The role of power electronics and drive systems in the modern all-electric and digital society – from airplanes to datacenters

ETH Seminar, January 24th, 2020

Robert Pilawa-Podgurski
University of California, Berkeley
pilawa@berkeley.edu

Berkeley | EECS
Electrical Engineering and Computer Sciences

Acknowledgment

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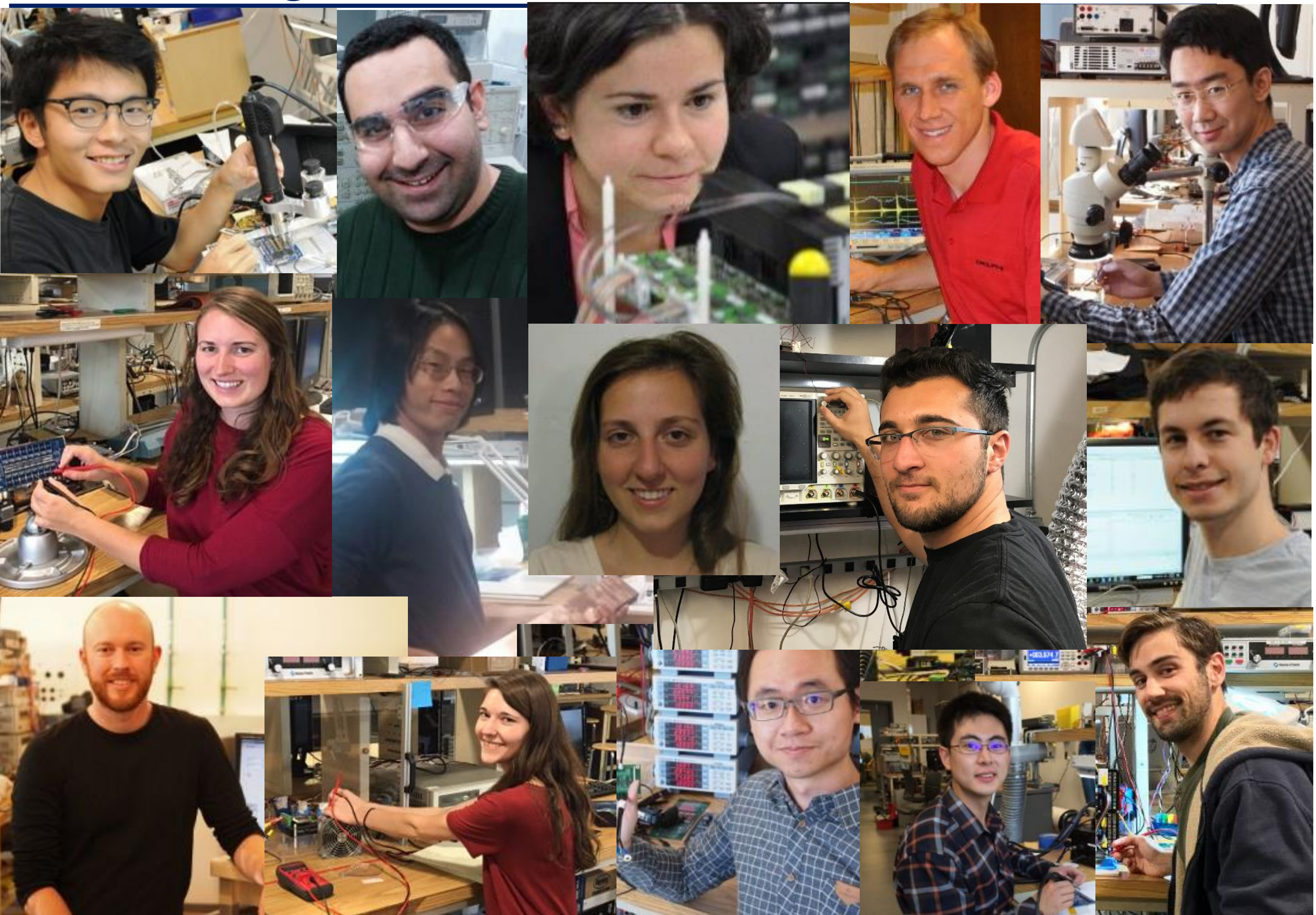
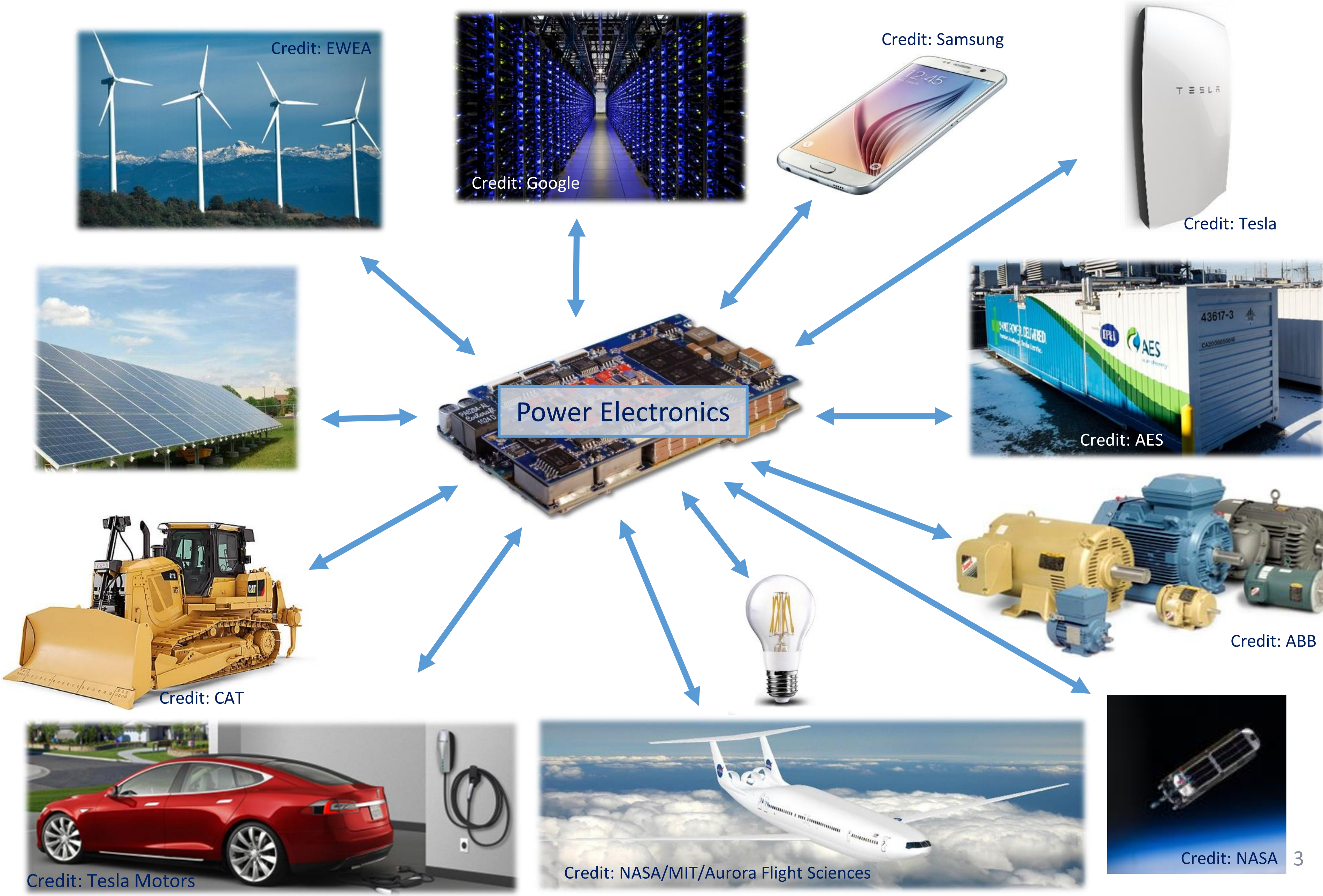


The Role of Power Electronics



The Goal of Power Electronics

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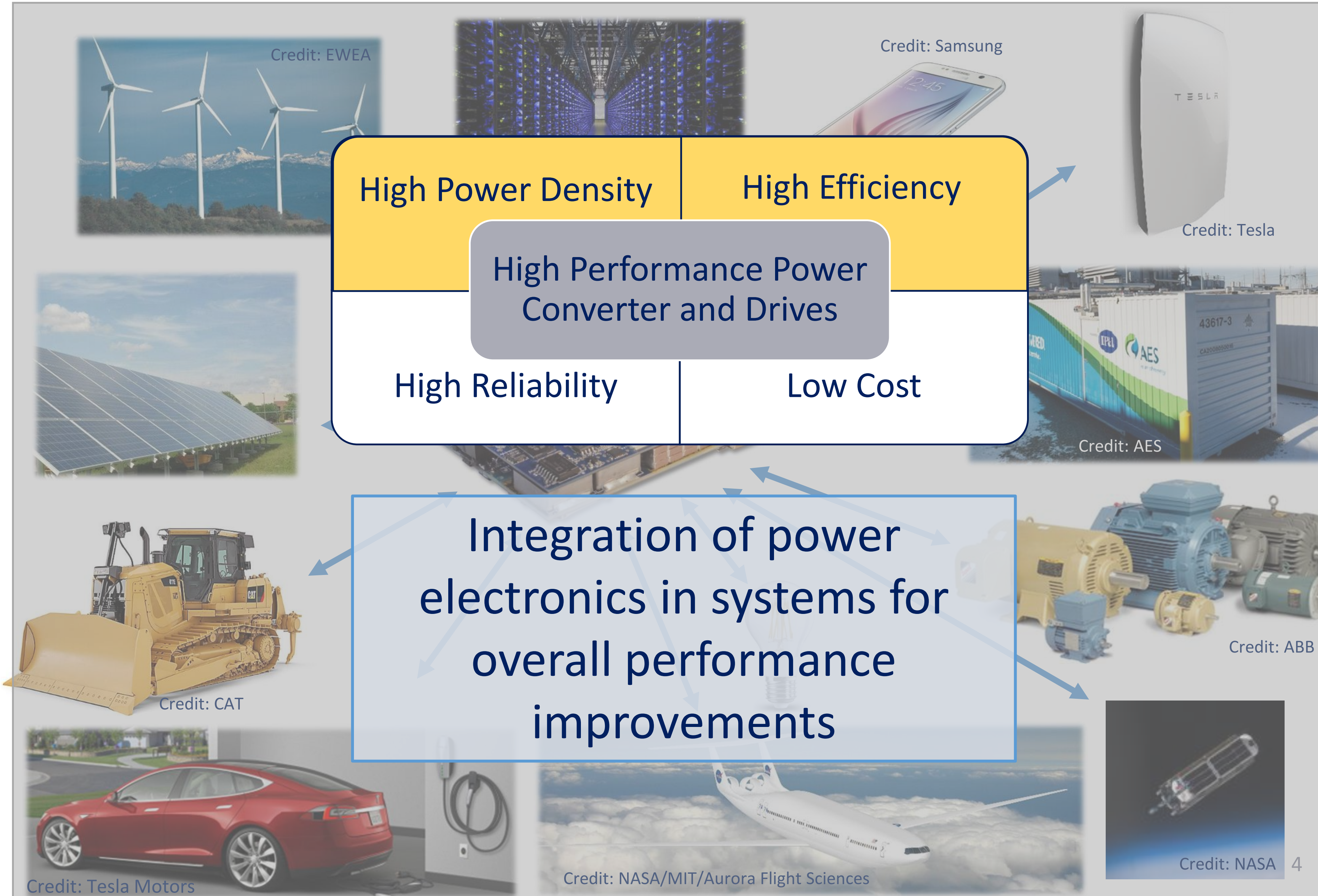

High Power Density	High Efficiency
High Reliability	Low Cost

High Performance Power Converter and Drives

Integration of power electronics in systems for overall performance improvements

Integration of Power Electronics – Example 1

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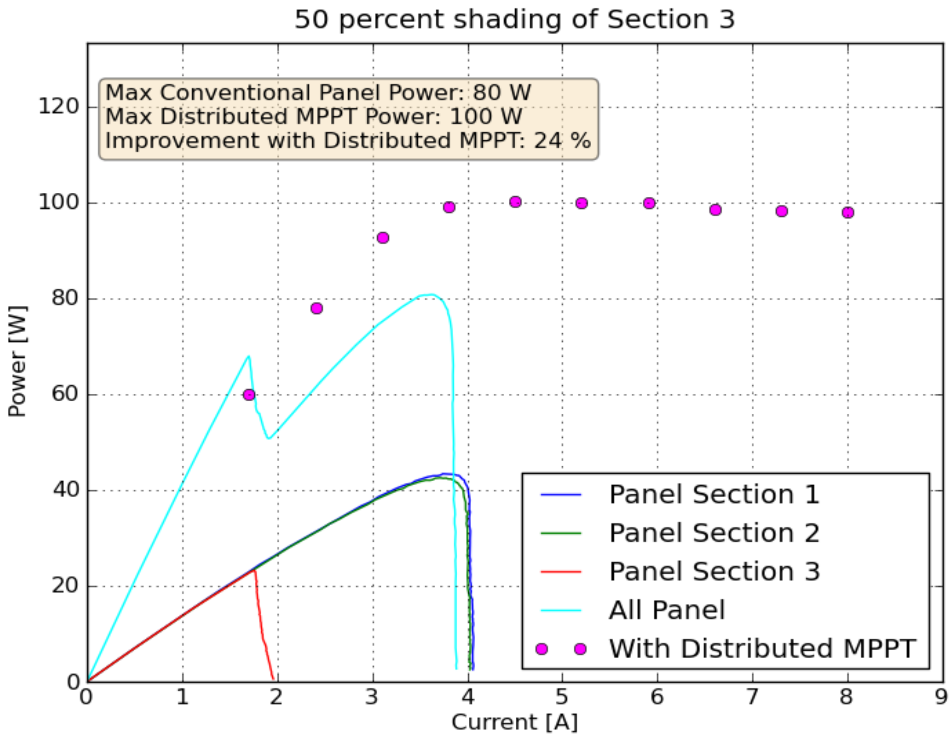
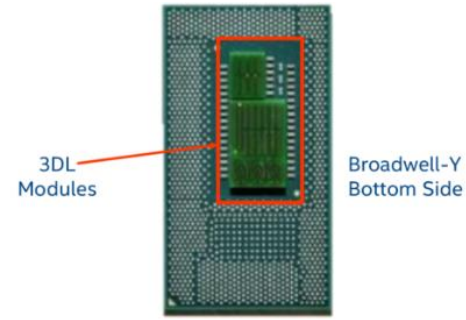


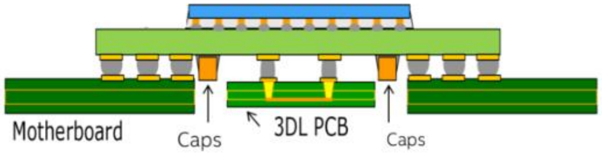
- Embedded power electronics increases energy yield
  - Diagnostics
  - Safety shut-off

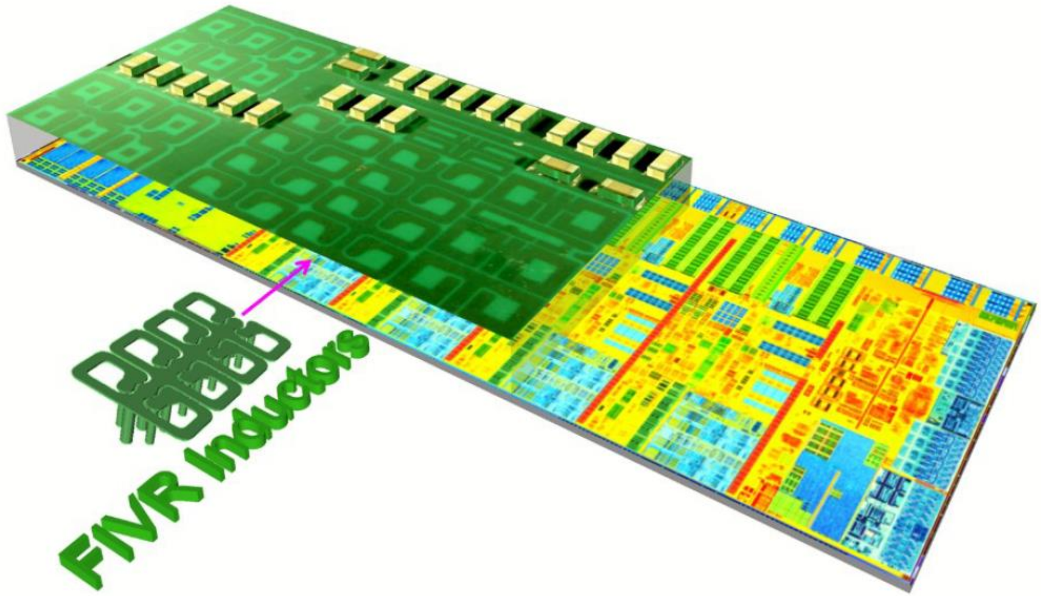
R.C.N. Pilawa-Podgurski, D.J. Perreault "Sub-Module Integrated Distributed Maximum Power Point Tracking for Solar Photovoltaic Applications," IEEE Transactions on Power Electronics, Vol. 28, No. 6, June 2013

Integration of Power Electronics – Example 2

- CPUs with Fully Integrated Voltage Regulators
  - Each core runs at optimum voltage
  - Improved battery life (50%)
  - Increased available power
  - Increased product flexibility



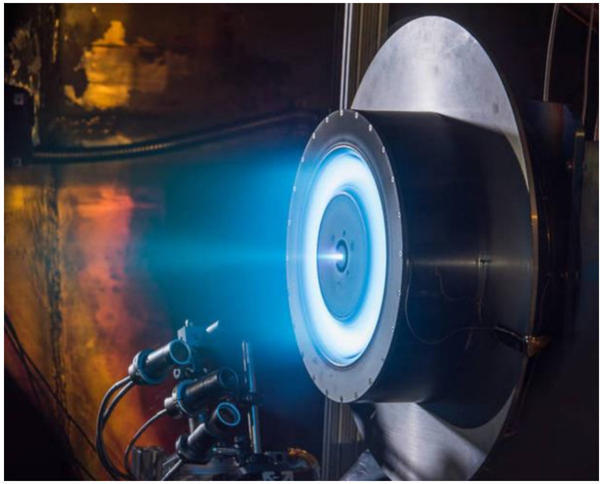




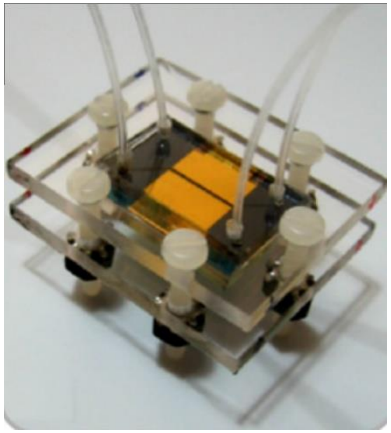
E.A Burton et al. "FIVR — Fully integrated voltage regulators on 4th generation Intel® Core™ SoCs", APEC 2014

Integration of Power Electronics – Future

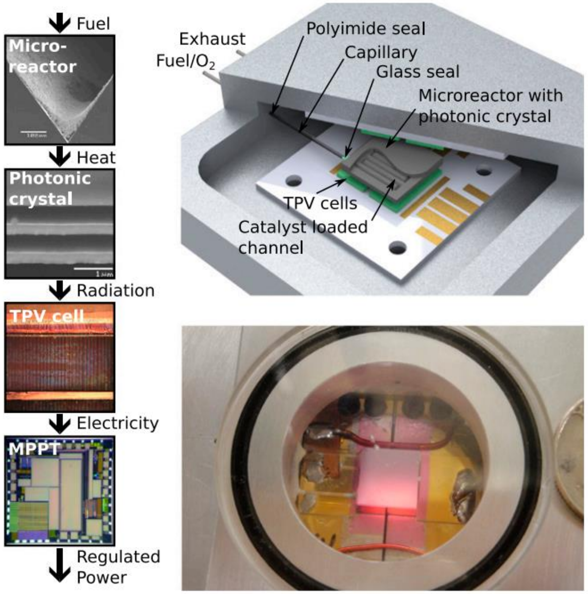
- Research progress requires cross-domain collaborations



Hall Thruster. NASA



Micro Fuel Cell, P. Kenis, UIUC



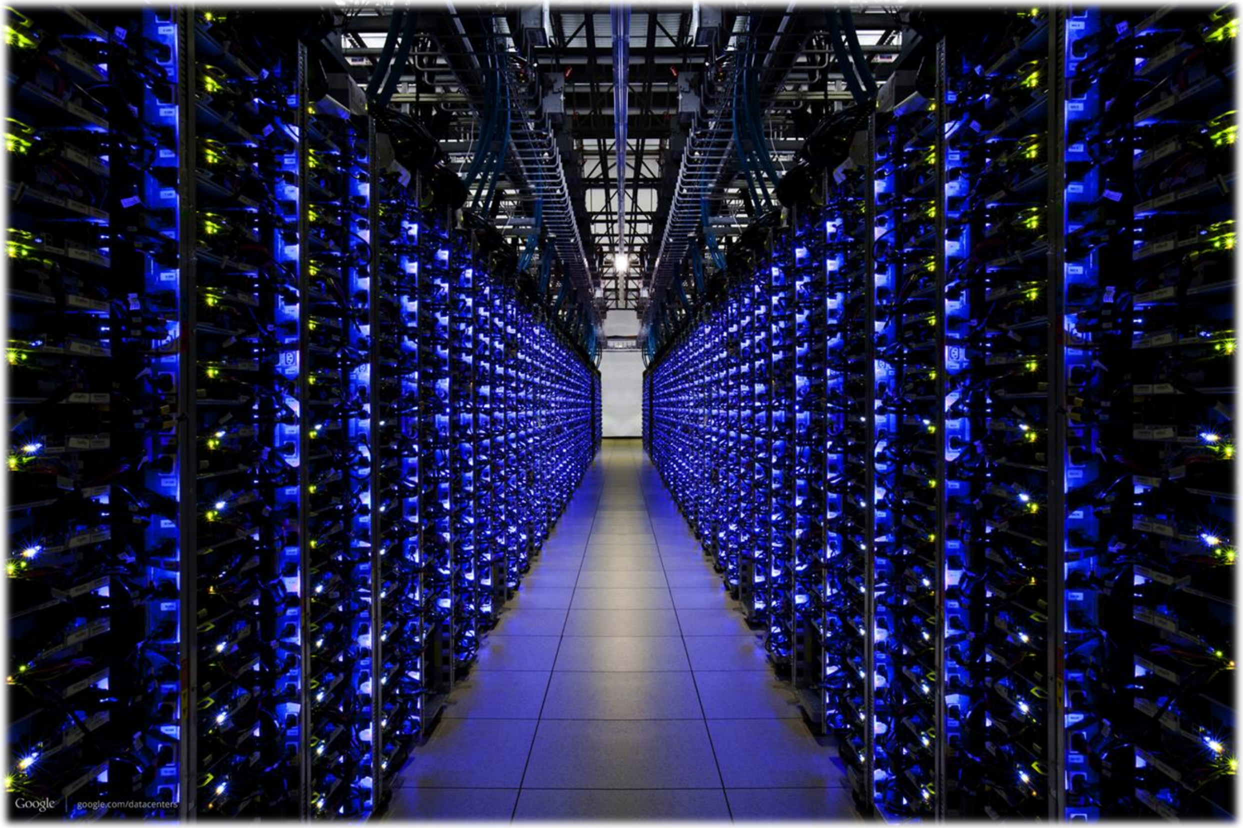
Thermophotovoltaic power generator [1]

[1]W.R. Chan et al. “Toward high-energy-density, high-efficiency, and moderate-temperature chip-scale thermophotovoltaics,” Proceedings of the National Academy of Sciences, February 25, 2013.

Powering the Digital Revolution

Power converters with zero cost and size, 100% efficiency, and infinite lifetime

Datacenters



Datacenters

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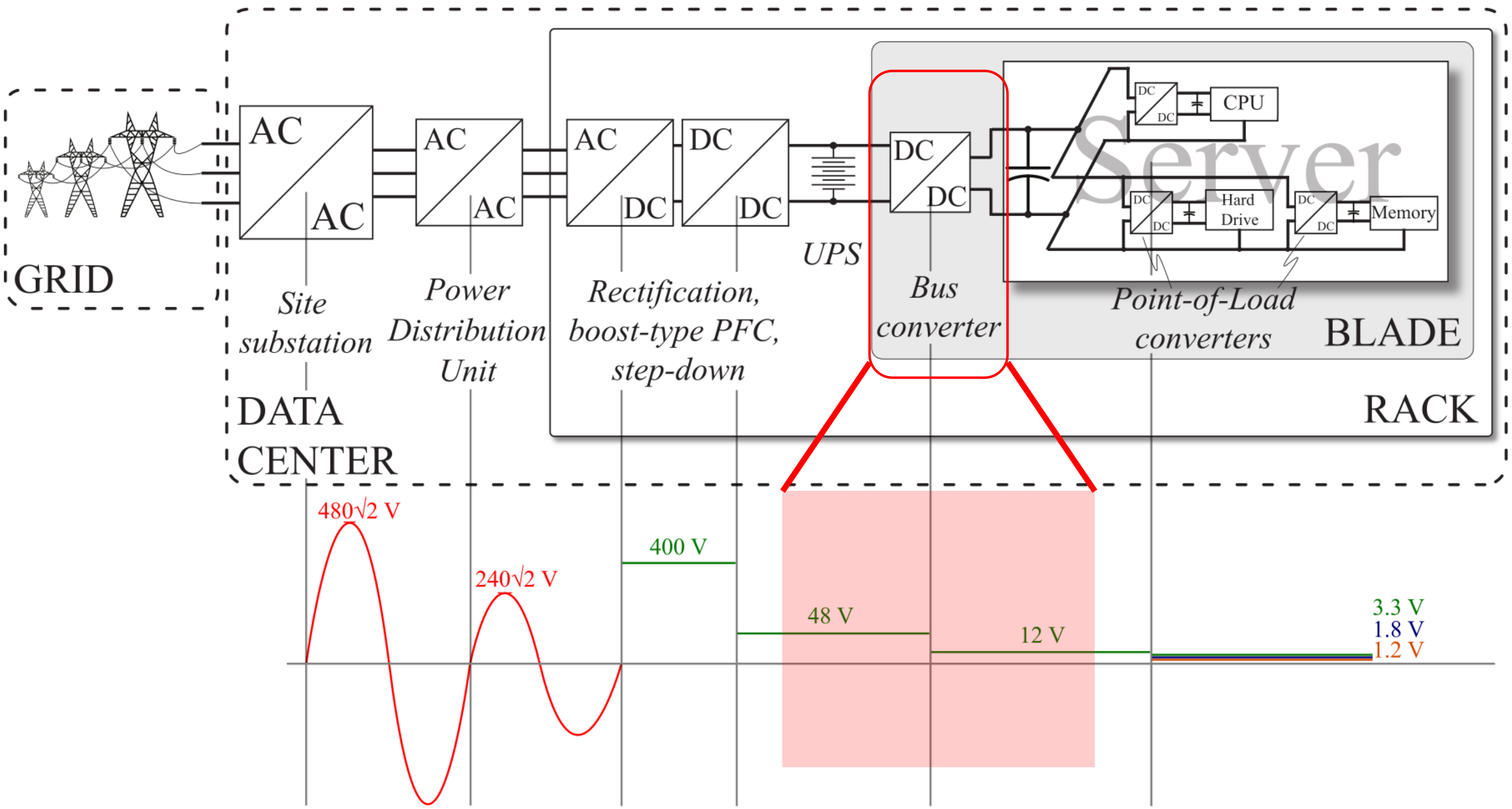
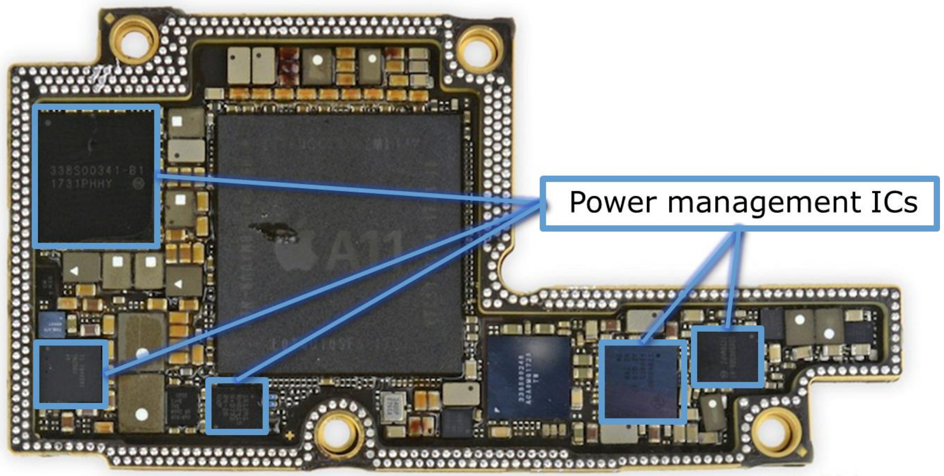


If each conversion is 95% efficient, 23% of the power is dissipated (as heat) before reaching the load

Digital Loads – A Demanding Application

- Small form factor, slim solutions
- Low weight
- Very high efficiency
  - Cost (data centers)
  - Thermal limits (e.g., portable solutions)
- Large voltage step-down
  - ~1V final voltage

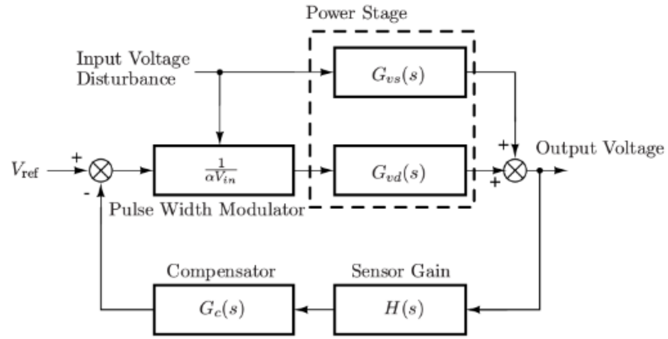
iPhone X

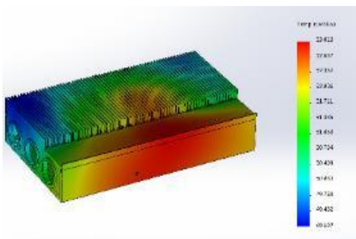


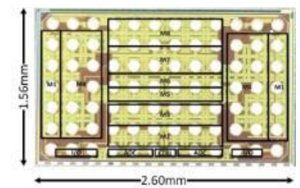
Credit: iFixit

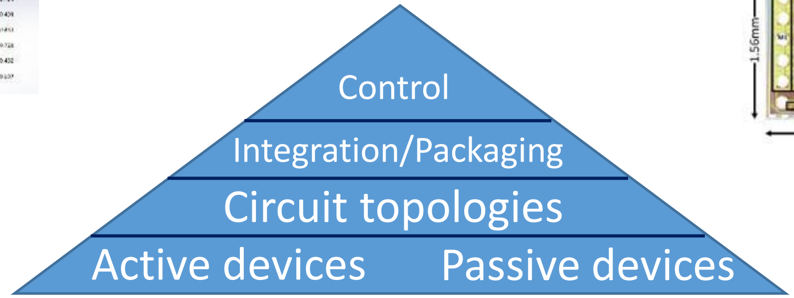
Apple AirPower (cancelled)

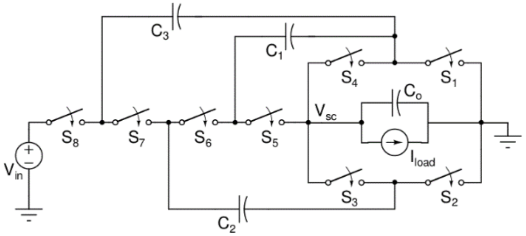
The Tools of Power Electronics



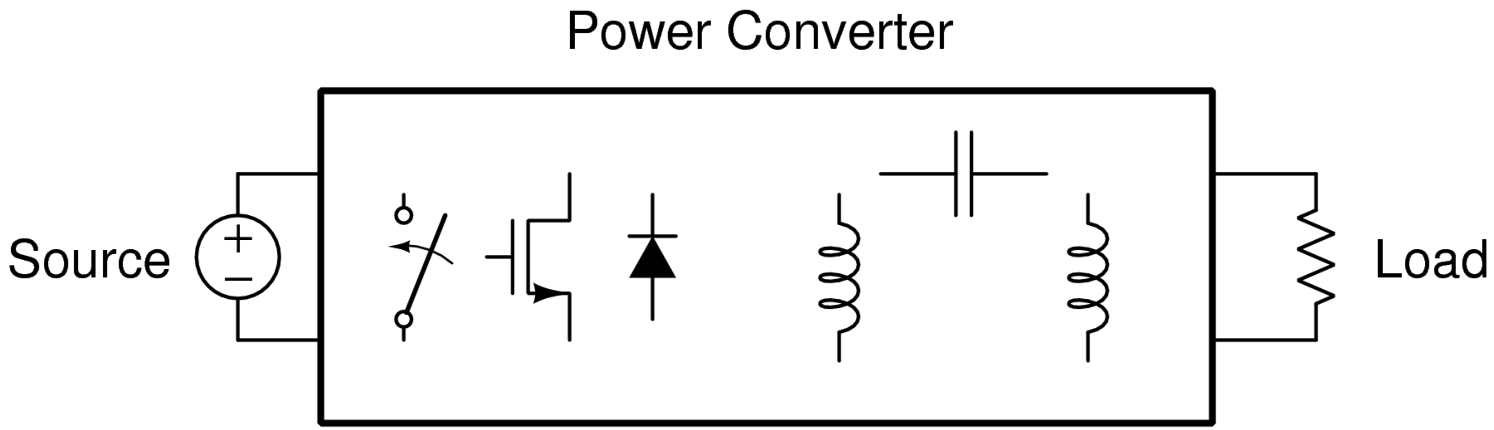


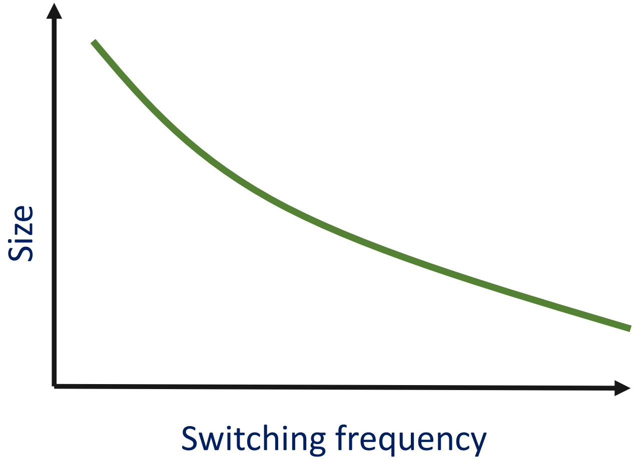


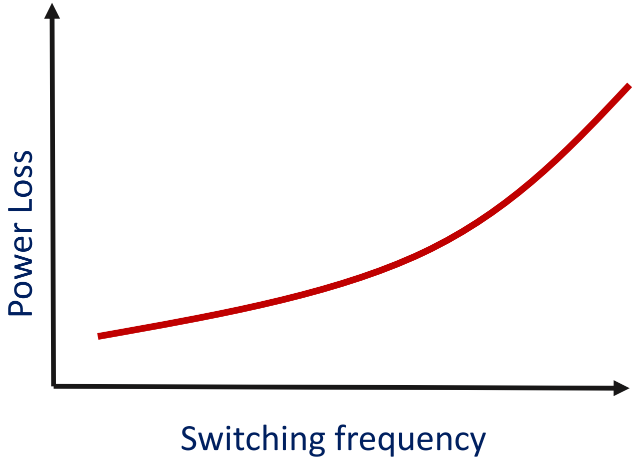




Conventional Path to High Power Density

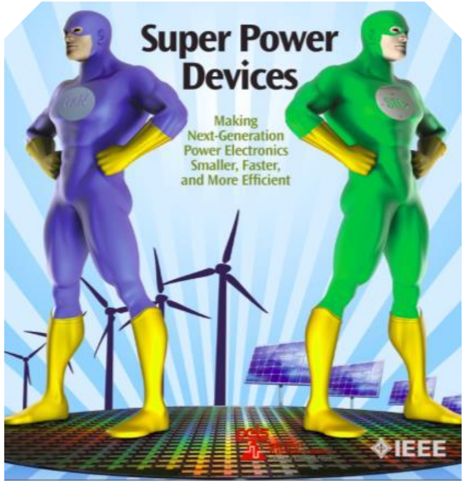


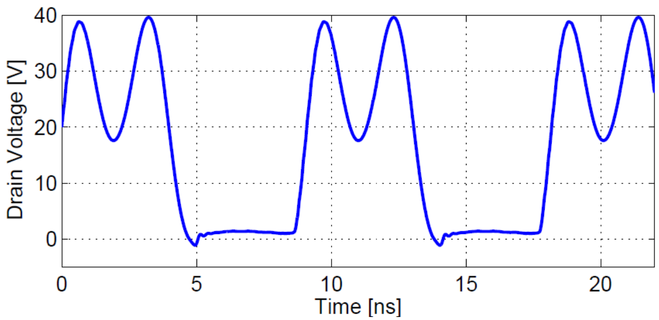


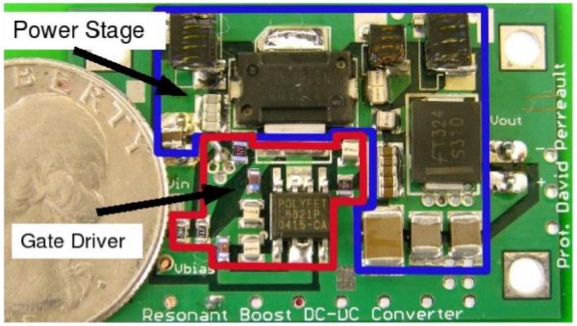


Paths to increased switching frequency

- Improved power semiconductor devices
  - SiC, GaN, Si
- Circuit techniques to limit impact of power transistor parasitics
  - Soft-switching, resonant techniques







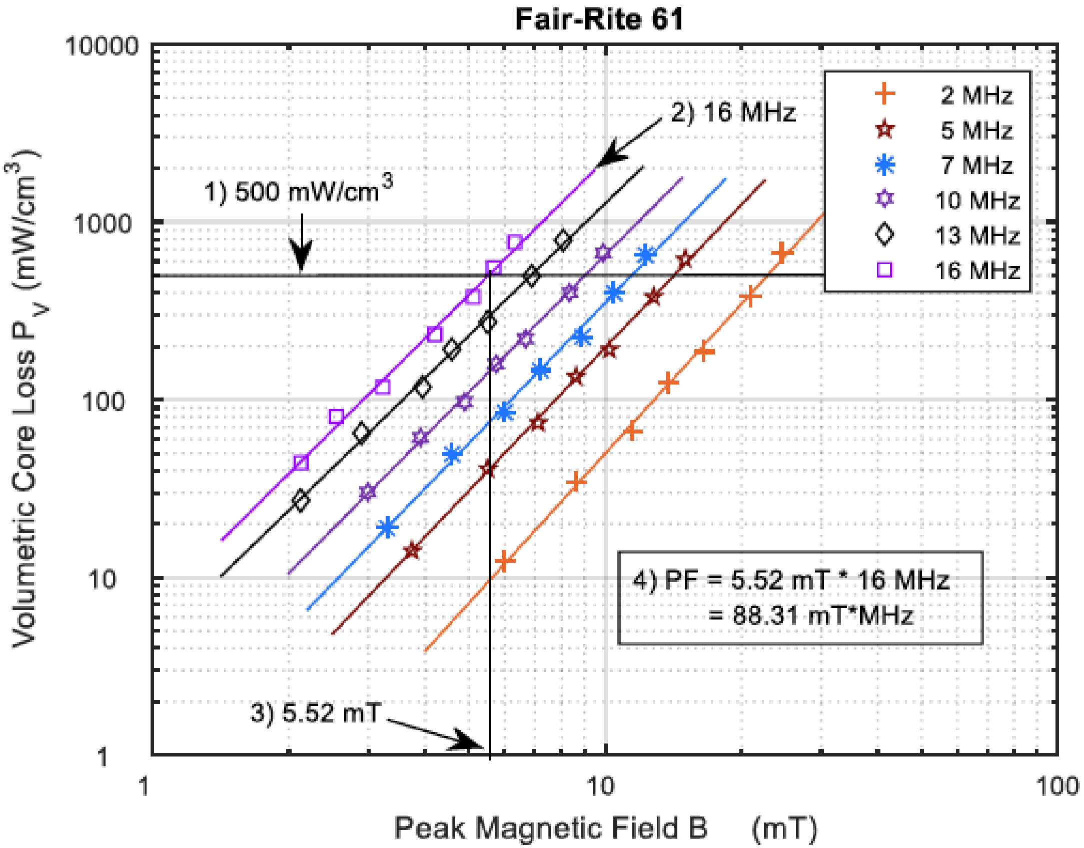
110 MHz resonant boost converter [1]

Given the improvement in circuit techniques and power devices, why are current industrial power converters still operating below 1 MHz?

[1]] R.C.N. Pilawa-Podgurski, A.D. Sagneri, J.M. Rivas, D.I. Anderson, and D.J. Perreault, “Very High Frequency Resonant Boost Converters,” IEEE Transactions on Power Electronics, Vol. 24, No 6, pp. 1654-1665, 2009.

Challenge #1: Magnetic core losses

- Inductor size reduction through frequency scaling limited by core loss
  - At constant loss, the allowable flux density *decreases* with f



Credit: Prof. David Perreault

Opportunity: New core materials

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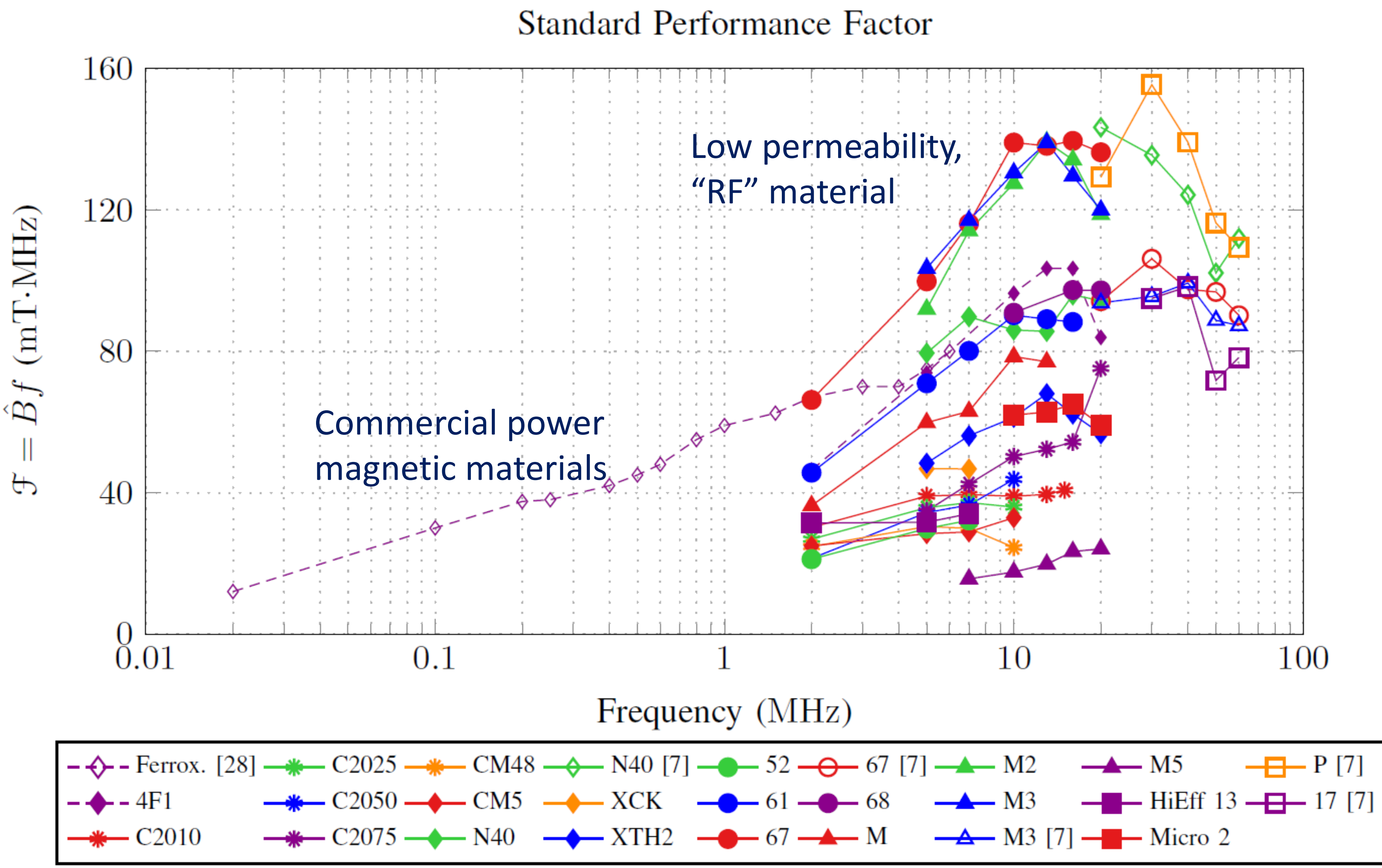
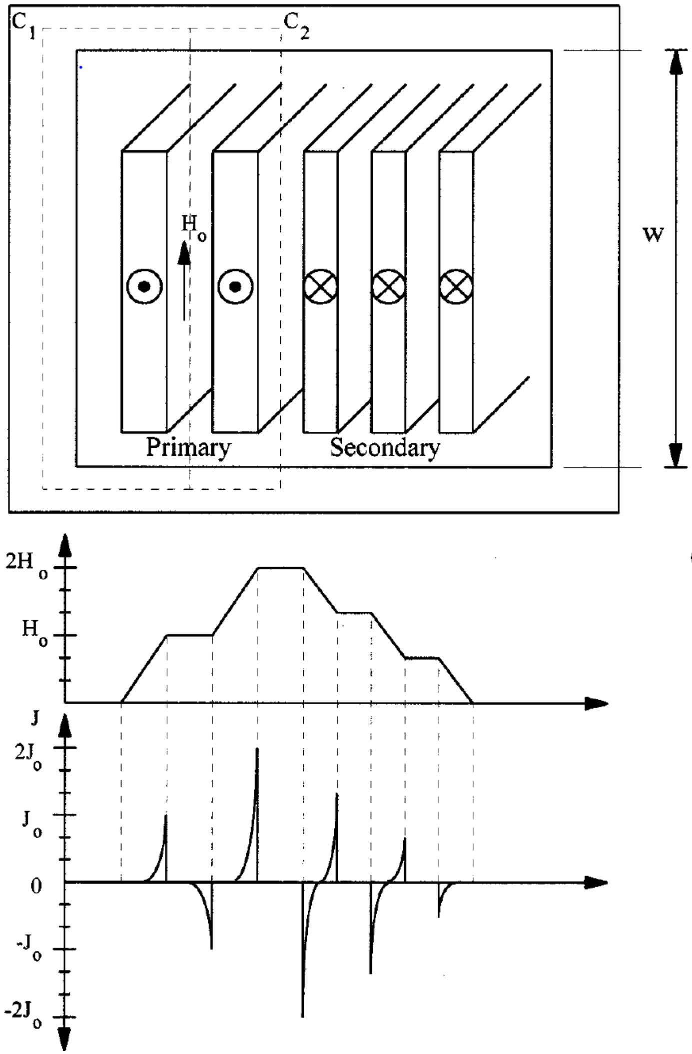
Performance factor $B_0 f$: power handling at *constant loss density and volume*



A.J. Hanson et al, "Measurements and Performance Factor Comparisons of Magnetic Materials at High Frequency," IEEE Transactions on Power Electronics, Vol. 31, No. 11, pp. 7909-7925, November 2016.

Challenge #2: Power magnetic structures

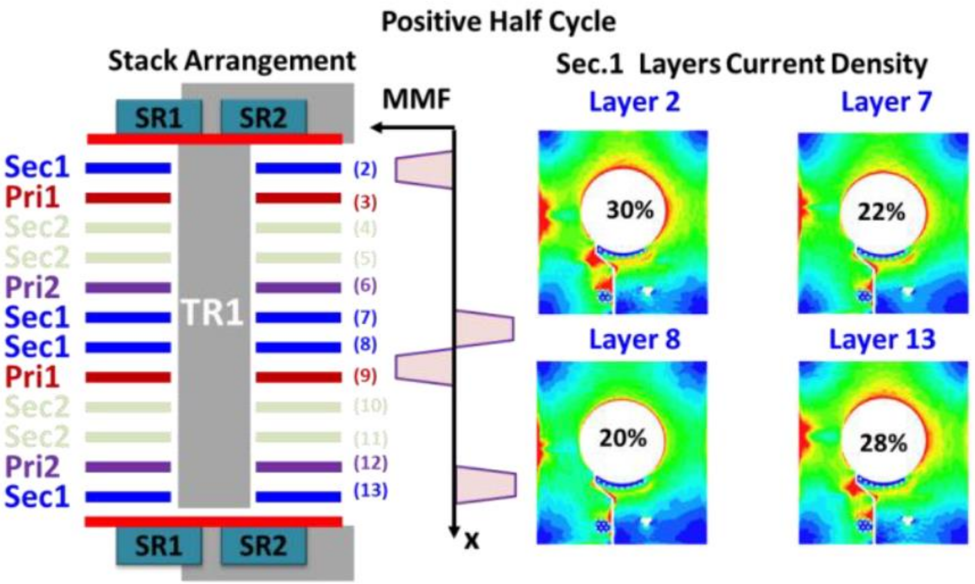
- At high currents and frequencies, skin and proximity effects become challenging
  - Size and placement of windings has large impact on performance
  - Litz wire challenging above a few MHz

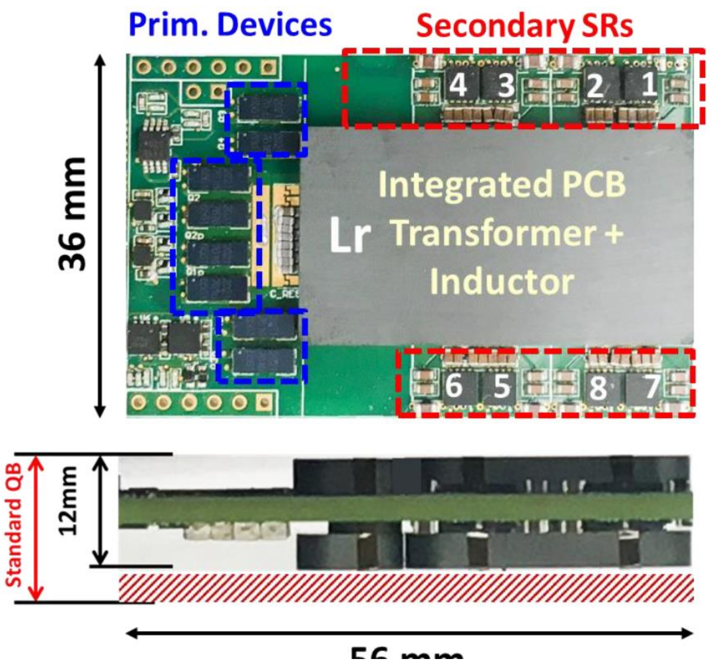


W.G. Hurley et al., “Optimizing the AC Resistance of Multilayer Transformer Windings with Arbitrary Current Waveforms”, TPELS 2000

Opportunity : Novel magnetic structures

- Planar magnetics offer manufacturing and performance benefits
  - PCB integrated windings
  - Repeatable, well-known manufacturing

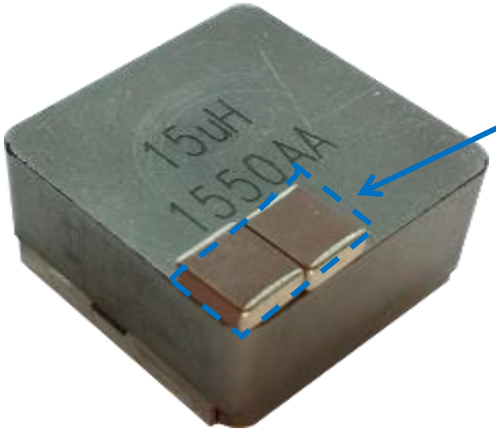




M. Ahmed et al., “Low Loss Integrated Inductor and Transformer Structure and Application in Regulated LLC Converter for 48V Bus Converter”, JESTPE 2019

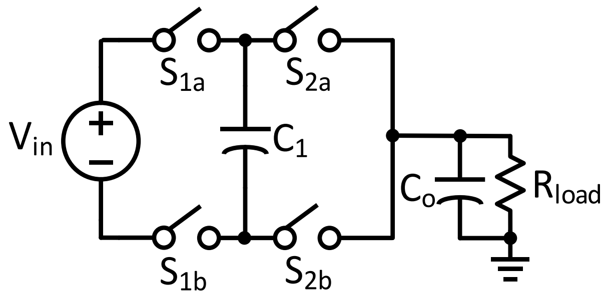
Component Choices

4 mJ of inductive energy storage

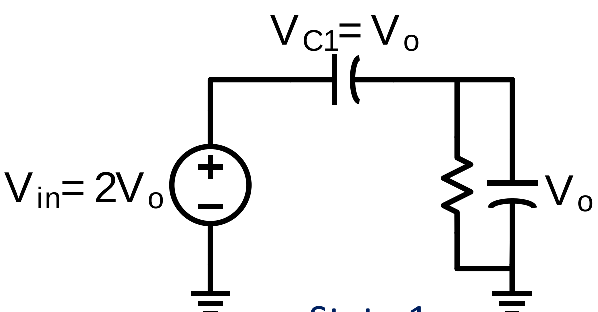


80 mJ of capacitive energy storage (after dc-derating)

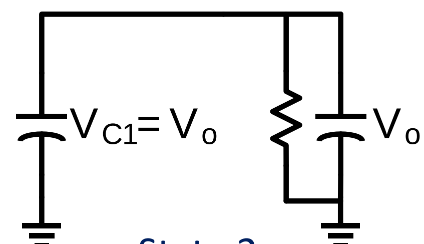
Exploiting Capacitor Energy Density?



2-to-1 SC Converter

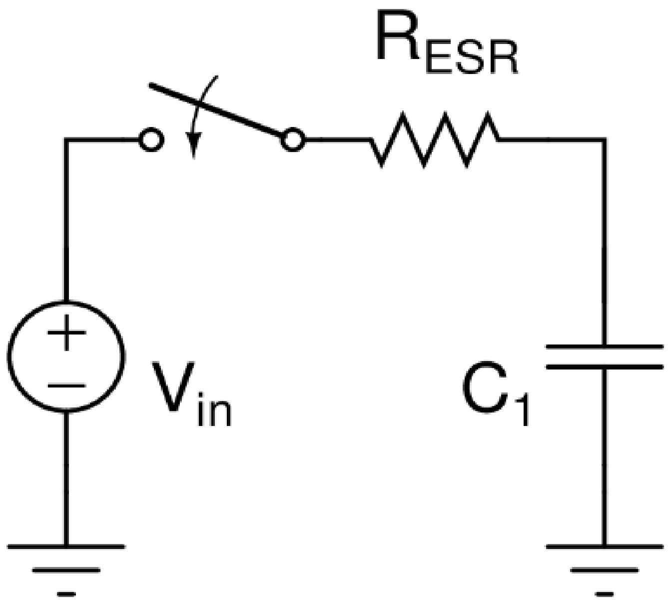


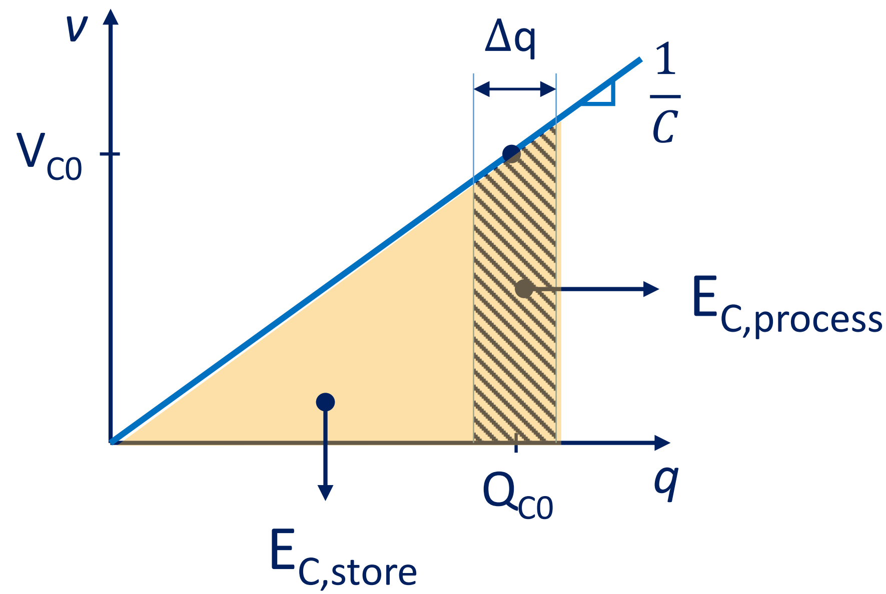
State 1

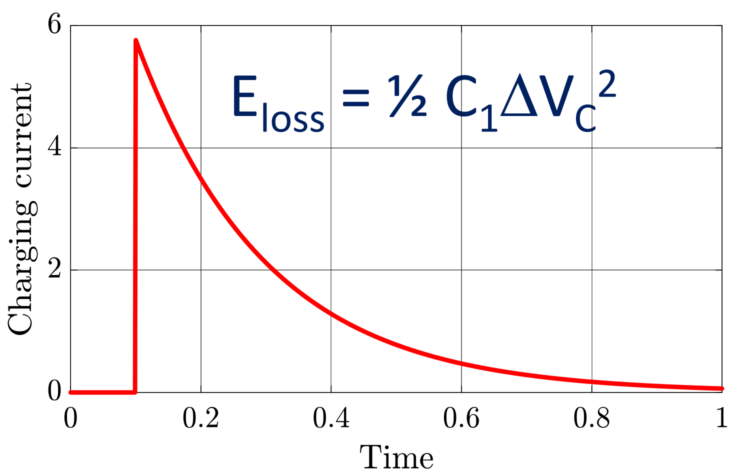


State 2

Fundamental Limitations of SC converters

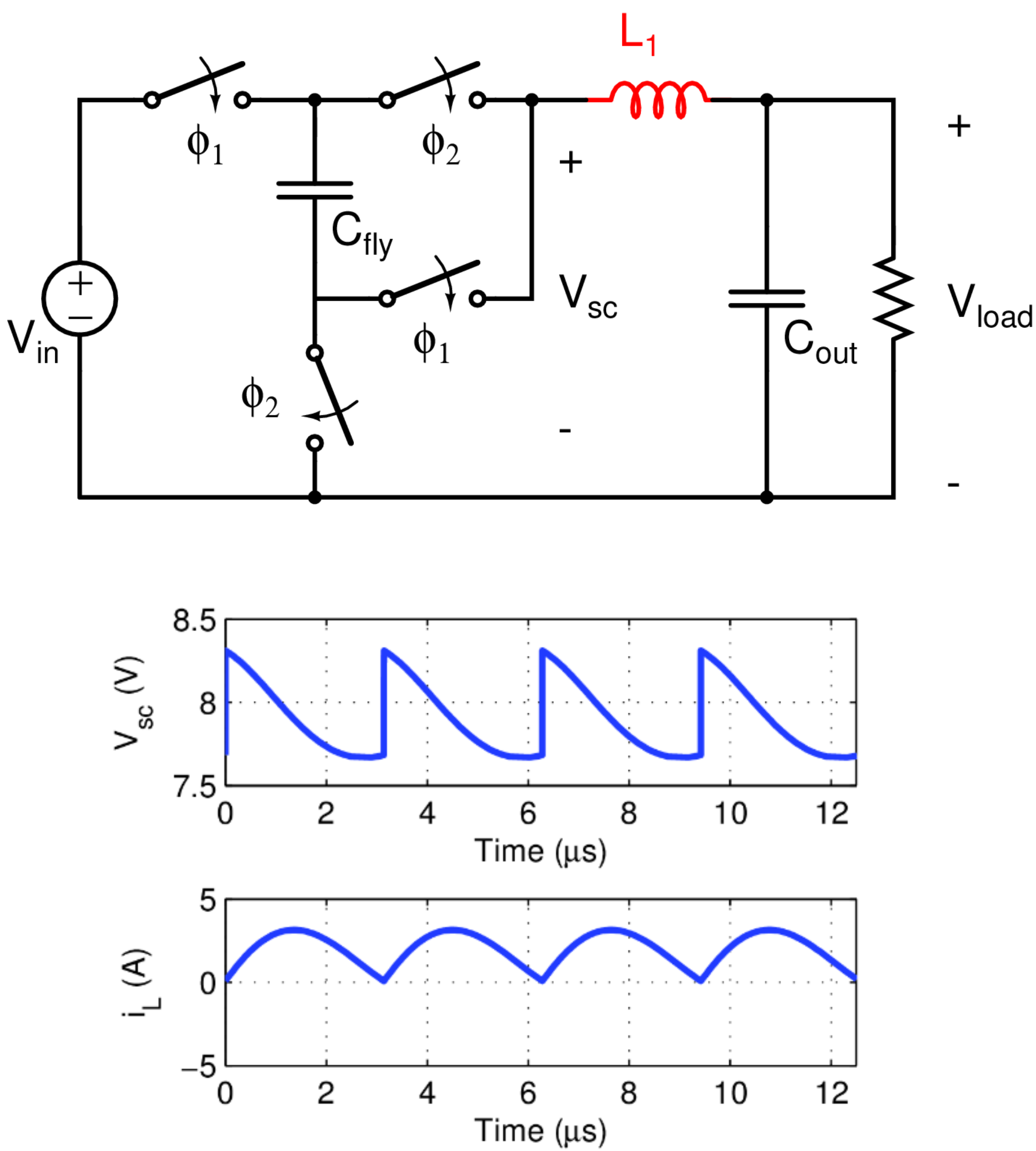






$$\mu_C = \frac{E_{C,\text{process}}}{E_{C,\text{store}}} = \frac{2\frac{\Delta V_C}{V_C}}{(1+\frac{1}{2}\frac{\Delta V_C}{V_C})^2}$$

Might a Hybrid Approach Work?



Resonant Switched-Capacitor Topologies

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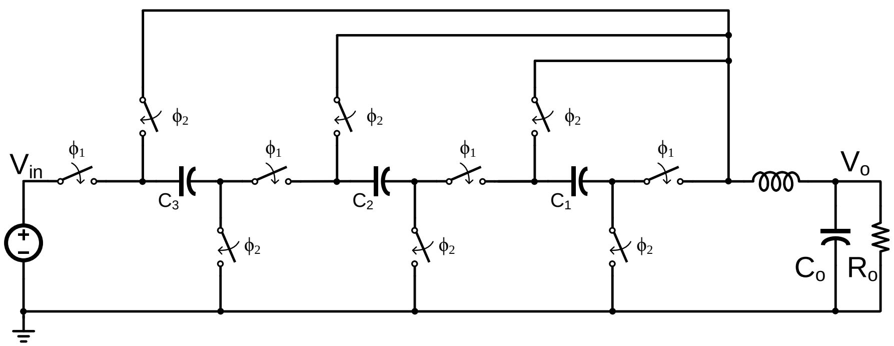
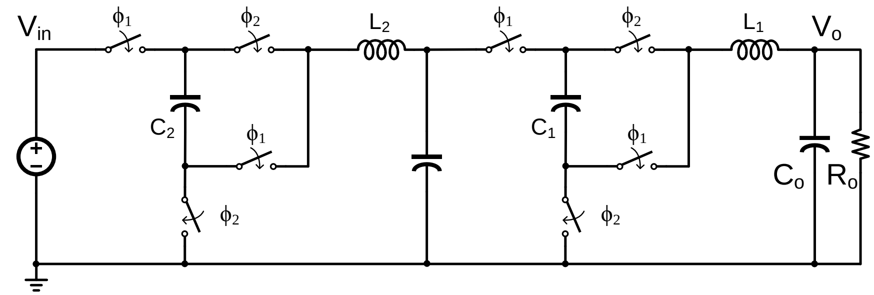
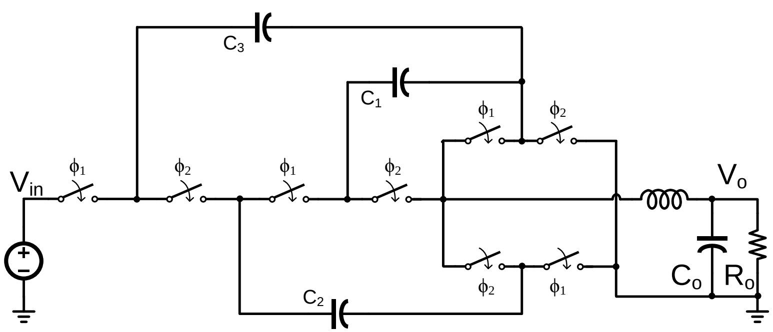


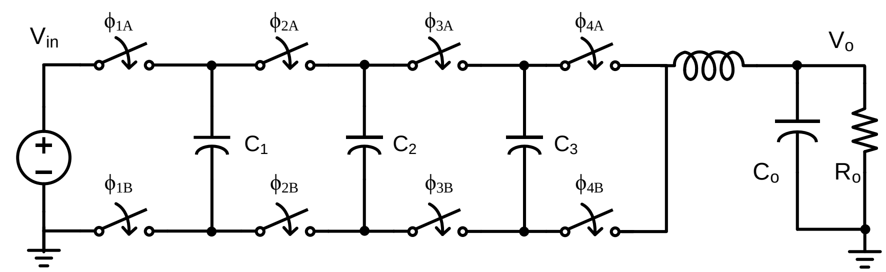
4:1 Series-Parallel



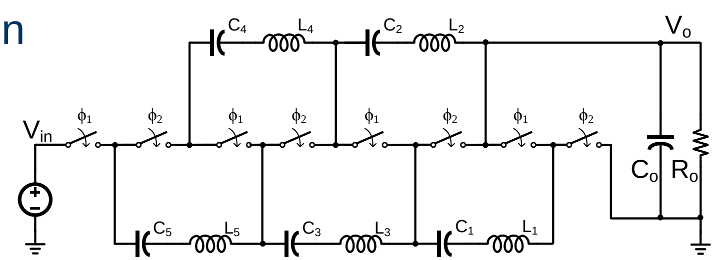
4:1 Doubler (Cascaded Resonant)



4:1 Dickson



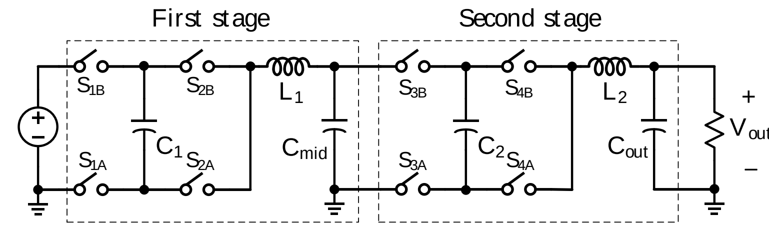
4:1 FCML

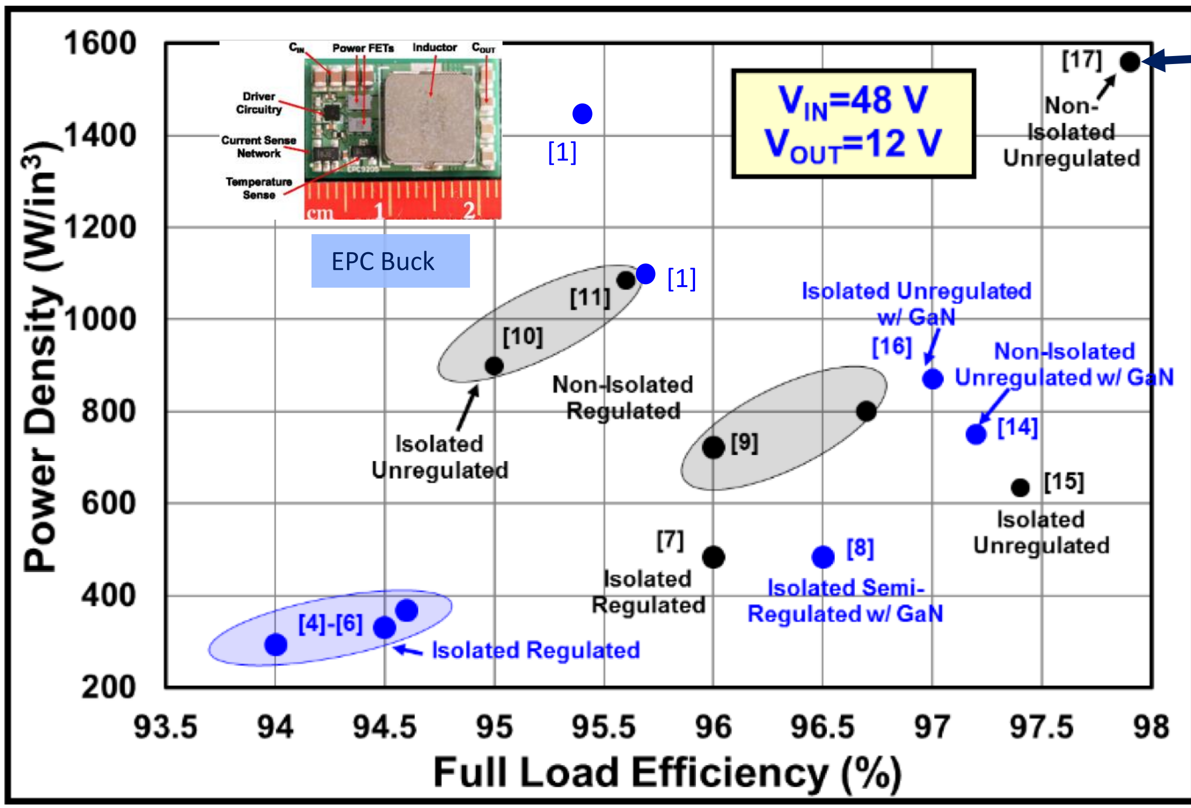


4:1 Ladder

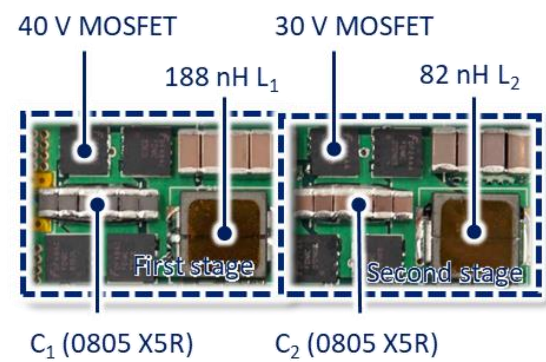
Y. Lei, R.C.N. Pilawa-Podgurski "A General Method for Analyzing Resonant and Soft-charging Operation of Switched-Capacitor Converters", IEEE Transactions on Power Electronics, 2015

GaN vs. Si & Hybrid SC vs Buck





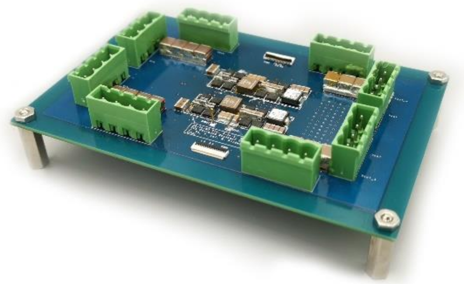
Resonant Doubler Topology

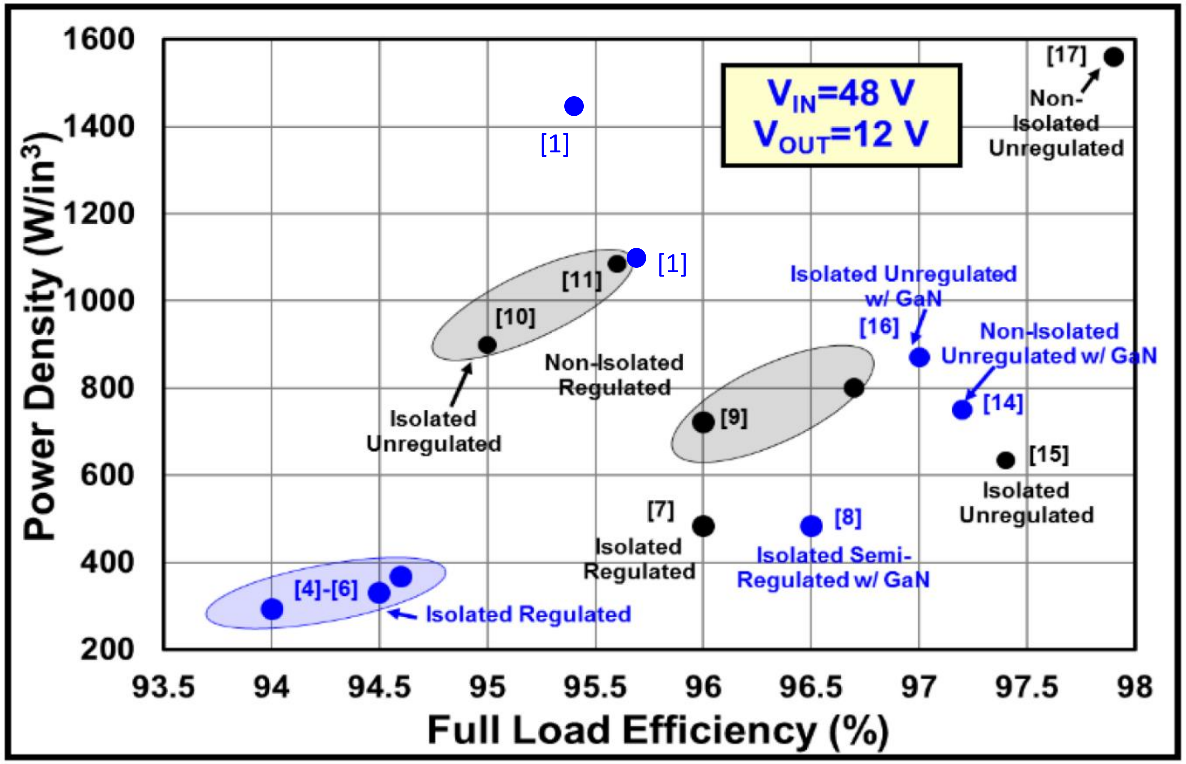


[1] D. Reusch , S. Biswas, Y. Zhang, “System Optimization of a High Power Density Non-Isolated Intermediate Bus Converter for 48 V Server Applications” IEEE Transactions on Industry Applications, 2019

More Optimized Design

APEC 2019: 900 W, 99.0%, 2500 W/in^3





Z. Ye, Y. Lei, R.C.N. Pilawa-Podgurski, "A 48-to-12 V Cascaded Resonant Switched-Capacitor Converter for Data Centers with 99% Peak Efficiency and 2500 W/in3 Power Density", APEC 2019

Extending to Lower Voltages

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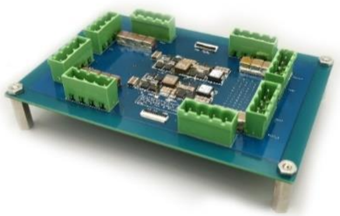
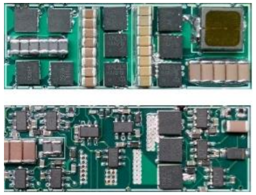
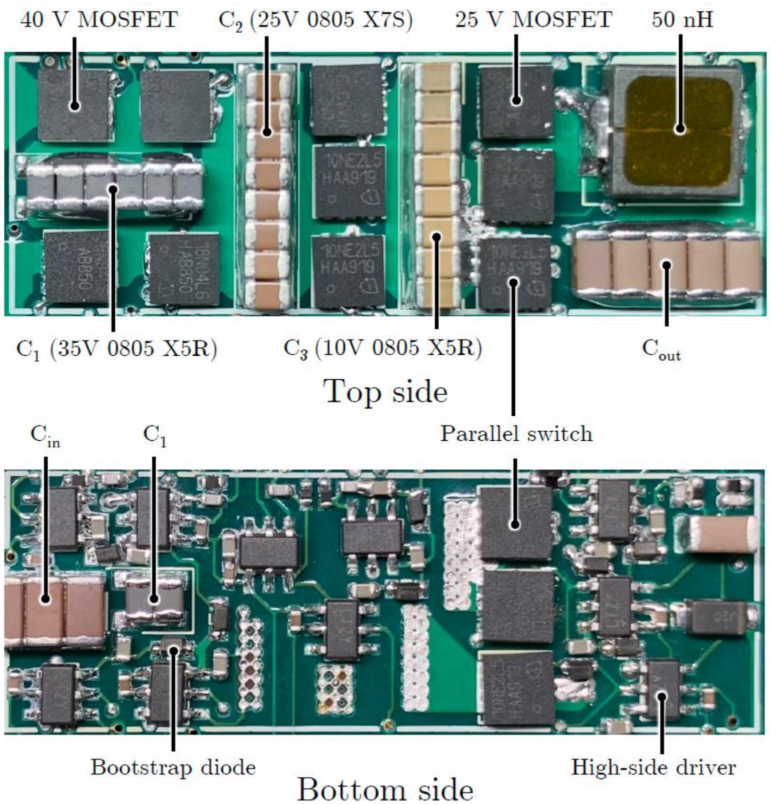
48 V to	12 V	8 V	6 V	4 V
	Cascaded Resonant [1]	*Unpublished*	Multi-Resonant Doubler [Ye, APEC 2020]	Two-stage cascaded [Liu, APEC 2020]
Peak system efficiency	99.0%	98.5%	98.0%	97.0%
Power density by box volume	2500 W/in^3	2250 W/in^3	1675 W/in^3	1150 W/in^3





[1] Z. Ye, Y. Lei, R.C.N. Pilawa-Podgurski, "A 48-to-12 V Cascaded Resonant Switched-Capacitor Converter for Data Centers with 99% Peak Efficiency and 2500 W/in3 Power Density", APEC 2019

Further Improvements - Integration



- Packaging and integration
  - PCB embedded components
  - 3D integration
  - Thermal management
  - CMOS integration

Area where strong industry collaboration will be essential

Powering the Electric Transportation Revolution

Flight – Ultimate Frontier in Electrification

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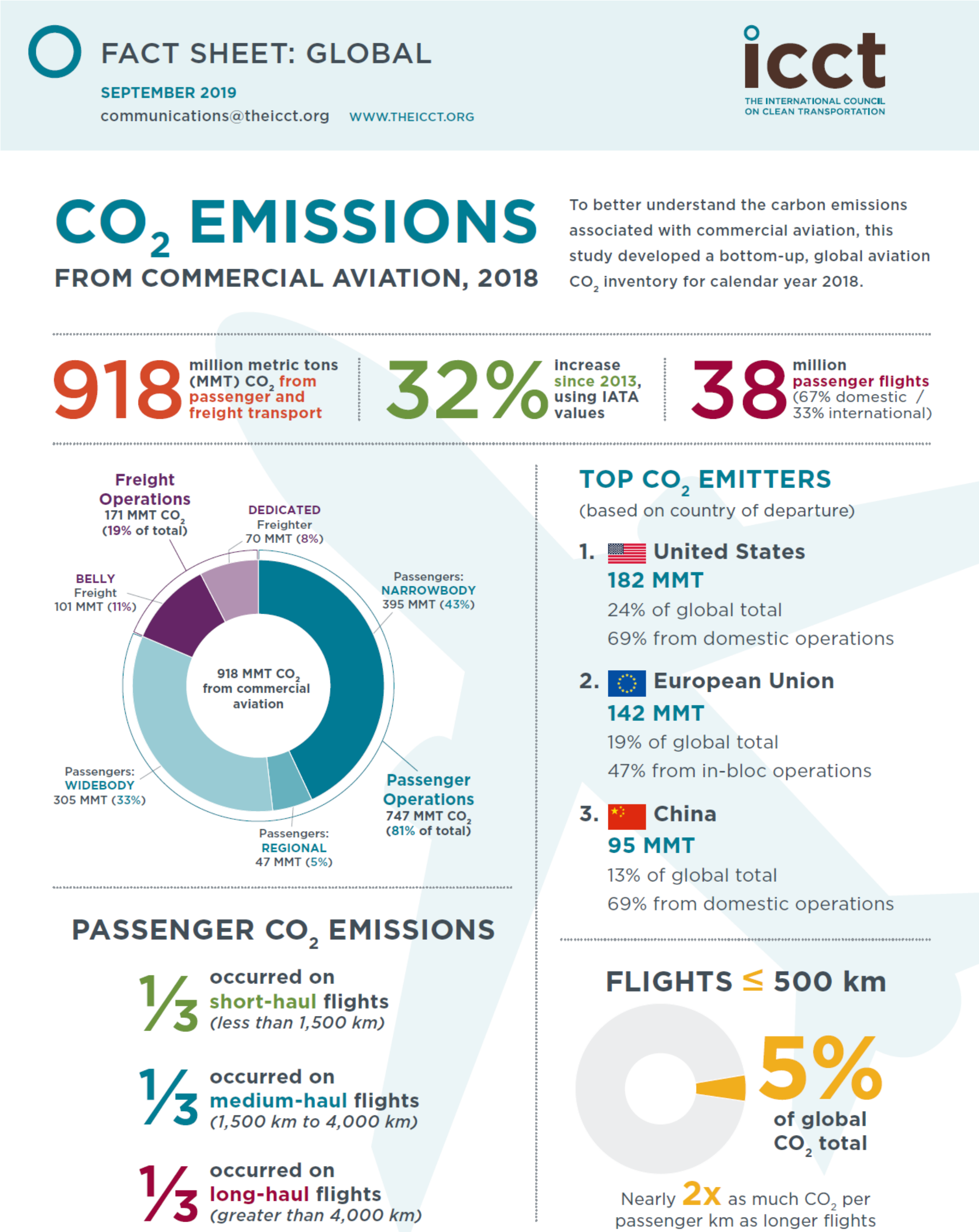
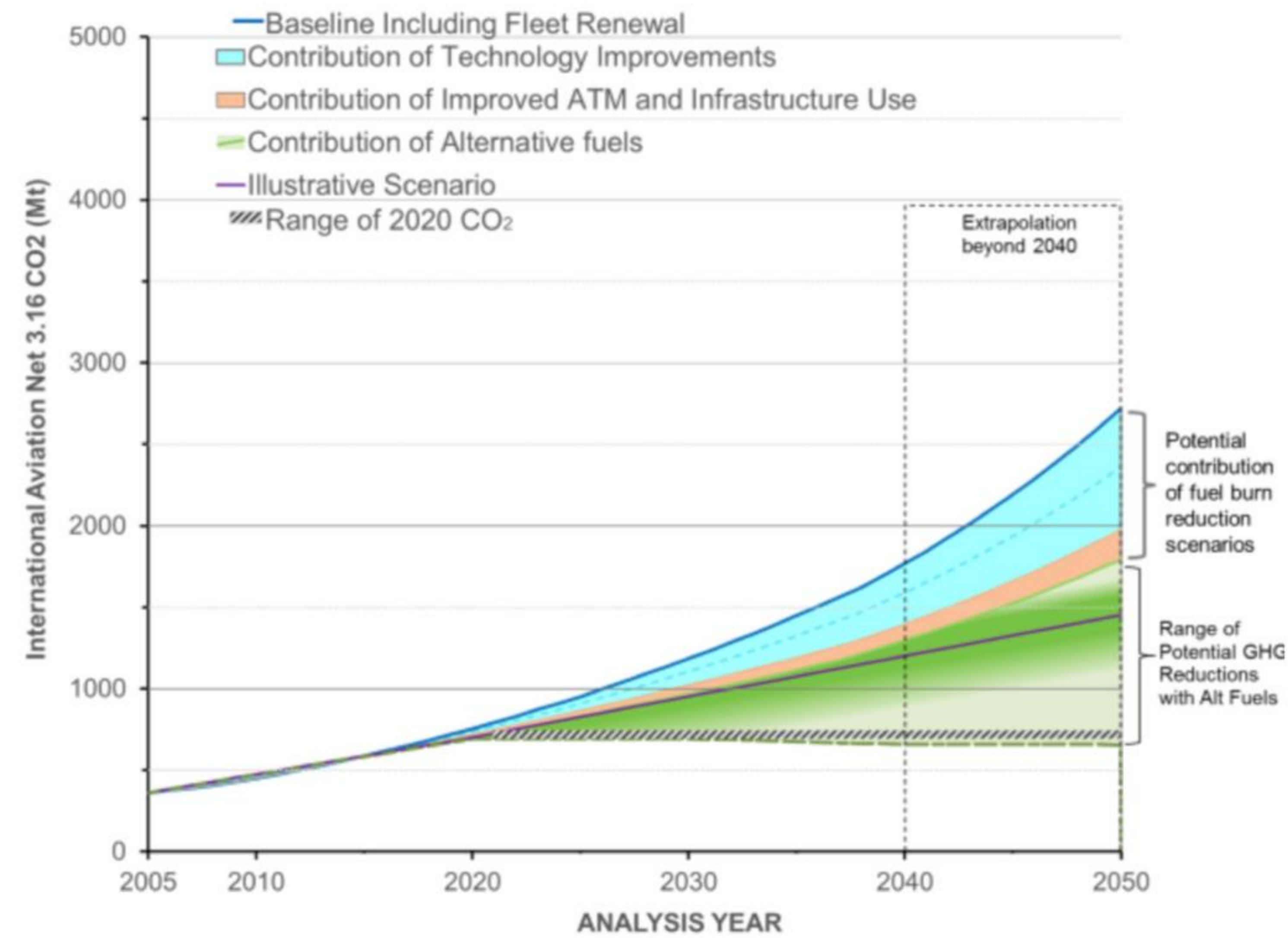


Flygskam!

Future projections



International Civil Aviation Authority, 2016 report

2012 Tesla Model S85 – A Vehicle of Excess

- 362 HP, 3-phase, four-pole AC induction motor
- 85 kWh on-board battery, range of 426 km
- 249 km/h top speed, 0 to 97 km/h in 3.2 seconds
- Price of around $70,000
- Curb weight of 2,107 kg (BMW 5 series 1745 kg)

Benefits of electrification (series hybrid)

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- Example of Benefits for ~~737-800~~ A320 class aircraft:
  - 32 dB reduced noise
  - 60% reduced LTO NOx and CO_2 emissions
  - 33% reduced energy consumption
- Specific power density (kW/kg) is key!
  - Electric motor and power electronics identified as key bottlenecks [2]

N3-X conceptual design

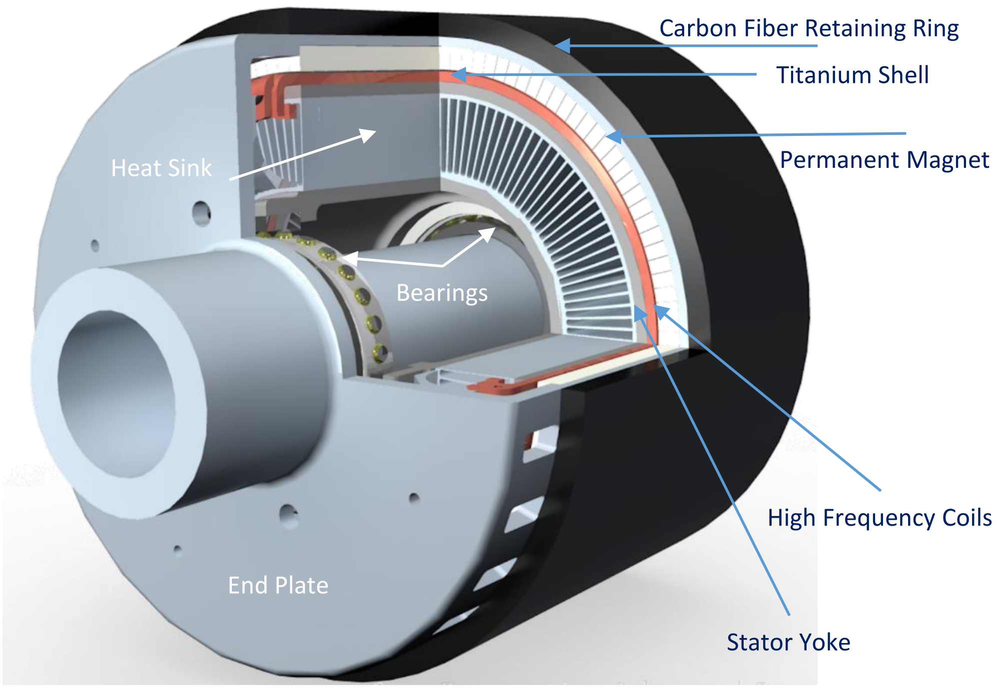
NASA's X-57 “Maxwell” will be a fully battery powered research aircraft using distributed propulsion.

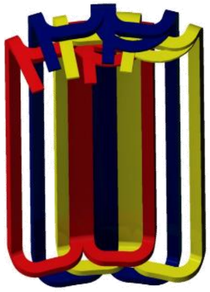
[1] NASA release “NASA Electric Research Plane Gets X Number, New Name” (June, 17 2016)

[2] Jansen, Ralph H., et al. "Turboelectric Aircraft Drive Key Performance Parameters and Functional Requirements." (2015).

1 MW, PM Machine with Integrated Drive

- Development of 1 MW electric machine and drive, 13 kW/kg target (77 kg total)
  - >96 % efficiency
  - Carbon-fiber construction, permanent magnet machine
  - 12,000 rpm, 3 kHz fundamental frequency

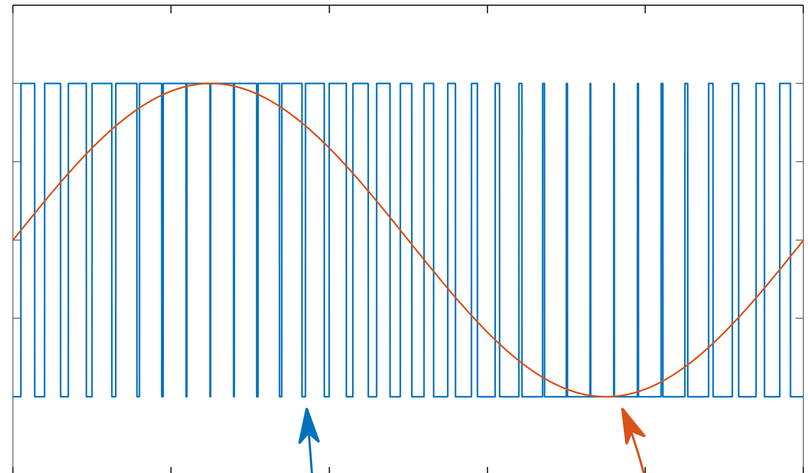




Work funded by NASA, in collaboration with Prof. Kiruba Haran at UIUC

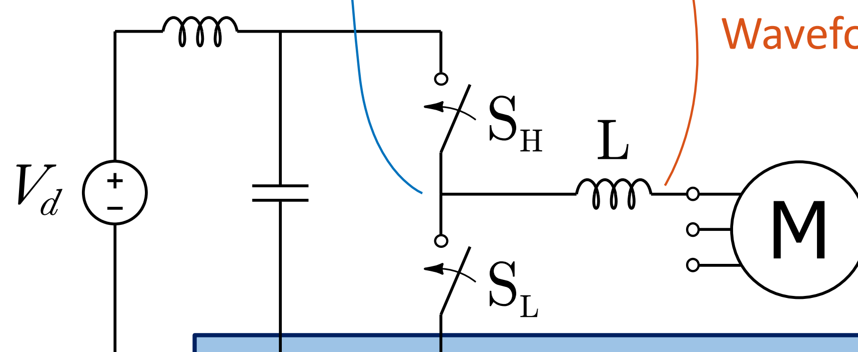
Standard motor drive approach

- 2-level PWM generation
  - Increased motor losses due to harmonics
  - Large bus capacitance required
  - Cooling can be challenging due to hot spots
  - Requires large inductive filters (dv/dt limitations)



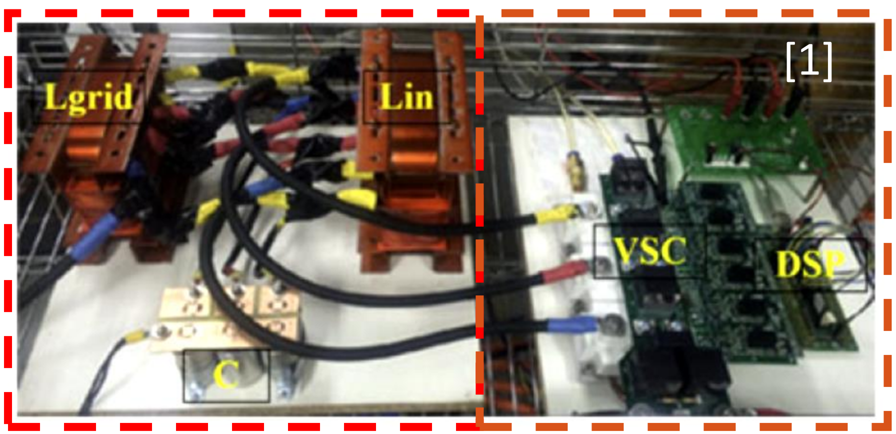
Unfiltered Waveform

Filtered Waveform



Filter

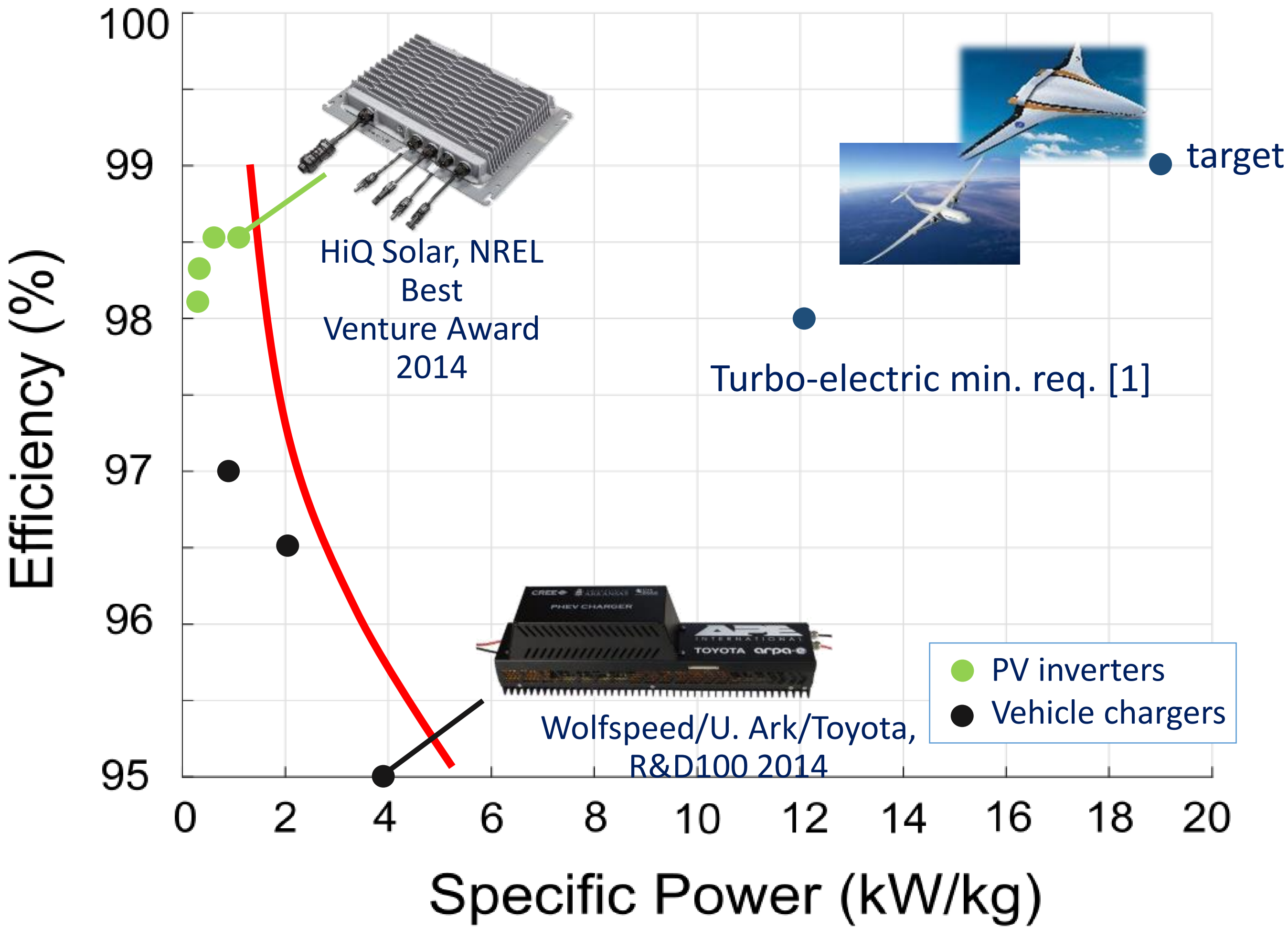
2-Level Inverter



Not suitable for ultra light-weight, low-inductance machine. We need to produce a more sinusoidal drive current.

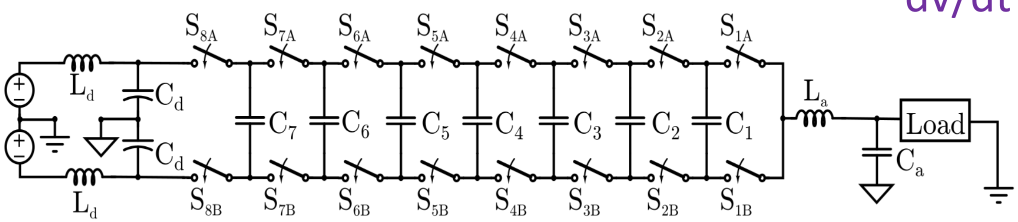
[1] Liu, et al., "LCL Filter Design of a 50-kW 60-kHz SiC Inverter with Size and Thermal Considerations for Aerospace Applications," IEEE TIE, 2017.

Converter Requirements

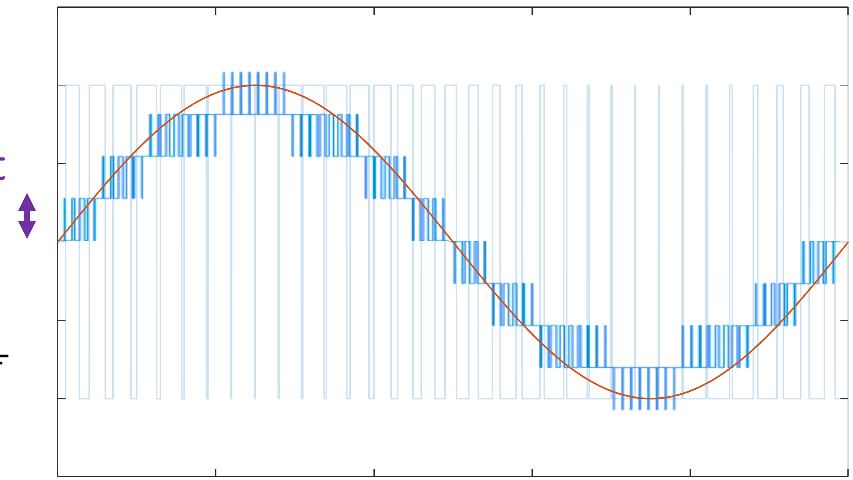


[1] Jansen, Ralph H., et al. "Turboelectric Aircraft Drive Key Performance Parameters and Functional Requirements." (2015).

Unconventional Approach



9-level Flying Capacitor Multi-Level Inverter [1]



Summary of benefits

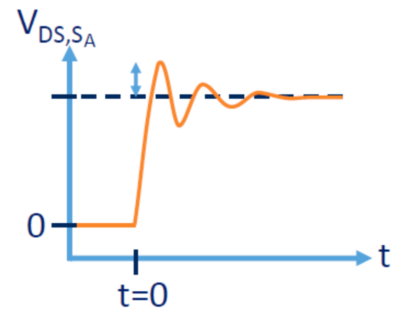
- Works well at high level-count (lower dv/dt)
- High effective switching frequency at output
- Energy dense capacitors process power
- Lower device stress allows lower voltage devices

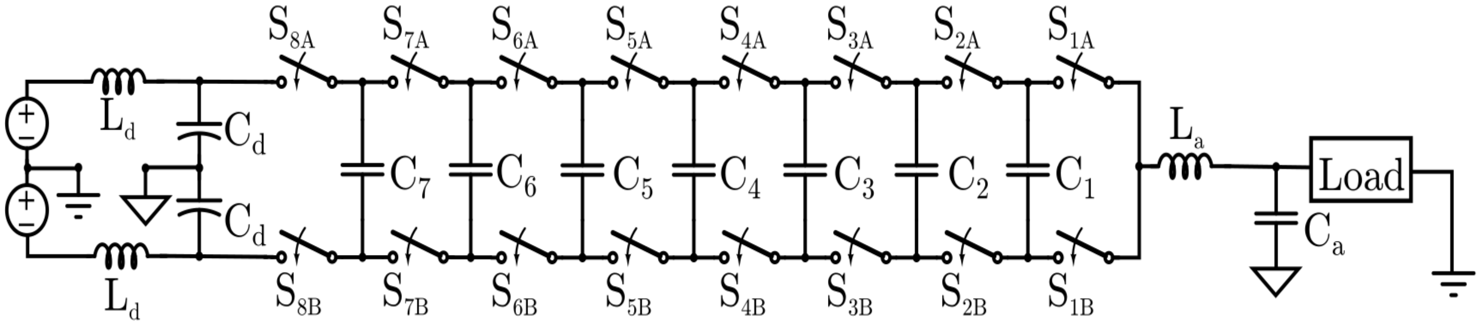
Key Benefit [16]	2-Level	FCML
Switch Stress	$V_{in} / (N-1)$	$V_{in} / (N-1)$
V_{sw} Ripple Amplitude	$V_{in} / (N-1)$	$V_{in} / (N-1)$
V_{sw} Ripple Frequency	f_{sw}	$f_{sw} \times (N-1)$
Output Inductance	$L_{2\ level}$	$L_{2\ level} / (N-1)^2$

[1] T. Meynard and H. Foch, “Multilevel conversion: high voltage choppers and voltage-source inverters,” IEEE PESC, 1992.

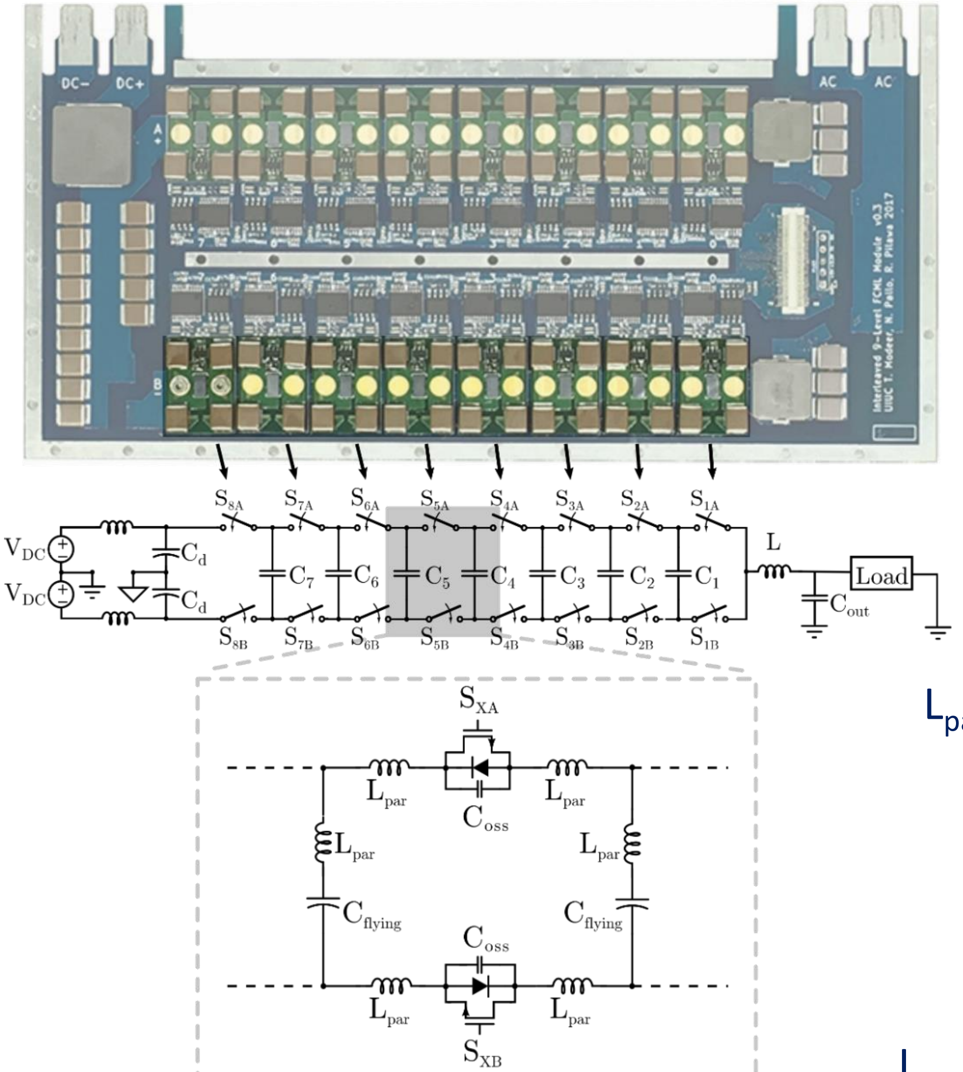
Practical Challenges

- Gate driving, level shifting
- Control complexity
- Signal integrity
- High voltage, high current commutation loops for high speed switching
- Thermal management

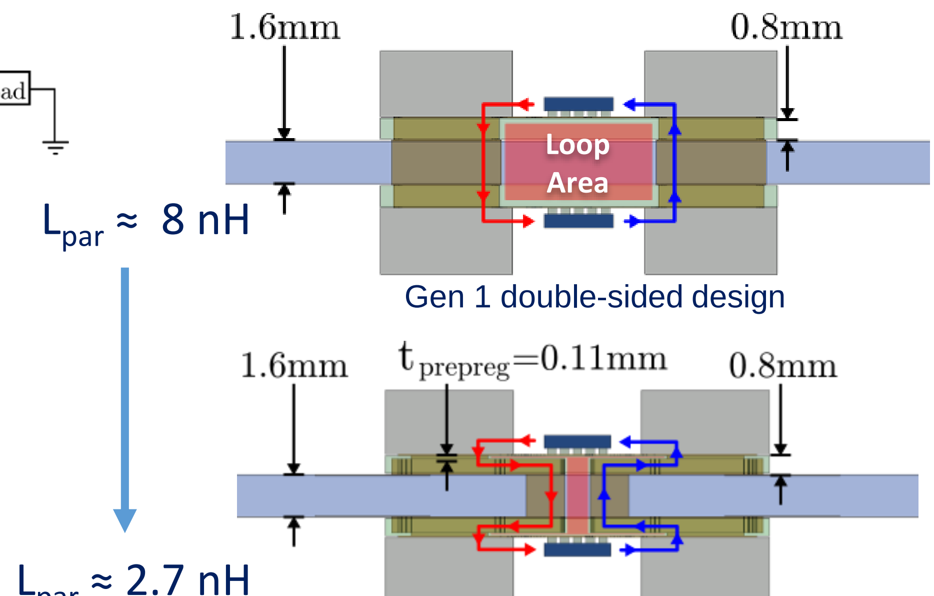




Interleaved inverter module (ILM)



- Use double-sided design to handle 1 kV creepage and clearance at altitude
- Inductance is proportional to cross-sectional area
- "Electrically thin" design using blind and buried vias further reduces loop inductance.

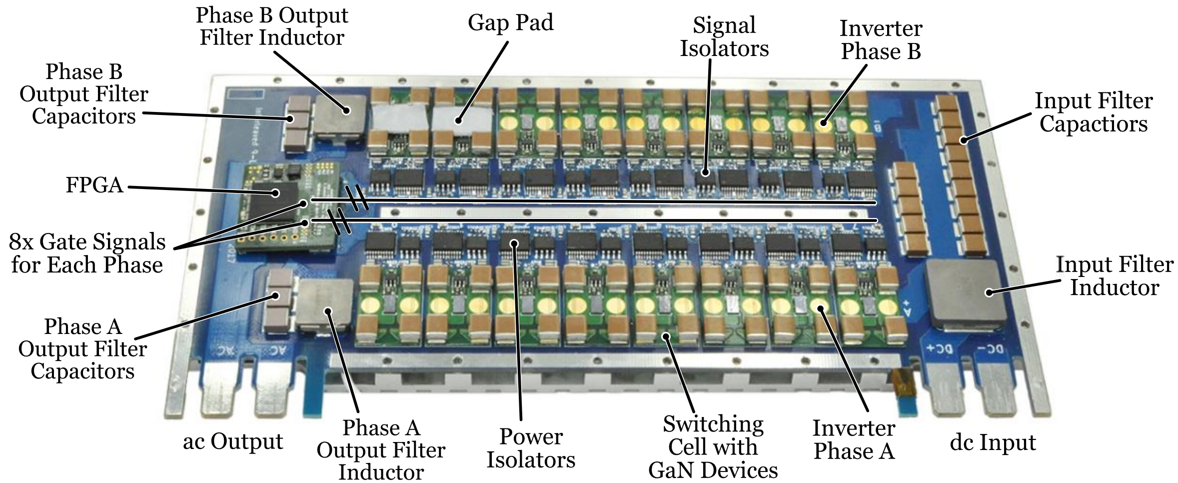


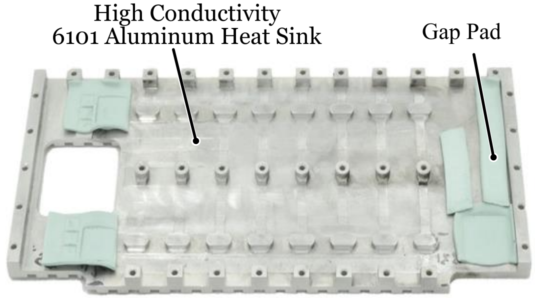
Gen 1 double-sided design

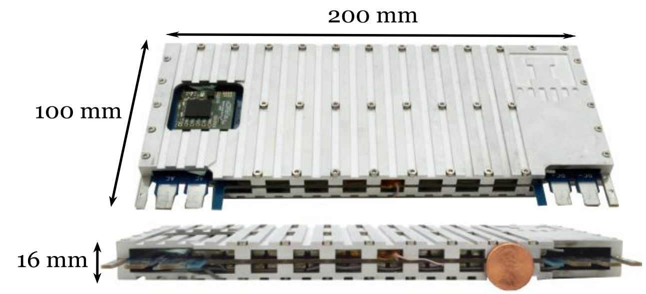
Electrically thin design for Gen 2

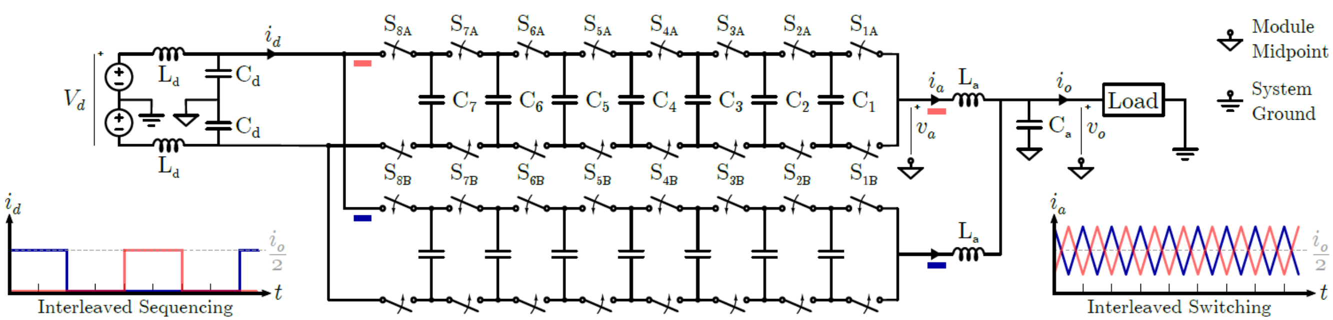
N. Pallo, T. Modeer, R.C.N. Pilawa-Podgurski," Electrically thin approach to switching cell design for flying capacitor multilevel converters", *WiPDA 2017*

Hardware development

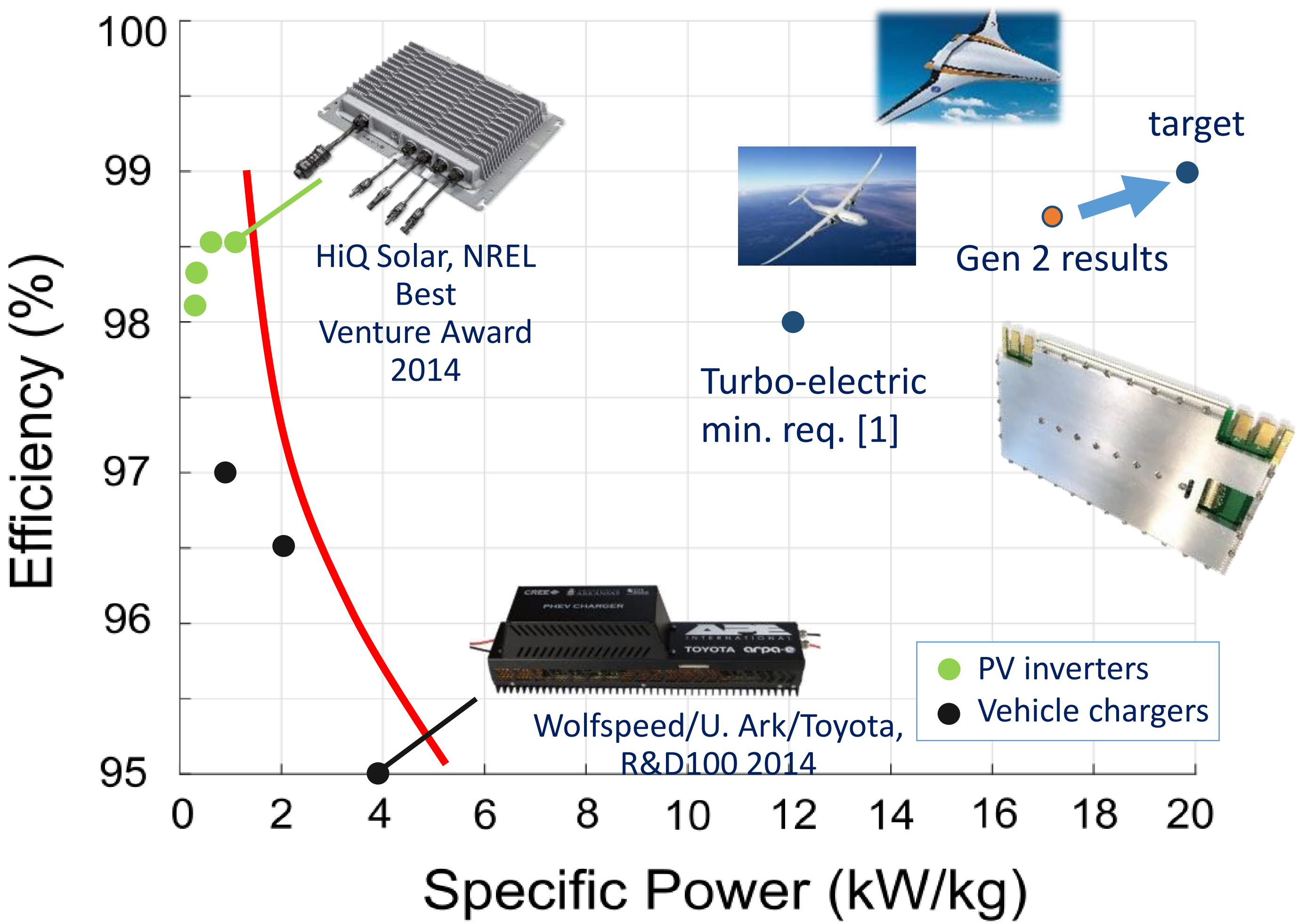






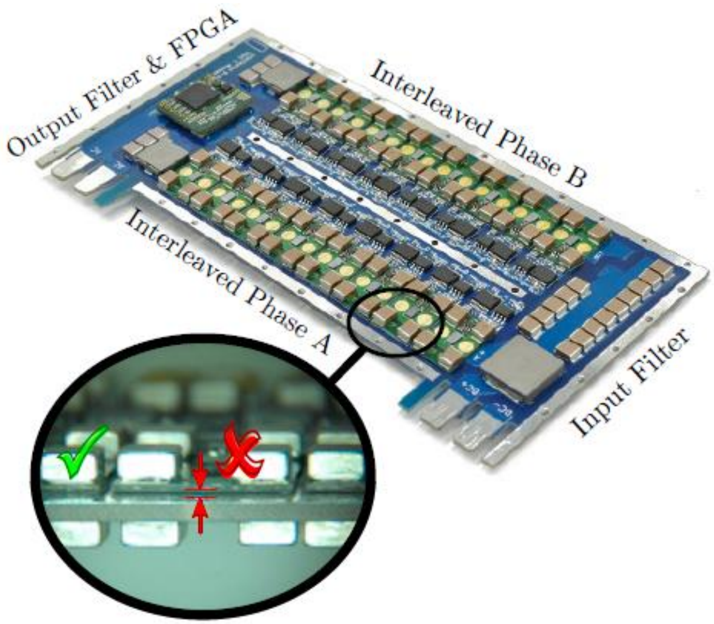


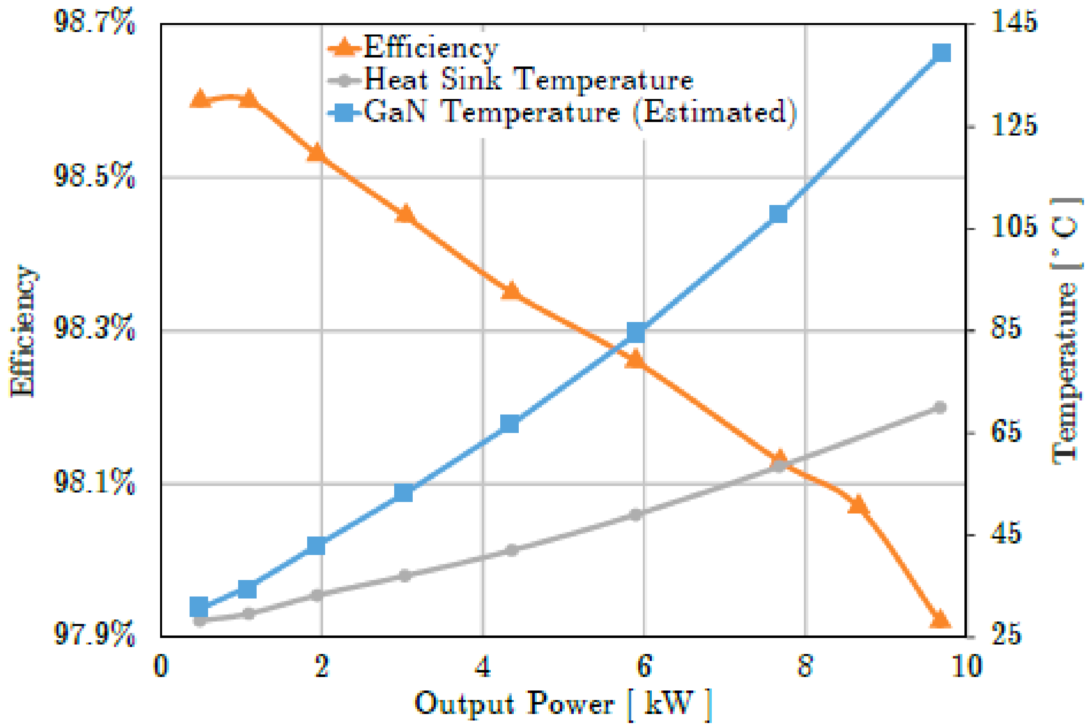
Gen 2 Performance



[1] Jansen, Ralph H., et al. "Turboelectric Aircraft Drive Key Performance Parameters and Functional Requirements." (2015).

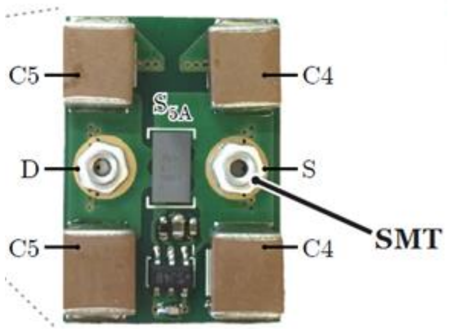
Thermal Challenges





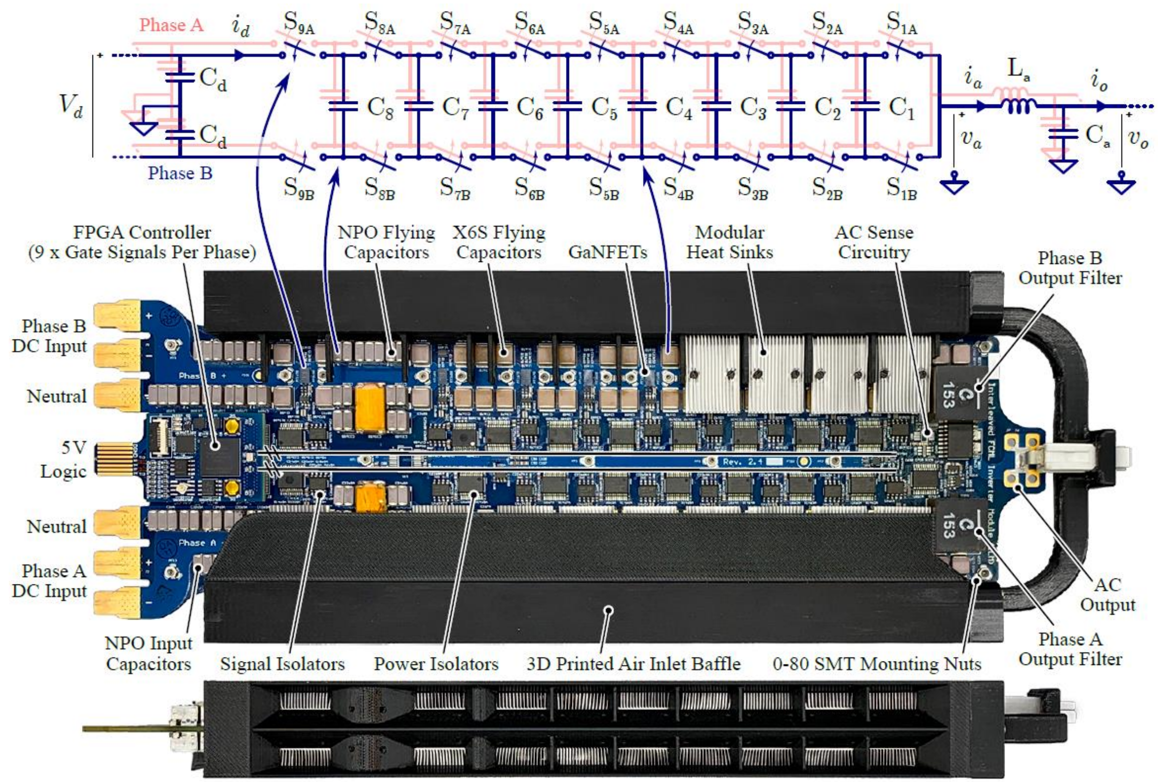
- As with most power converters, maximum output power is limited by thermal considerations

Additively Manufactured Thermal Mgmt.



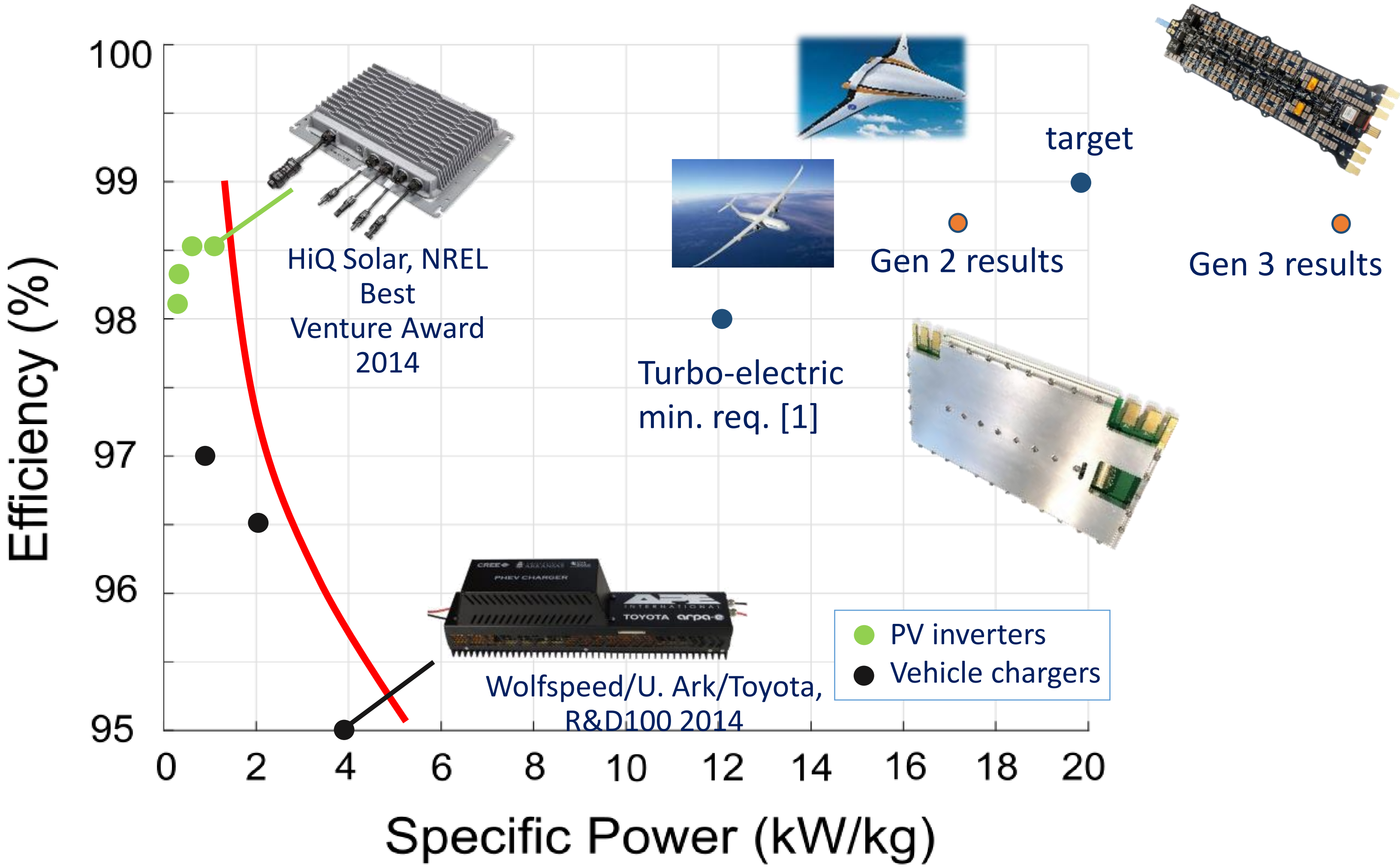
Side view of the switching cell with heat sink mounted to the SMT nuts with plastic screws

Front view of the heat sink with post contacting the GaN device (center)



- Distributed, per-device micro-heatsinks
  - Each GaN/heatsink interface individually tensioned

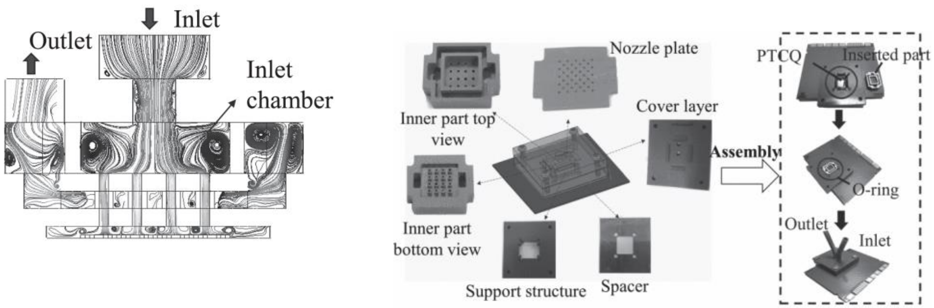
Gen 3 Performance



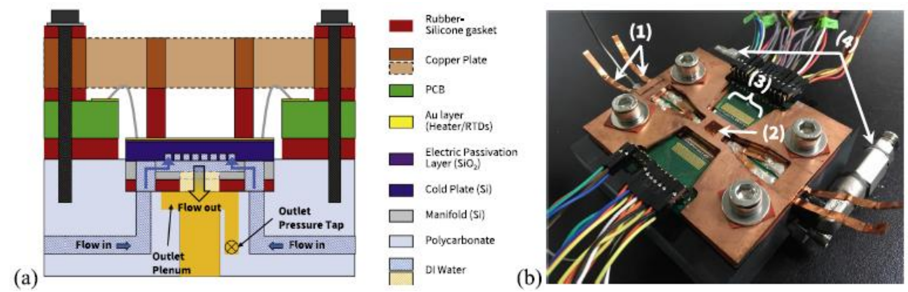
[1] Jansen, Ralph H., et al. "Turboelectric Aircraft Drive Key Performance Parameters and Functional Requirements." (2015).

Packaging and Thermal Opportunities

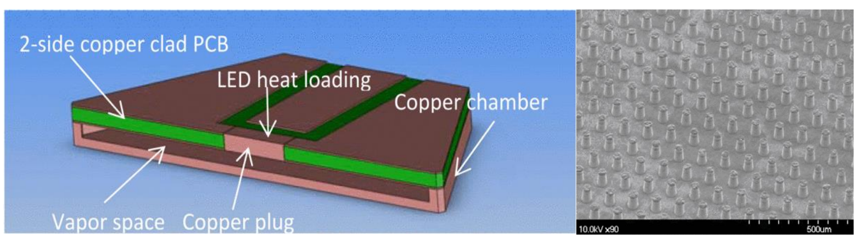
Jet-impingement [1]   60 kW/m^2-K



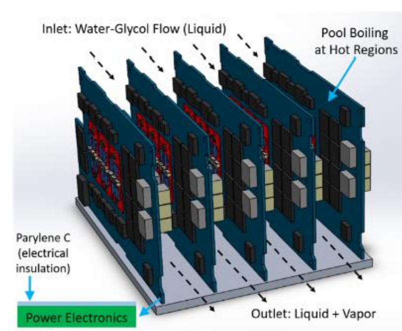
Microchannel [3]   10-80 kW/m^2-K

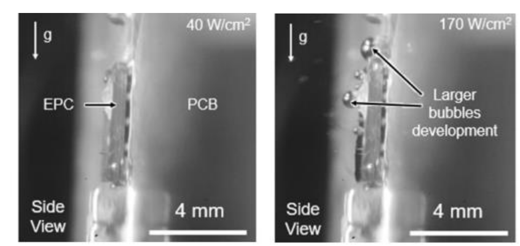


Wicking, Two-Phase [2]   20 kW/m^2-K



Immersion [4]   1-50 kW/m^2-K

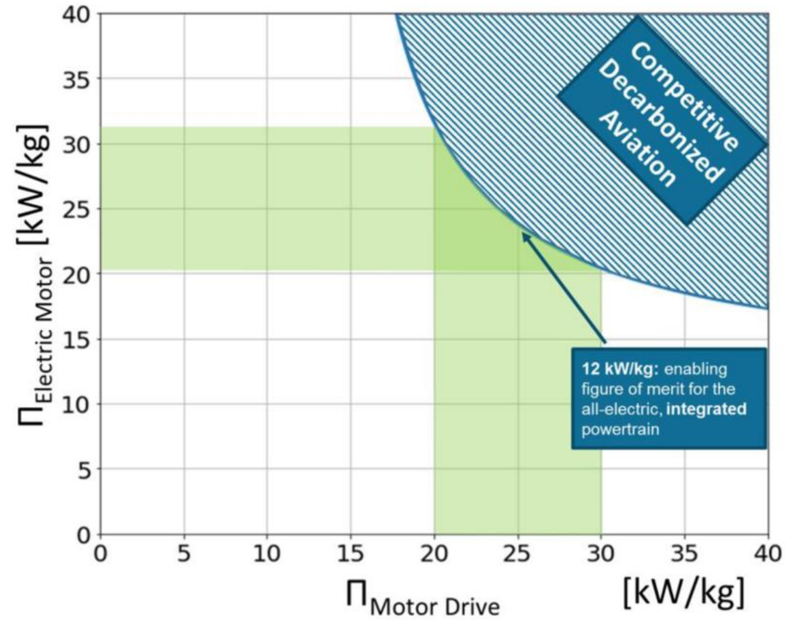


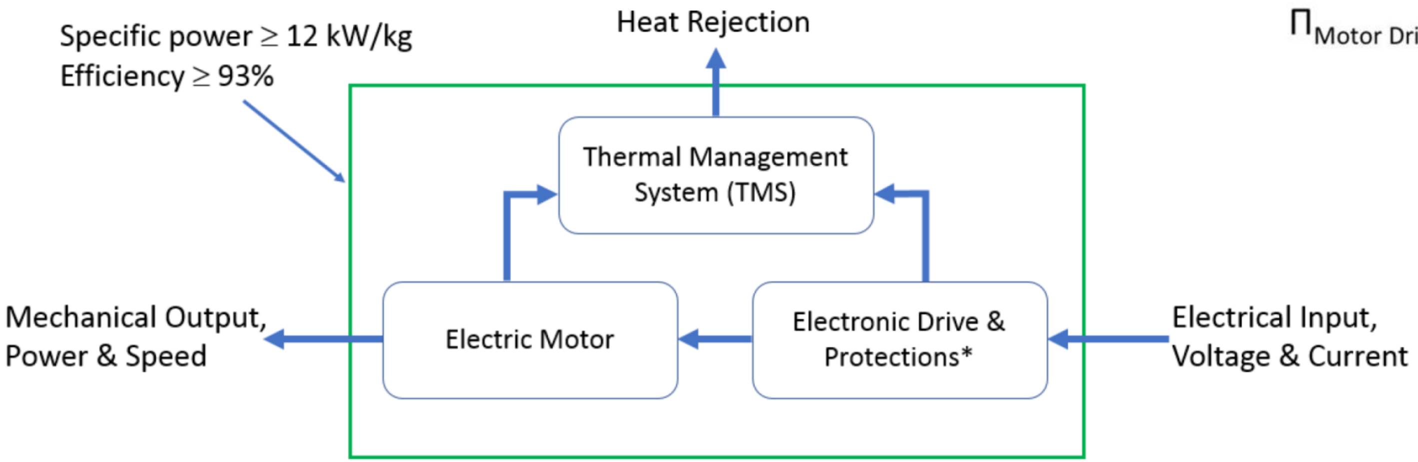


[1] T. Wei et al., “High-Efficiency Polymer-Based Direct Multi-Jet Impingement Cooling Solution for High-Power Devices," IEEE TPE, 2019.
[2] A. Fan, et al., “An innovative passive cooling method for high performance light-emitting diodes,” IEEE SEMI-THERM, 2012.
[3] Jung, K.W., et al., “Embedded cooling with 3D manifold for vehicle power electronics application: Single-phase ... performance,” IJHMT, 2019.
[4] Birbarah, et al., “Water immersion cooling of high power density electronics,” IJHMT, 2020.

Most Recent US Target

- Advanced Research Project Agency for Energy (ARPA-E)
  - Aviation-Class Synergistically Cooled Electric-Motors with Integrated Drives (ASCEND)





* Only protections between motor and electronic drive subsystems are included

Peak Power	Specific Power	Efficiency	DC Bus	MTBF	Certification	Cost/kW
250 kW	≥ 12 kW/kg	≥ 93 %	1 kV	≥ 35,000 hrs	DO-160	≤ 350

Challenge is System Integration

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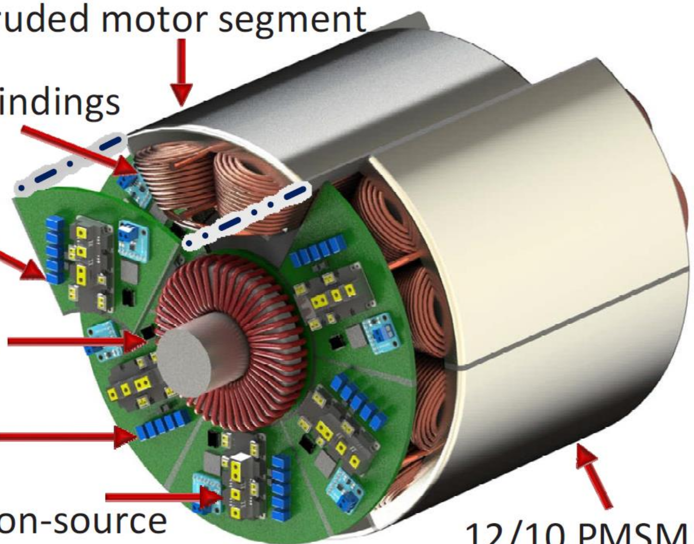

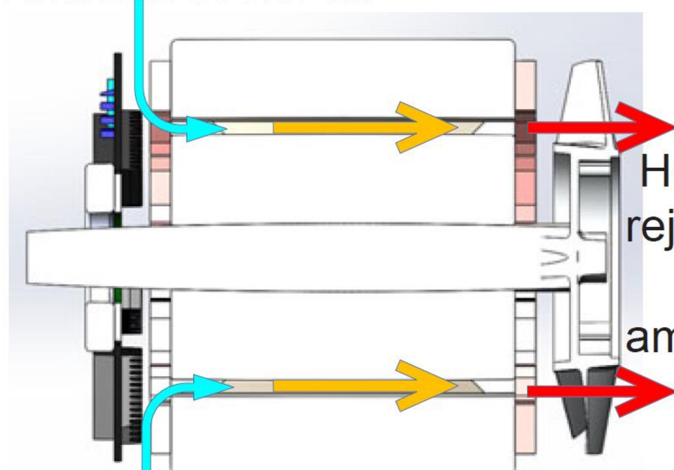

Thermal, Electrical, Mechanical co-design is essential

H. Dai et al., “Development of High-Frequency WBG Power Modules with Reverse-Voltage-Blocking Capability for an Integrated Motor Drive Using a Current-Source Inverter”

Electric Drive Challenges

- Circuit topology is important, but far from the most challenging
  - Thermal management
    - Additive manufacturing opens up possibilities
  - High voltage packaging
    - Even the best power semiconductor is limited by packaging
  - Signal integrity
    - Differential, optical, layout, etc.
  - Reliability and redundancy
    - Component and system level
  - Control complexity

Concluding Thoughts

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- Future innovations in power electronics and drives will likely require strong cross-discipline collaborations
  - Materials, devices, packaging, thermal, sensing, control
- Moving from power converters, to power conversion systems
  - Managing complexity will be essential
- Approaches that leverage integration and digital approaches will scale well
  - Integration -> Number of components is not limiting factor
  - Control complexity can be managed with improved computing
- Industry/Foundry collaborations will likely be essential to remain relevant. A concern for the field in general
- ETH is well positioned to remain at the forefront of power electronics and drives, with strong collaborators and industry ties

Acknowledgments

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UNITED STATES AIR FORCE

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