switches T2 (left) and T3 (right)
Yellow: Vds of switch, Green: voltage of complimentary diode, Purple: drain current, Blue: Vgs

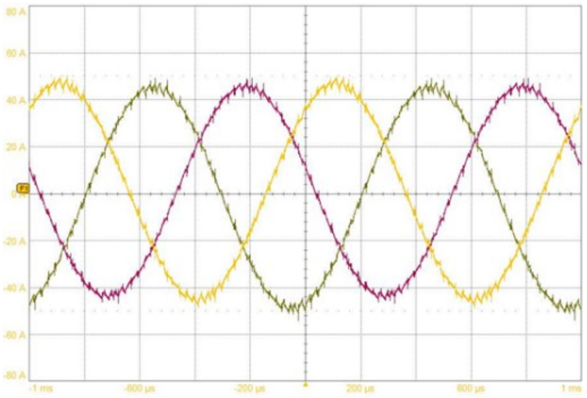


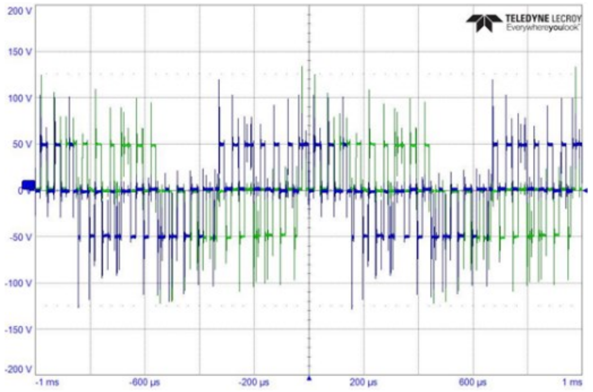

SWITCHING LOSSES

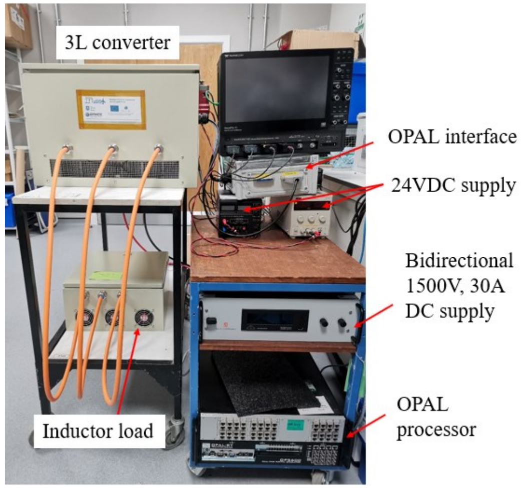
| Devices | 800V/300A | | 1080V/200A | |
|---|---|---|---|---|
| | Turn-on | Turn-off | Turn-on | Turn-off |
| T1 | 1.6mJ | 4.5mJ | 2.6mJ | 3.9mJ |
| T2 | 1.3mJ | 5.3mJ | 1.7mJ | 4.3mJ |
| T3 | 1.4mJ | 4.6mJ | 1.3mJ | 4.0mJ |
| T4 | 1.5mJ | 3.3mJ | 2.9mJ | 3.4mJ |

# Power modules for MEA: converter tests







# Conclusion

- WBG Power electronics will be crucial for electrification of aviation and enabling the MEA/AEA
- Analyses of optimal topologies and devices selection require detailed Multiphysics tools including electrical and thermal analsys
- Multi-level topologies will be essential in future MEA power systems as the voltages increase beyond 270V
- First $400A, 2.6m\Omega$, three-level NPC fully SiC module demonstrated

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Jingru Dai, Yangang Wang, Anne Harry, **Dynex Semiconductors**

Power through Innovation

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