High density capacitor-based power converters - application challenges and requirements

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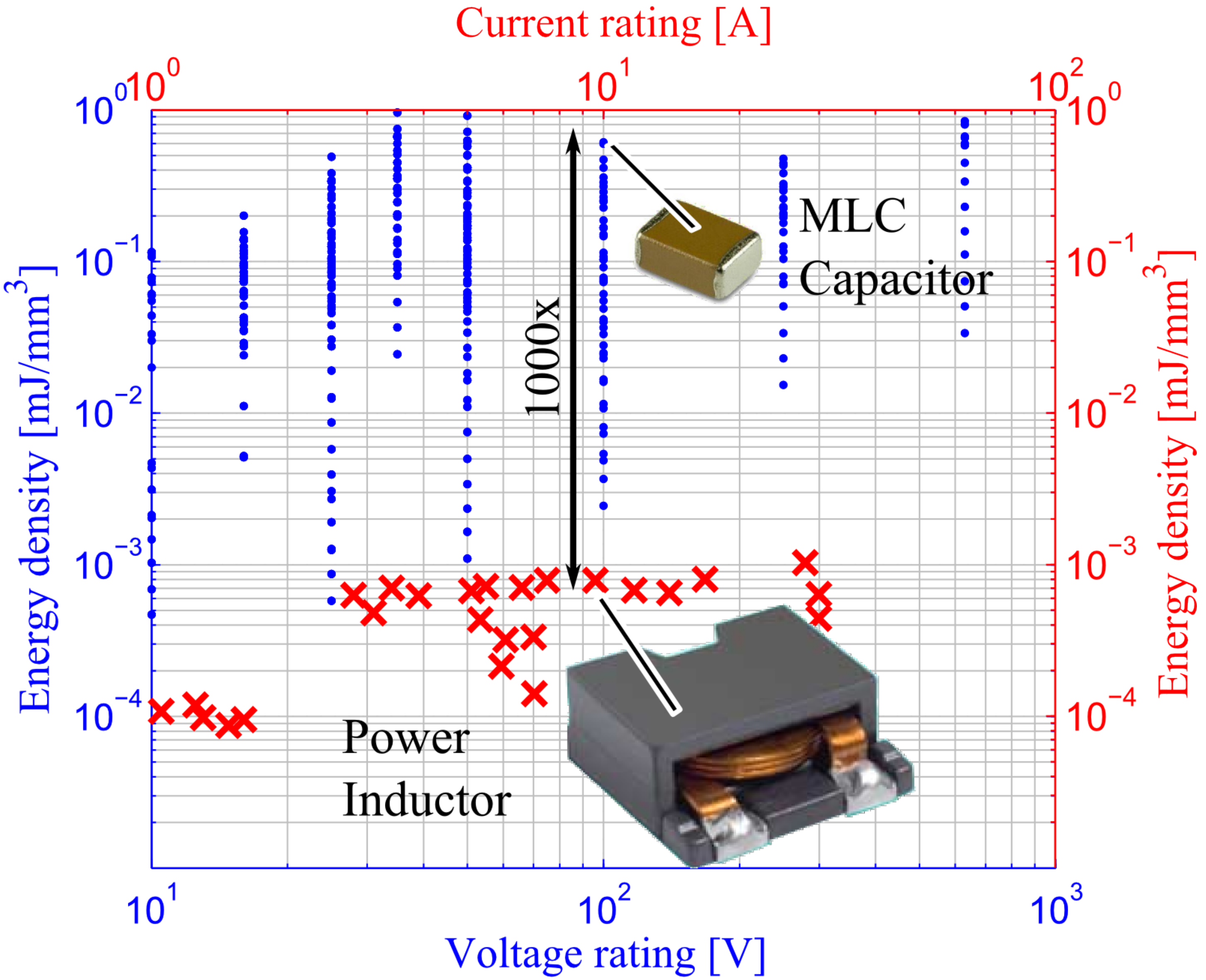
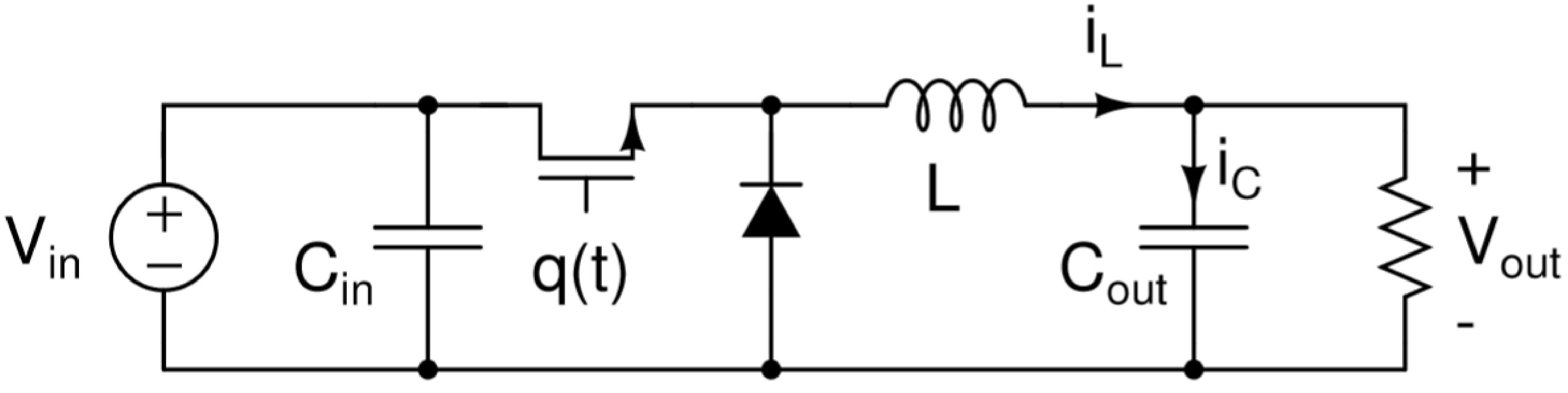
Motivation for capacitor-based converter

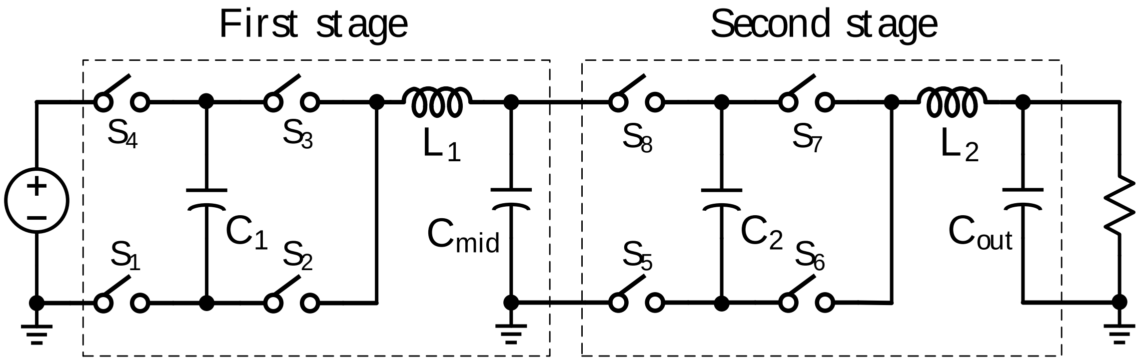


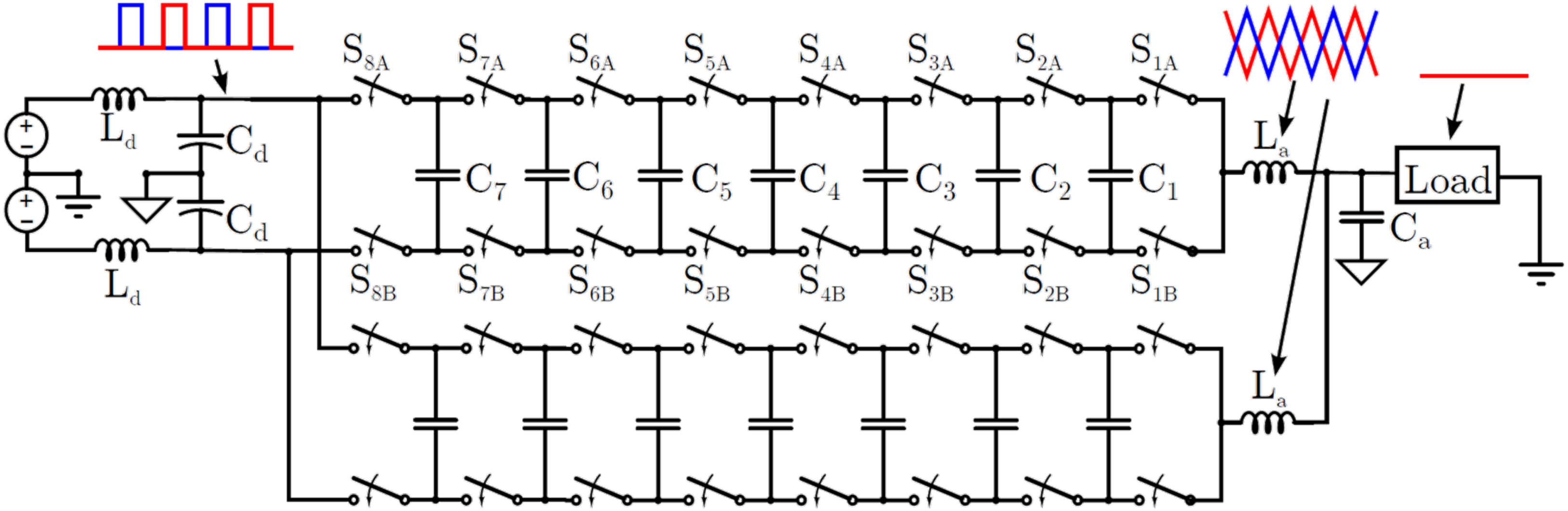
Conventional role – input output filtering



- Inductor key energy transfer element
  - Large, lossy, difficult to design (see room next door 😉)
- Capacitor filter input and output voltages
- What if we did the majority of the energy transfer using high density capacitors?
  - Reduce the job demanded of the inductor
  - Inductor size is determined by volt-seconds

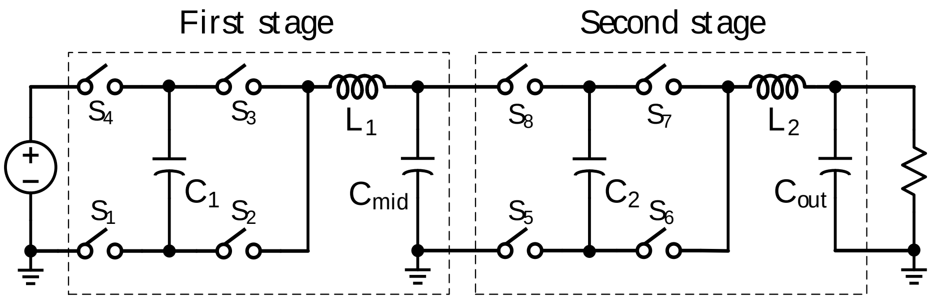
Capacitors for energy transfer



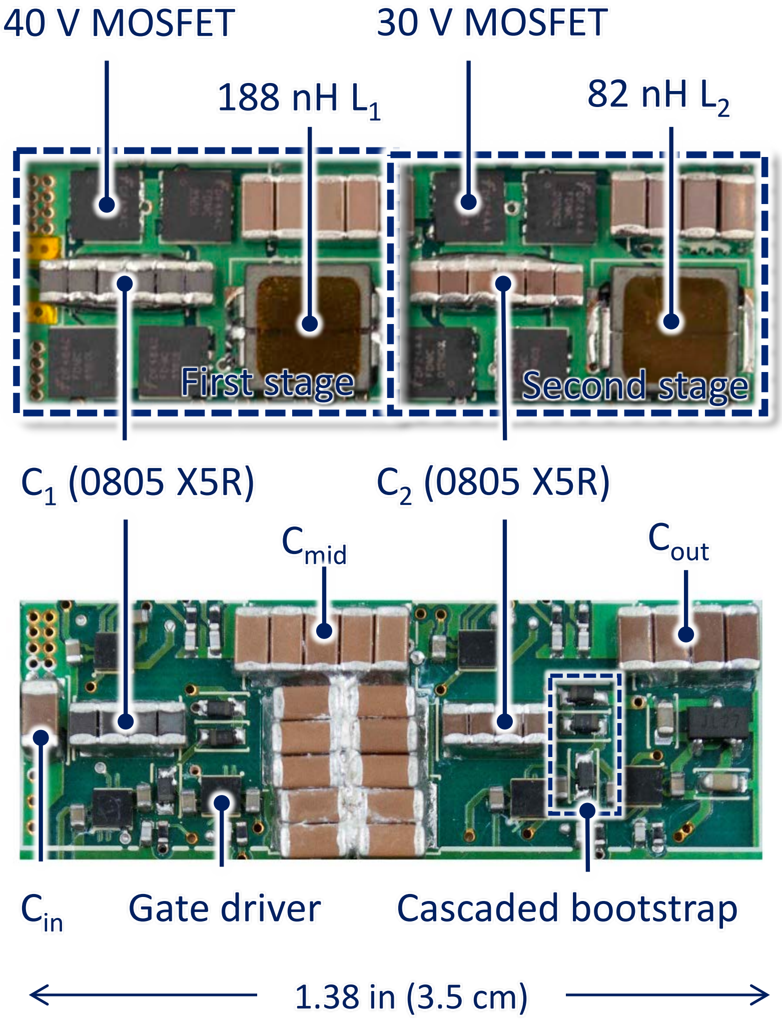


- Hybrid switched-capacitor power converters – majority capacitors, but include one or more inductor

48 V to 12 V resonant hybrid SC converter

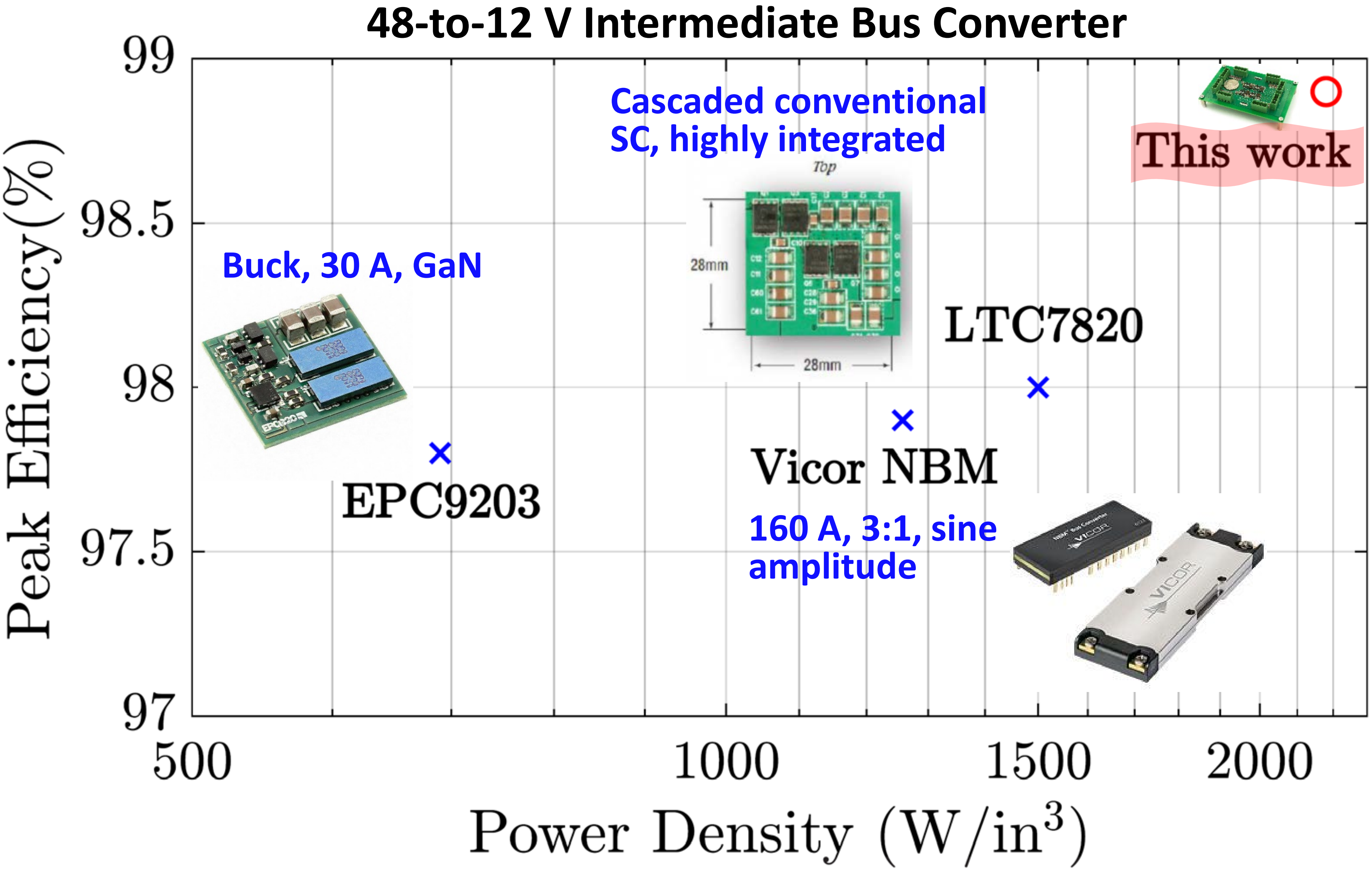


Input voltage range	36 – 60 V
Conversion ratio	4 : 1
Output current	Up to 40 A
Power density	Up to 2180 W/in^3
Peak efficiency	98.9 %
Full power efficiency	98 % (48-to-12 V)



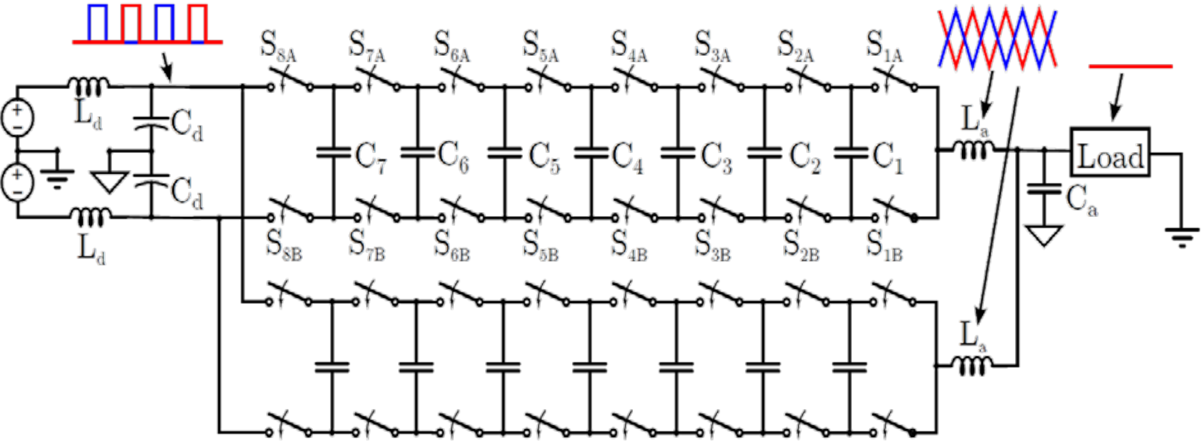
Z. Ye, Y. Lei, R.C.N. Pilawa-Podgurski, “A Resonant Switched Capacitor Based 4-to-1 Bus Converter Achieving 2180 W/In^3 Power Density and 98.9% Peak Efficiency”, APEC 2018 (Tuesday Session, T02)

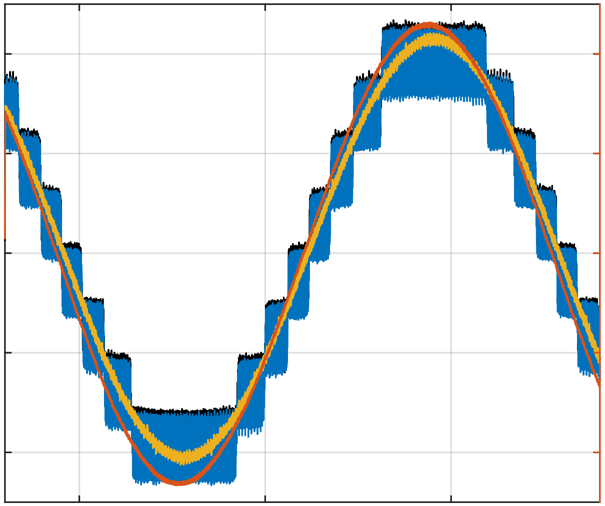
Comparison with state-of-the-art

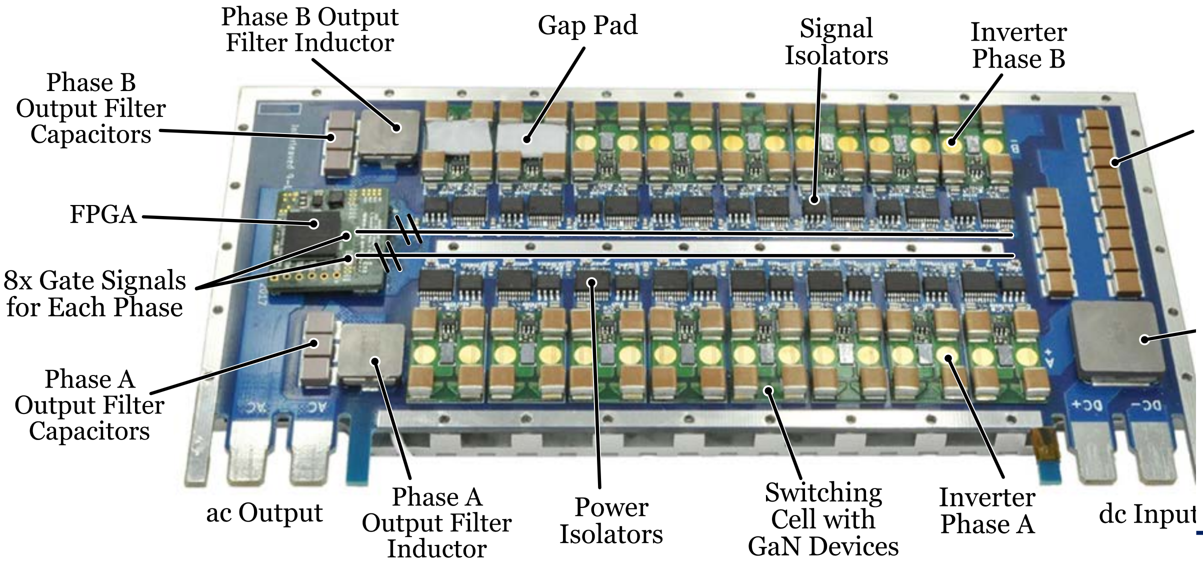


Z. Ye, Y. Lei, R.C.N. Pilawa-Podgurski, "A Resonant Switched Capacitor Based 4-to-1 Bus Converter Achieving 2180 W/In³ Power Density and 98.9% Peak Efficiency", APEC 2018 (Tuesday Session, T02)

High voltage DC-AC converters

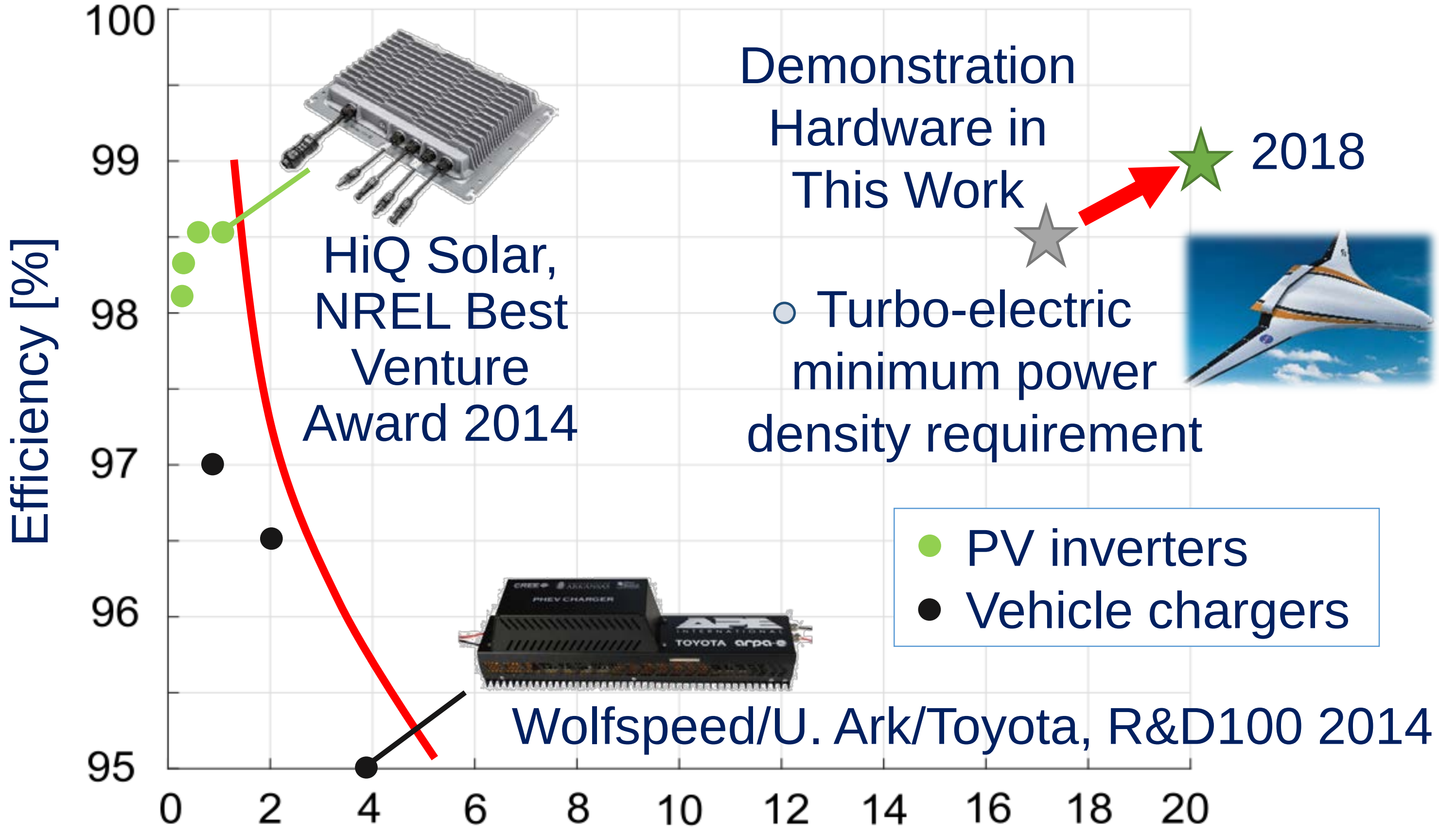






Input DC voltage	1000 V
Output AC voltage	353 V_{rms}
Peak power	9.7 kW
Peak efficiency	98.6%
Converter mass	561.6 g
Full power efficiency	17.3 kW/kg

Performance comparison



N. Pallo, T. Foulks, T. Modeer, S. Coday, R.C.N. Pilawa-Podgurski, "Power-Dense Multilevel Inverter Module Using Interleaved GaN-Based Phases for Electric Aircraft Propulsion ", APEC 2018 (Thursday Session, T35)

Capacitor demands and limitations

- Loss models
  - Need accurate large signal loss models
    - Datasheet gives small signal parameters
  - Loss models under dc bias
    - Datasheet gives ESR for zero bias condition
- Want highest energy density, and lowest loss
  - Ceramics currently favored for highest power density (but more challenging > 600 V)

For hybrid switched-capacitor power converters, accurate loss models are critical to achieve high efficiency and high power density

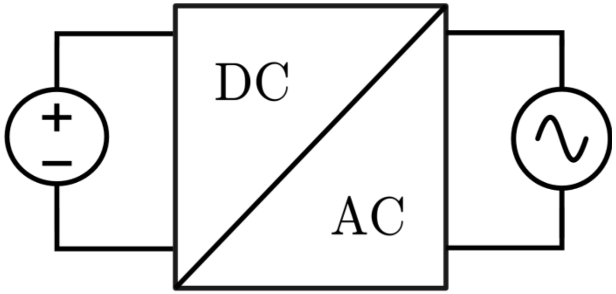
Single-phase DC/AC and AC/DC conversion

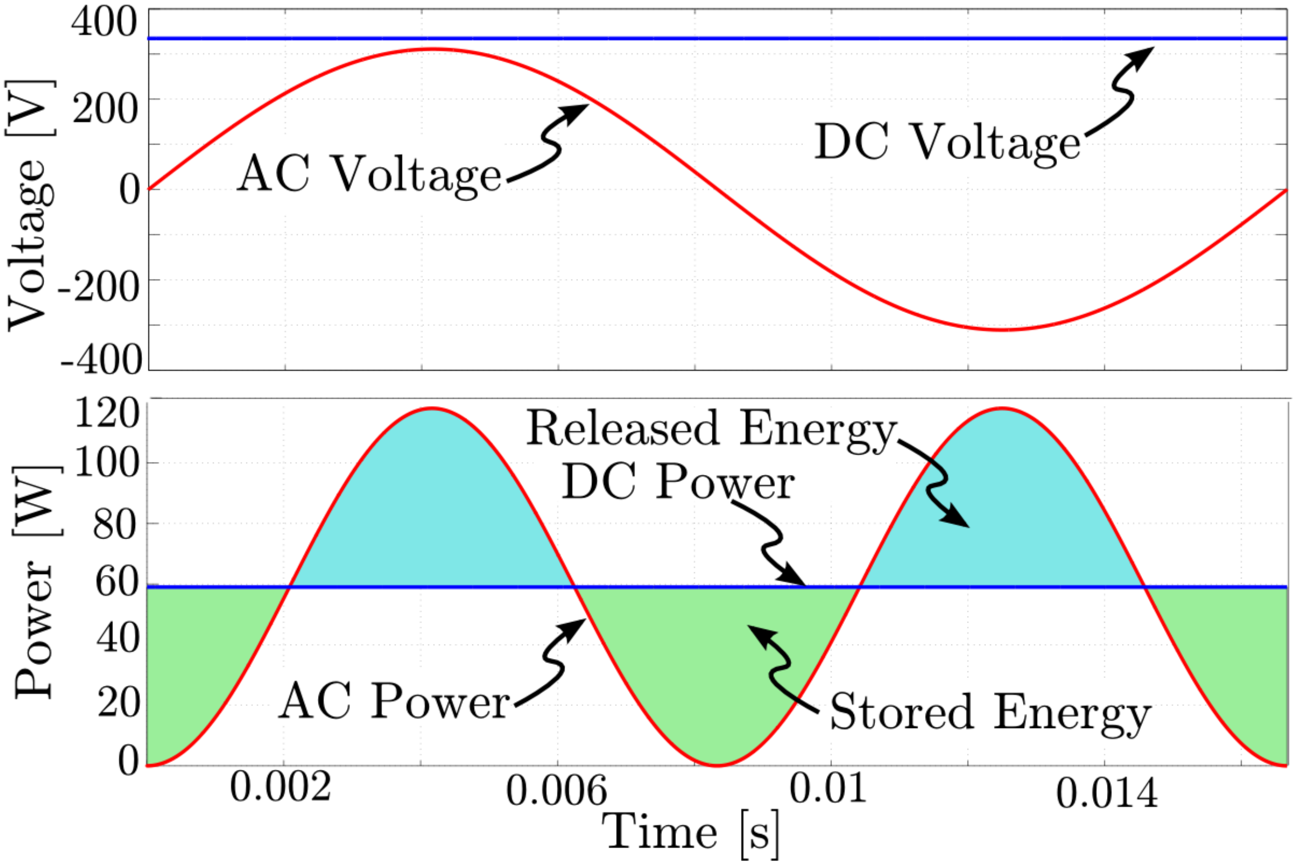
- High density requirements
  - On-board vehicle chargers
  - Grid integration
    - Storage, solar, etc.
  - Data centers
- Google/IEEE Little Box Challenge stimulated research in high density DC/AC conversion

2 kW, 400 VDC to 240 VAC converter, 213 W/in^3

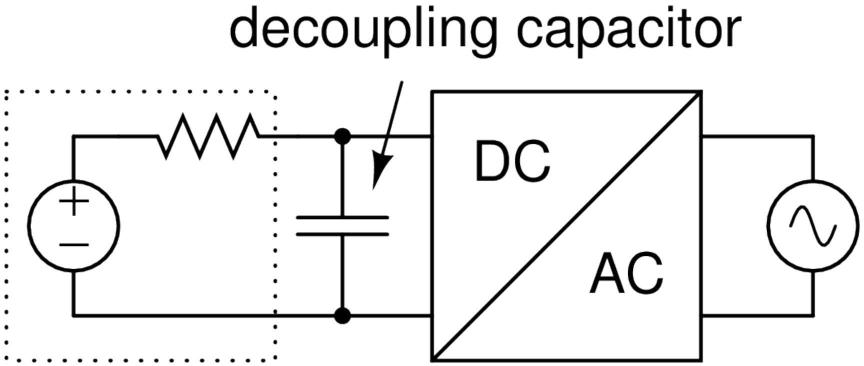
DC-AC Energy Conversion – Buffering Requirement

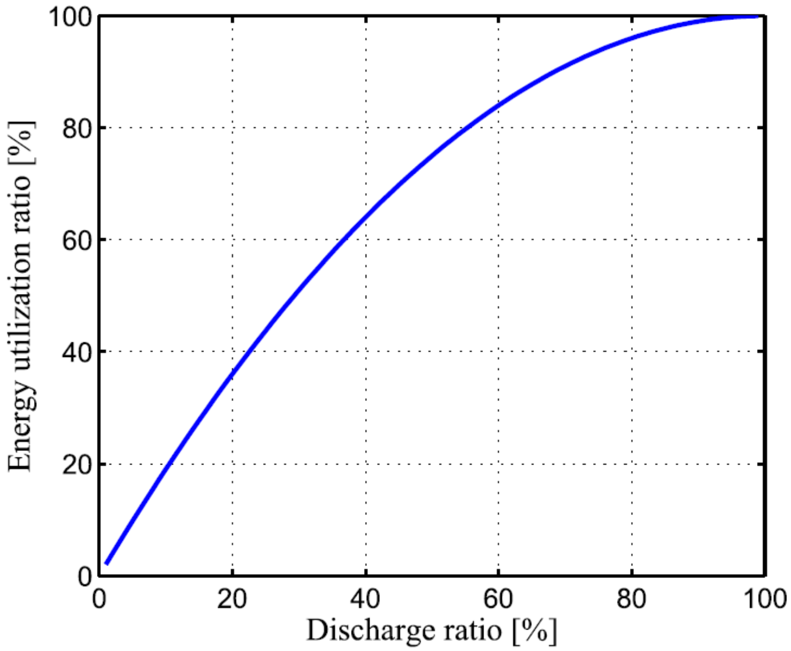
- Instantaneous power mismatch between DC and single-phase AC.
  - $\overline{P_{DC}} = \overline{P_{AC}}$, but $p_{dc} \neq p_{ac}$
  - $E_{store} = \frac{P_{dc}}{2\pi f_{line}}$





DC-AC Energy Conversion – Passive Buffer

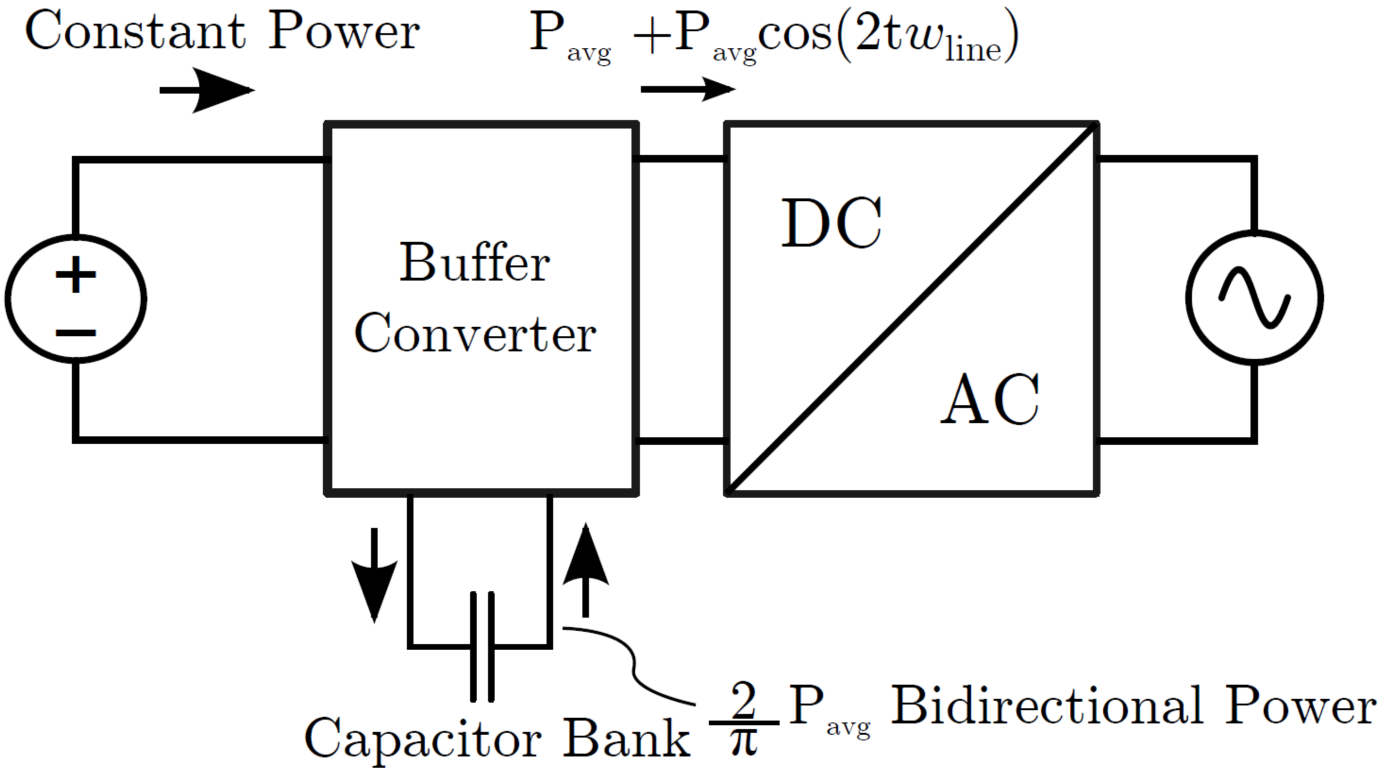

decoupling capacitor



- Capacitor as energy storage
  - $$E_{store} = \frac{P_{dc}}{2\pi f_{line}} = \frac{1}{2}CV_{max}{}^2 - \frac{1}{2}CV_{min}{}^2$$
    $$= C \times \underbrace{\frac{1}{2}(V_{max} + V_{min})}_{\text{nominal bus voltage}} \times \underbrace{(V_{max} - V_{min})}_{\text{bus voltage ripple}}$$
- Small ripple requires a large capacitance.
- Energy storage is underutilized – may be expensive.

DC-AC Energy Conversion – Active Buffer

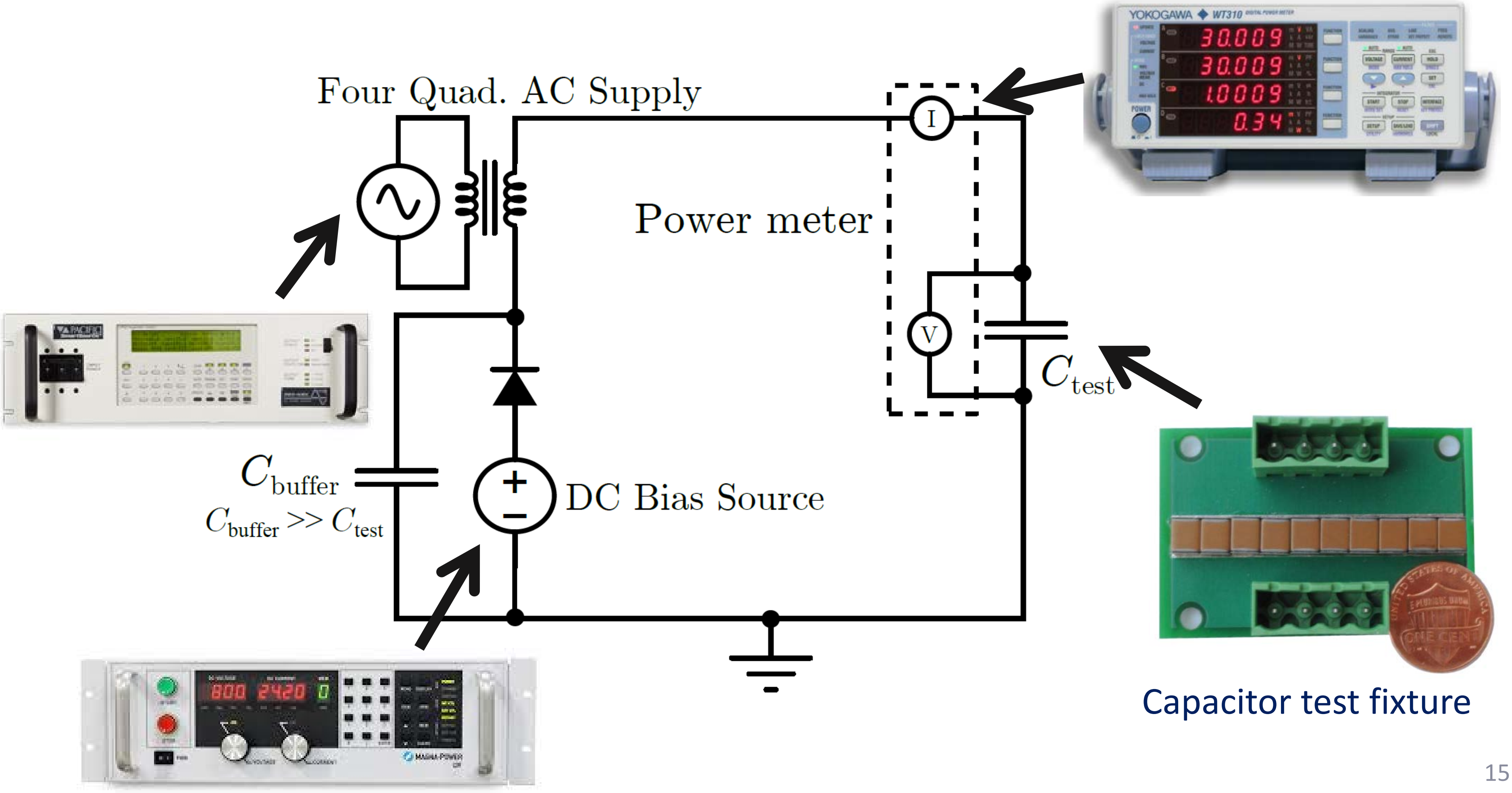
- Active power buffers increase capacitance utilization.
  - Capacitor voltage is cycled over large swing.



Krein et al., Minimum energy and capacitor requirement for single-phase inverters and rectifiers using a ripple port, IEEE TPELS, Nov, 2012

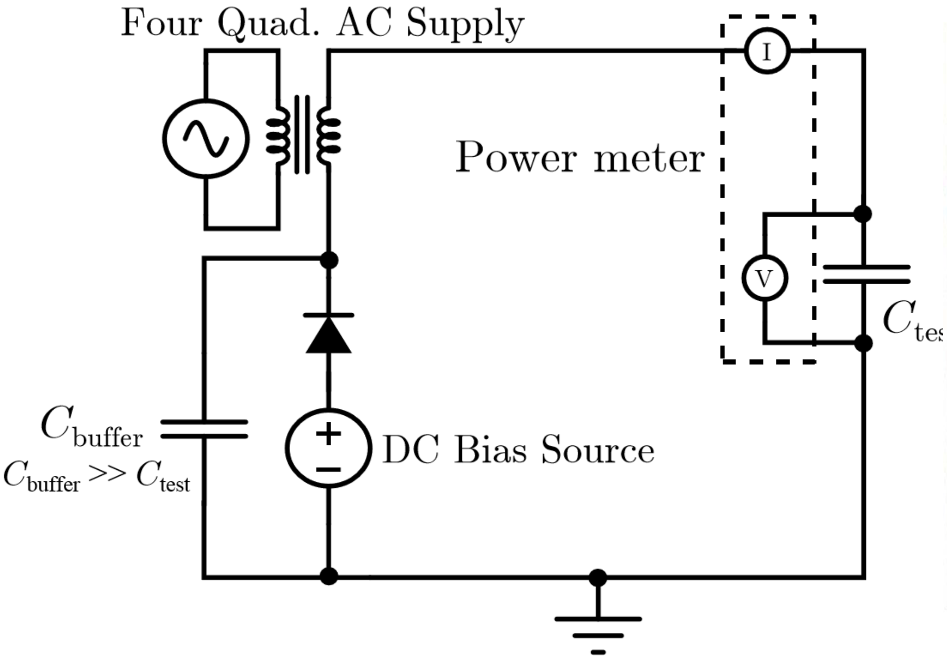
Loss measurements at low frequency

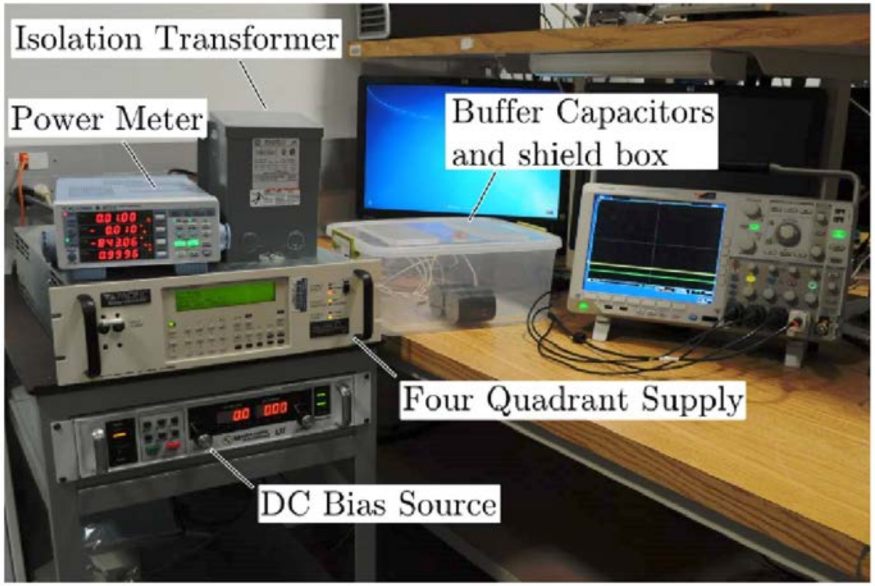
- Experimental test setup developed to measure loss and energy storage over wide voltage swing.
  - Voltage swing and bias are independently adjustable.

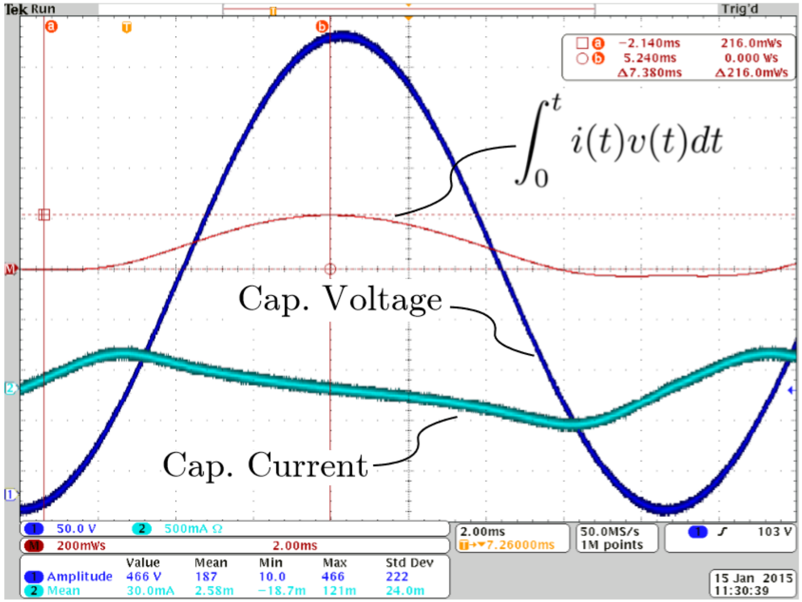


Capacitor test fixture

Loss measurements at low frequency



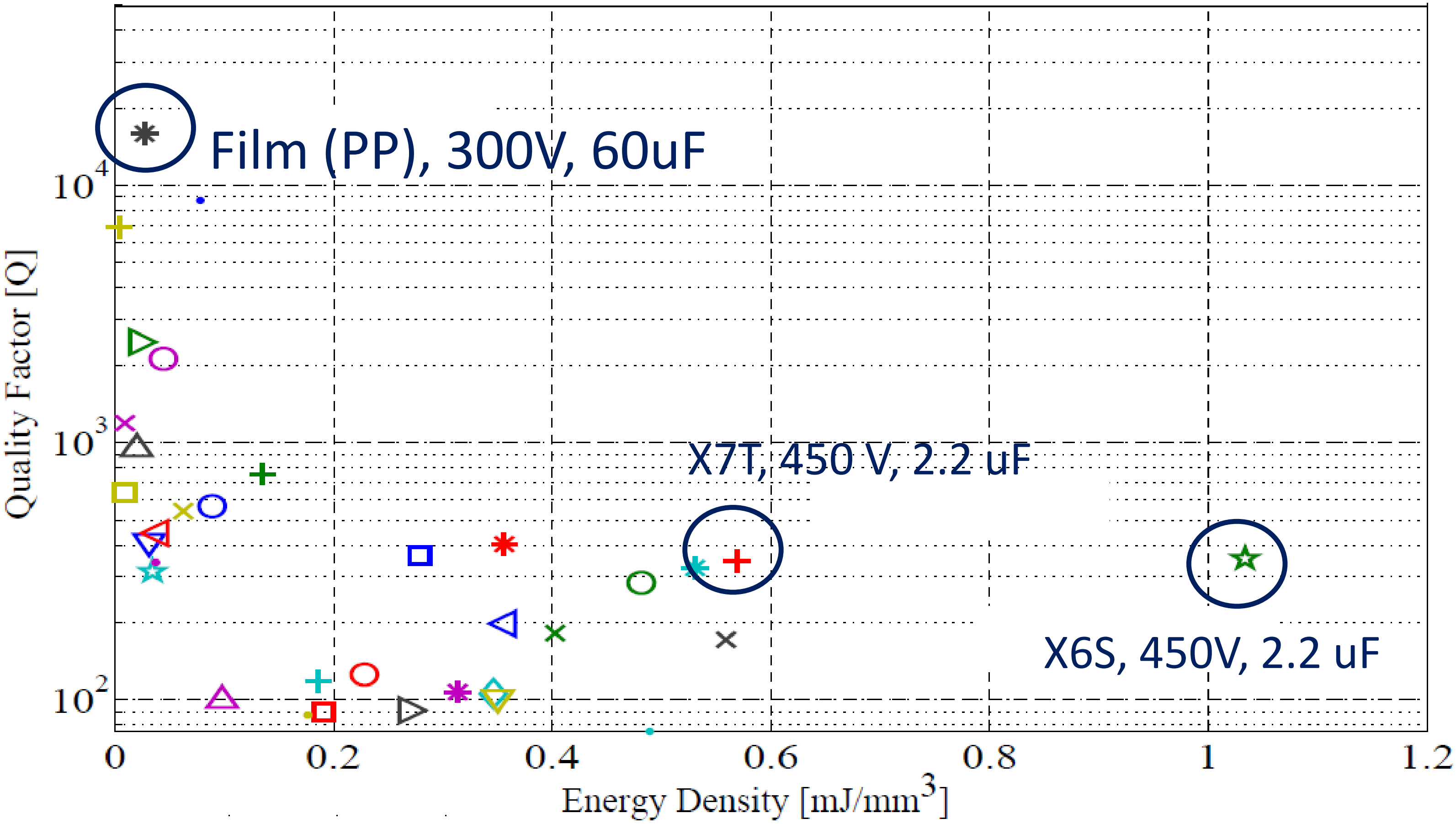




	Value	Mean	Min	Max	Std Dev
1 Amplitude	466 V	187	10.0	466	222
2 Mean	30.0mA	2.58m	−18.7m	121m	24.0m

Experimental Results

- Currently available products show a clear tradeoff between quality factor/efficiency and energy density.



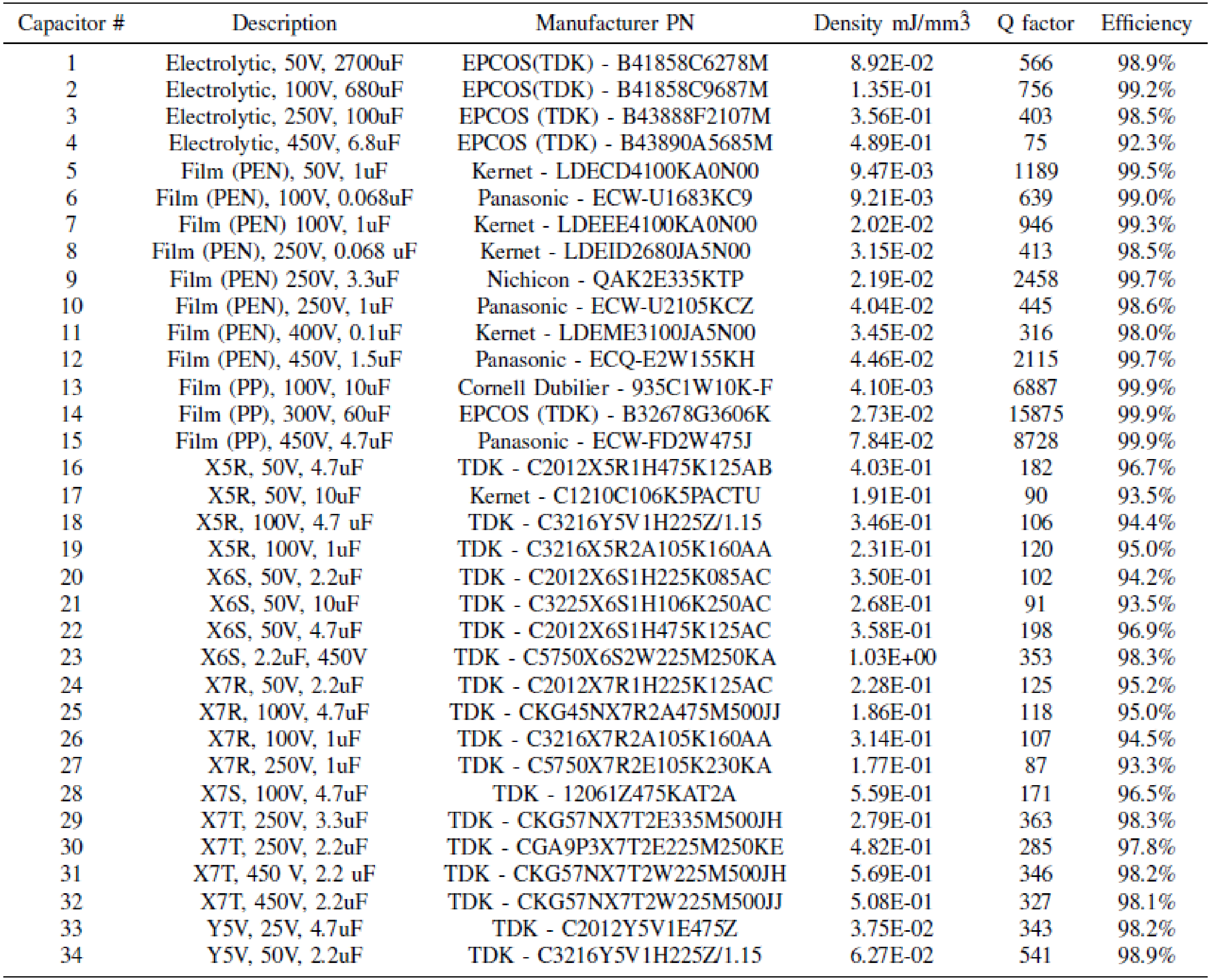
Film (PP), 300V, 60uF

X7T, 450 V, 2.2 uF

X6S, 450V, 2.2 uF

C. Barth, I. Moon, Y. Lei, S. Qin and R.C.N. Pilawa-Podgurski "Experimental Evaluation of Capacitors for Power Buffering in Single-Phase Power Converters," ECCE 2015

Experimental Results



Capacitor #	Description	Manufacturer PN	Density mJ/mm^3	Q factor	Efficiency
1	Electrolytic, 50V, 2700uF	EPCOS(TDK) - B41858C6278M	8.92E-02	566	98.9%
2	Electrolytic, 100V, 680uF	EPCOS(TDK) - B41858C9687M	1.35E-01	756	99.2%
3	Electrolytic, 250V, 100uF	EPCOS (TDK) - B43888F2107M	3.56E-01	403	98.5%
4	Electrolytic, 450V, 6.8uF	EPCOS (TDK) - B43890A5685M	4.89E-01	75	92.3%
5	Film (PEN), 50V, 1uF	Kernet - LDECD4100KA0N00	9.47E-03	1189	99.5%
6	Film (PEN), 100V, 0.068uF	Panasonic - ECW-U1683KC9	9.21E-03	639	99.0%
7	Film (PEN) 100V, 1uF	Kernet - LDEEE4100KA0N00	2.02E-02	946	99.3%
8	Film (PEN), 250V, 0.068 uF	Kernet - LDEID2680JA5N00	3.15E-02	413	98.5%
9	Film (PEN) 250V, 3.3uF	Nichicon - QAK2E335KTP	2.19E-02	2458	99.7%
10	Film (PEN), 250V, 1uF	Panasonic - ECW-U2105KCZ	4.04E-02	445	98.6%
11	Film (PEN), 400V, 0.1uF	Kernet - LDEME3100JA5N00	3.45E-02	316	98.0%
12	Film (PEN), 450V, 1.5uF	Panasonic - ECQ-E2W155KH	4.46E-02	2115	99.7%
13	Film (PP), 100V, 10uF	Cornell Dubilier - 935C1W10K-F	4.10E-03	6887	99.9%
14	Film (PP), 300V, 60uF	EPCOS (TDK) - B32678G3606K	2.73E-02	15875	99.9%
15	Film (PP), 450V, 4.7uF	Panasonic - ECW-FD2W475J	7.84E-02	8728	99.9%
16	X5R, 50V, 4.7uF	TDK - C2012X5R1H475K125AB	4.03E-01	182	96.7%
17	X5R, 50V, 10uF	Kernet - C1210C106K5PACTU	1.91E-01	90	93.5%
18	X5R, 100V, 4.7 uF	TDK - C3216Y5V1H225Z/1.15	3.46E-01	106	94.4%
19	X5R, 100V, 1uF	TDK - C3216X5R2A105K160AA	2.31E-01	120	95.0%
20	X6S, 50V, 2.2uF	TDK - C2012X6S1H225K085AC	3.50E-01	102	94.2%
21	X6S, 50V, 10uF	TDK - C3225X6S1H106K250AC	2.68E-01	91	93.5%
22	X6S, 50V, 4.7uF	TDK - C2012X6S1H475K125AC	3.58E-01	198	96.9%
23	X6S, 2.2uF, 450V	TDK - C5750X6S2W225M250KA	1.03E+00	353	98.3%
24	X7R, 50V, 2.2uF	TDK - C2012X7R1H225K125AC	2.28E-01	125	95.2%
25	X7R, 100V, 4.7uF	TDK - CKG45NX7R2A475M500JJ	1.86E-01	118	95.0%
26	X7R, 100V, 1uF	TDK - C3216X7R2A105K160AA	3.14E-01	107	94.5%
27	X7R, 250V, 1uF	TDK - C5750X7R2E105K230KA	1.77E-01	87	93.3%
28	X7S, 100V, 4.7uF	TDK - 12061Z475KAT2A	5.59E-01	171	96.5%
29	X7T, 250V, 3.3uF	TDK - CKG57NX7T2E335M500JH	2.79E-01	363	98.3%
30	X7T, 250V, 2.2uF	TDK - CGA9P3X7T2E225M250KE	4.82E-01	285	97.8%
31	X7T, 450 V, 2.2 uF	TDK - CKG57NX7T2W225M500JH	5.69E-01	346	98.2%
32	X7T, 450V, 2.2uF	TDK - CKG57NX7T2W225M500JJ	5.08E-01	327	98.1%
33	Y5V, 25V, 4.7uF	TDK - C2012Y5V1E475Z	3.75E-02	343	98.2%
34	Y5V, 50V, 2.2uF	TDK - C3216Y5V1H225Z/1.15	6.27E-02	541	98.9%

Test data from paper appendix.

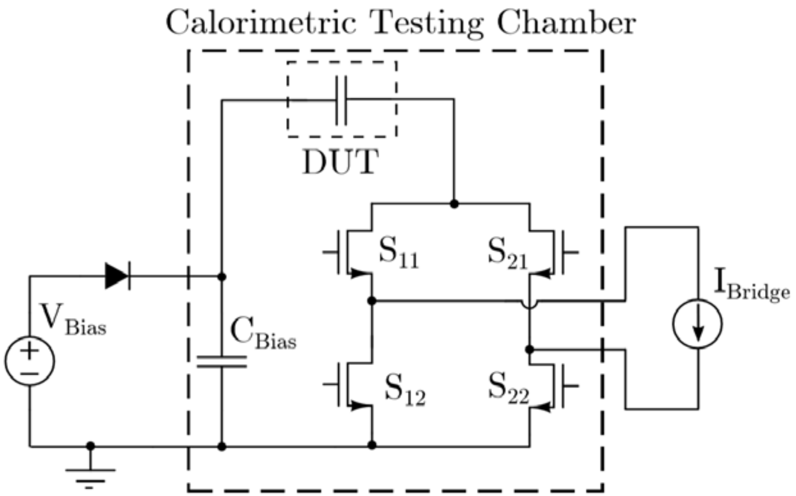
High Frequency Loss Measurement

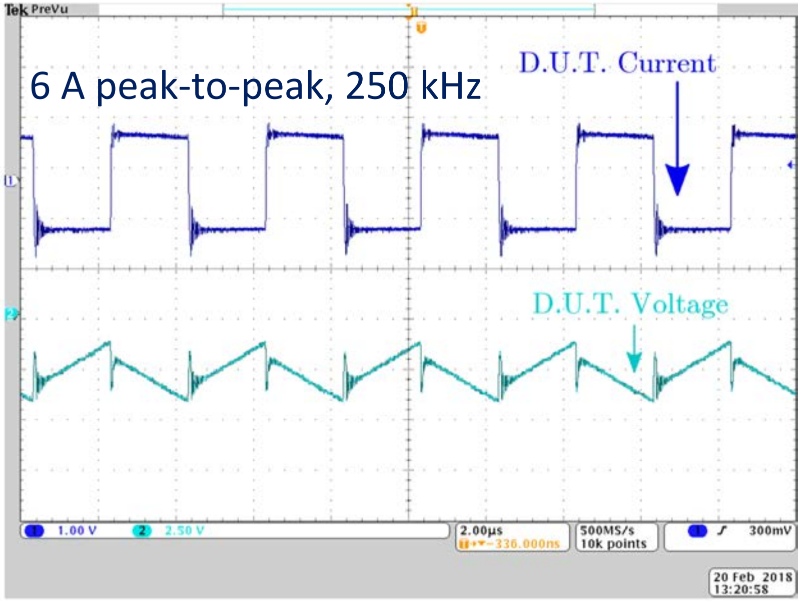
Can we employ the same technique to measure high (>100’s of kHz) frequency losses?

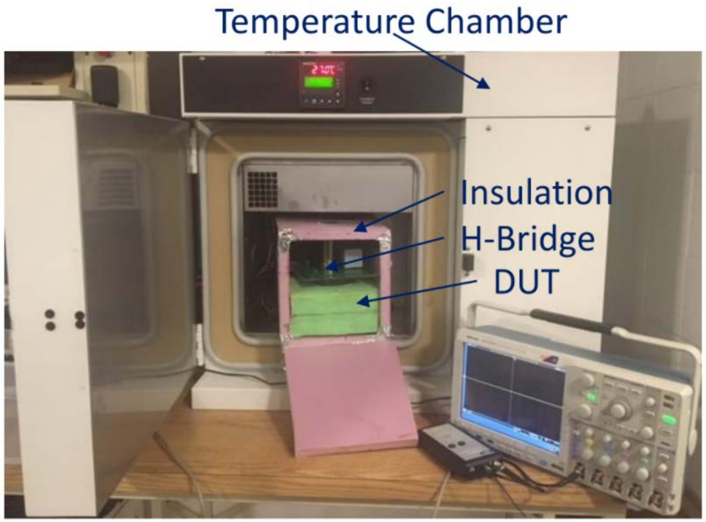
Very difficult to achieve high amplitude, high frequency, high resolution *electrical measurements* of sufficient quality

Large signal loss parameters at high frequency

- Currently exploring calorimetric methods



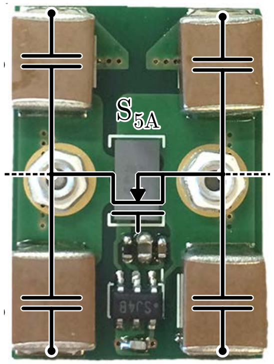


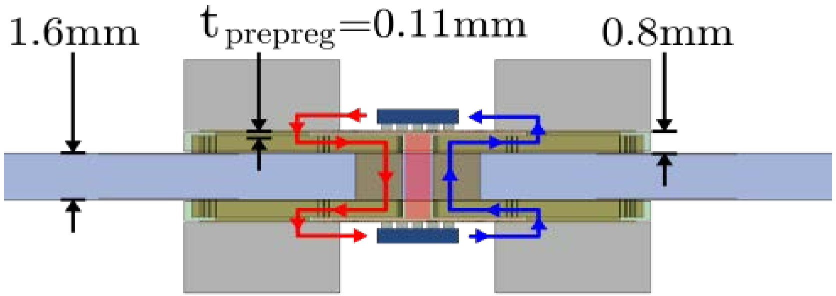


DC bias voltage	Power Loss
0 V	2.67 W
100 V	2.85 W
200 V	3.25 W
400 W	4.35 W

Packaging and reliability concerns

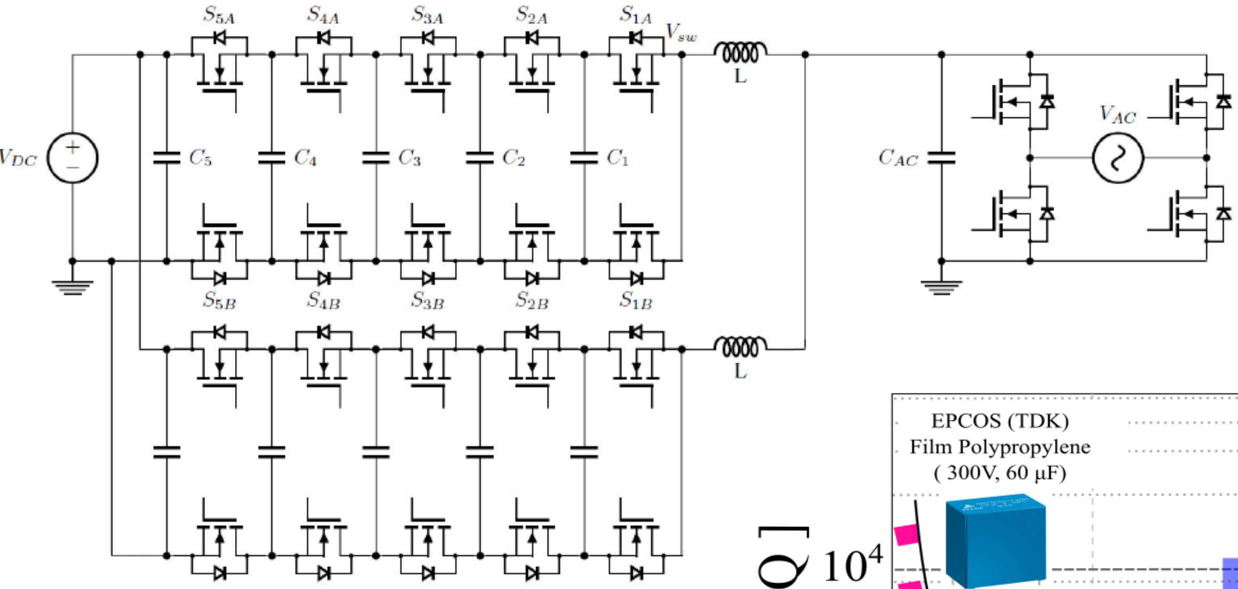
- Many distributed capacitors throughout the circuit, all near transistors
  - Need small form factors, small values are OK
  - Low inductance packages extremely important
  - Placed near significant heat sources
- Mechanical concerns
  - Heatsink pressure, clearances
  - Soft termination appears helpful
  - Piezoelectric effects observed

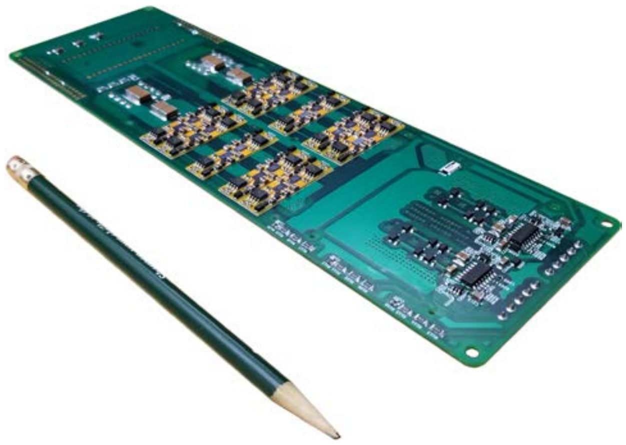


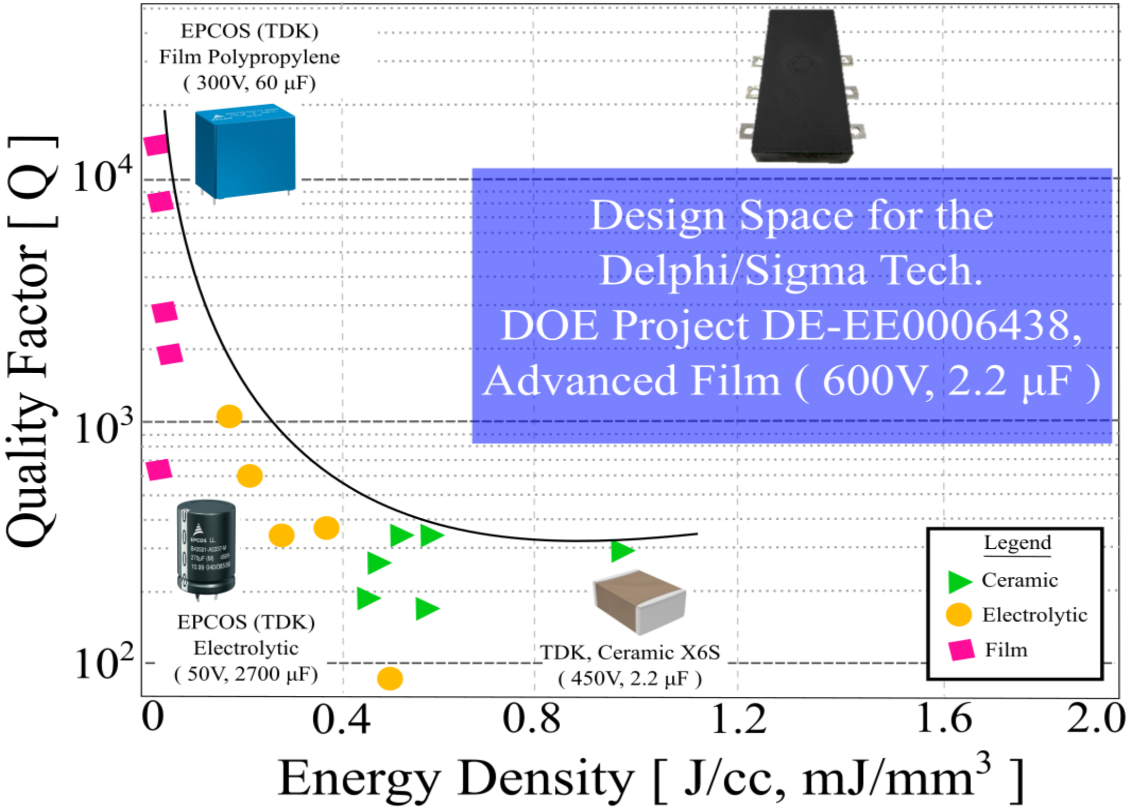


Advanced converter/capacitor development

- ARPA-E funded 6.6 kW bi-directional EV charger (2018)



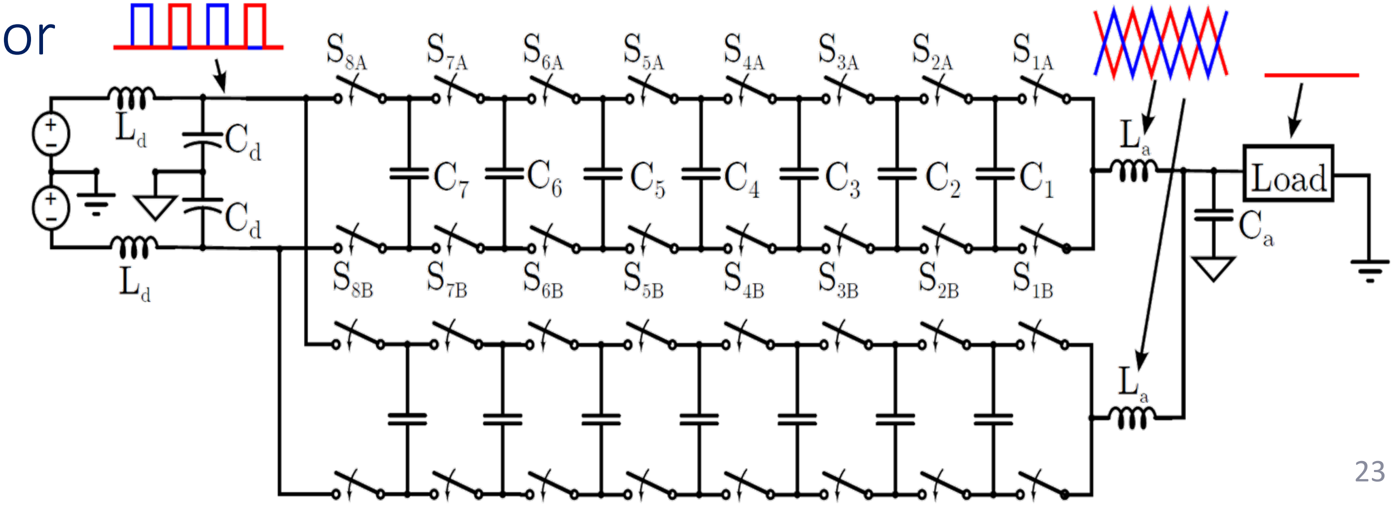




Design Space for the Delphi/Sigma Tech. DOE Project DE-EE0006438, Advanced Film (600V, 2.2 µF)

Conclusions

- Capacitor-based power converters
  - Ready for prime time
  - Show great promise to achieve superior efficiency and power density compared to inductor based designs
- Need better models/data
  - Larger signal loss parameters
  - Impact of DC bias
- Need even better capacitors
  - Energy density
  - Quality factor
  - Reliability



Acknowledgments

- NASA
- Google
- National Science Foundation and the Center for Power Optimization of Electro-thermal Systems (POETS)