Potential of Hybrid Converters in Compute Platform Power Delivery

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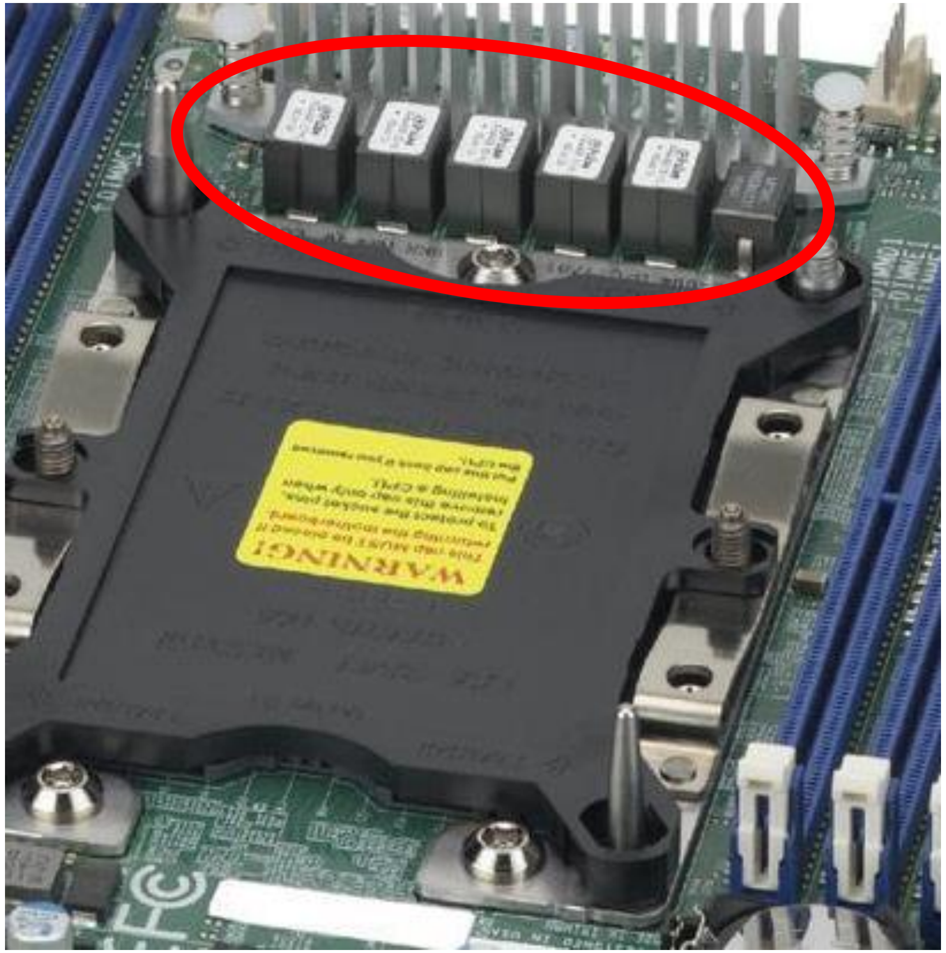
Power Delivery Today - Server

- 12 V to 1.8 V still dominates
- 48 V not yet entering mainstream

Challenges

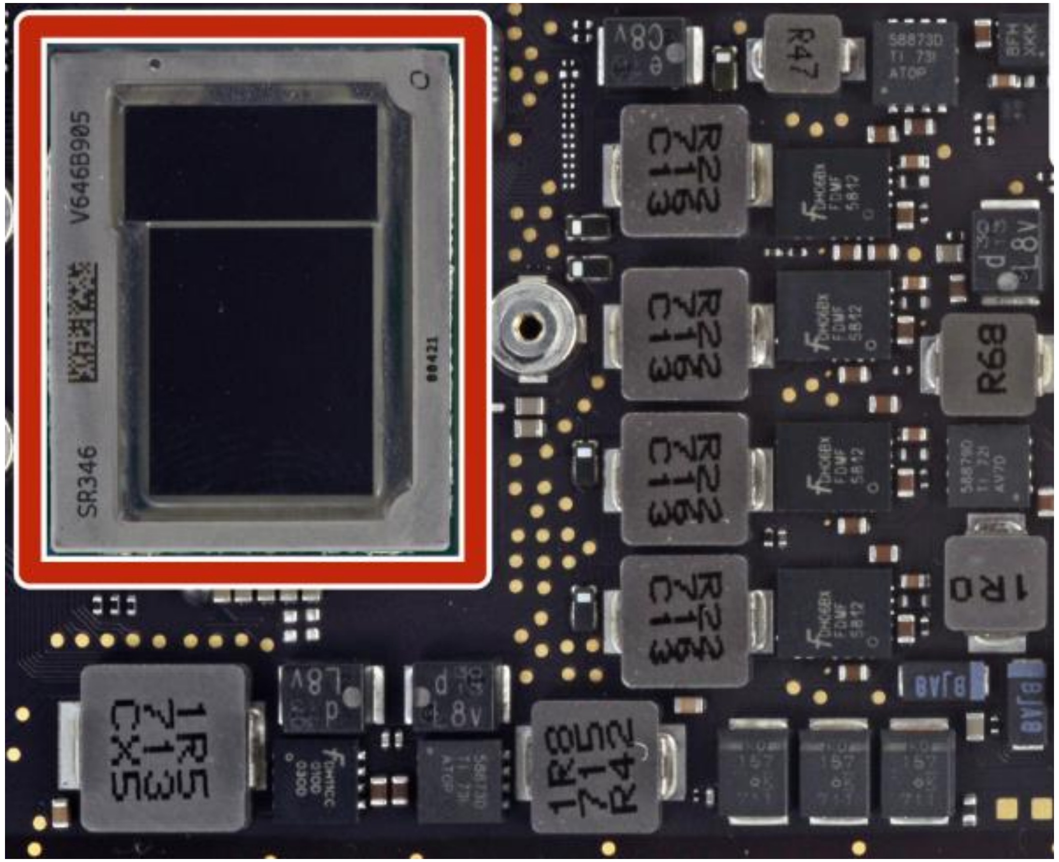
- ➢ Current levels approaching 1kA
- ➢ Large VRs and passives cause high distribution losses and ac loadline
- ➢ Bottleneck for scaling in fixed-form factor
- ➢ Efficiency is $ (expecting 95% for 12 to 1.8V)



Source: SUPERMICRO

Power Delivery Today – Client

- Mobile most challenging
- 2/3S NVDC and 20V to 0.5-1.8V



Source: ifixit.com

Challenges

- ➢ Highly dynamic currents (7W TDP SOC may require 50A for short time)
- ➢ Transient requirements (limited decoupling)
- ➢ Low profile (~1mm) for passives
- ➢ Efficiency across wide load range

Power Conversion Directions

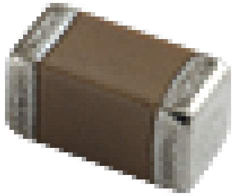
Increase Switching Frequency

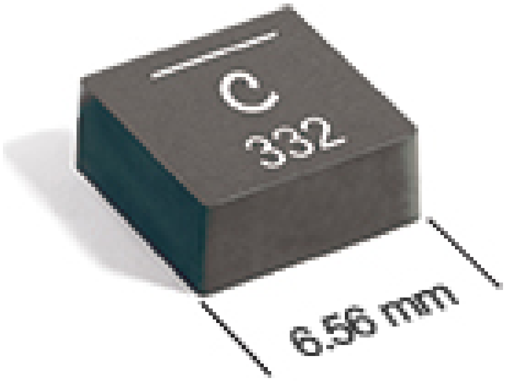
- ❑ Can reduce size and increase bandwidth
- ❑ Better devices and passives needed to maintain efficiency (e.g. GaN)

New topologies

- ❑ Use devices and passives available today
- ❑ Shift to topologies which use switched capacitor techniques
- ❑ Recent work hybrid/resonant converters shows great potential

Why capacitors?





Ceramic Capacitor (0402)
Murata GRM155B31A225KE95

Ferrite Inductor
Coilcraft XAL6030-102ME

Value	2.2 µF	1 µH
Size	1x0.5x0.5 mm	6.4x6.6x3.1 mm
Energy Density	440 $\mu J/mm^3$	2 $\mu J/mm^3$
Q @ 1MHz	2000	20*

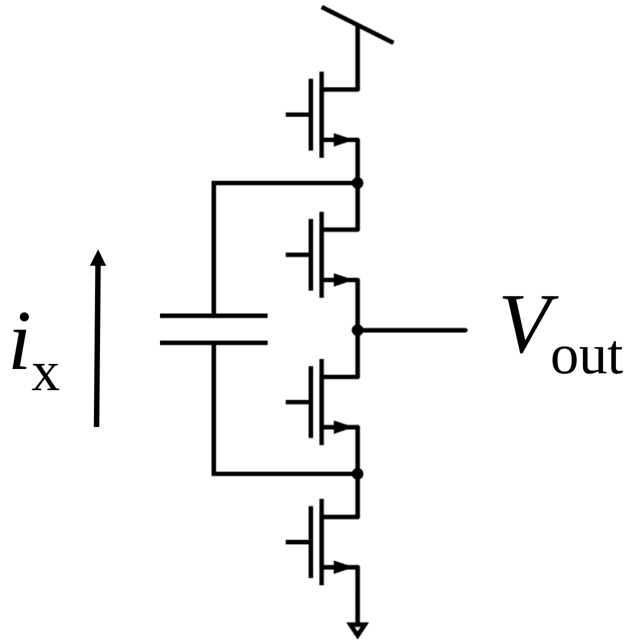
*includes core losses per Coilcraft calculator

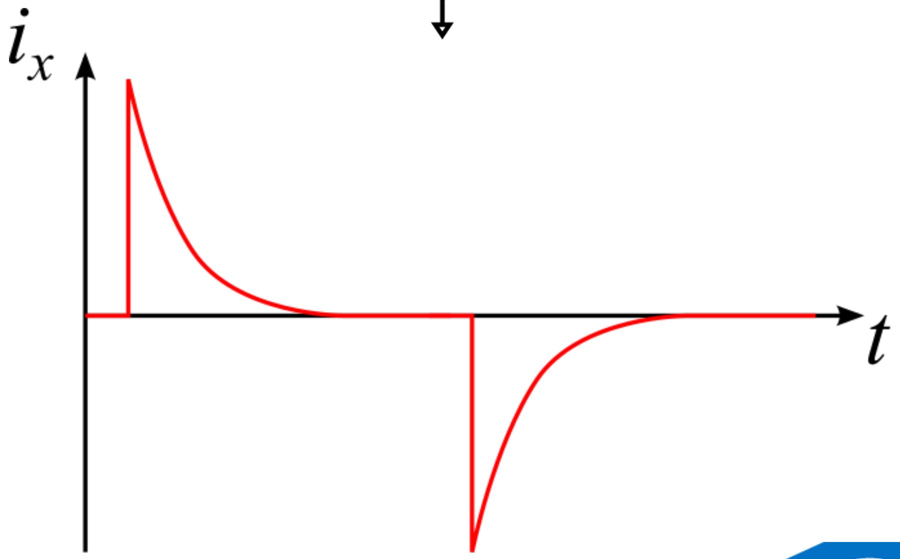
Murata GRM155B31A225KE95 (https://psearch.en.murata.com/capacitor/product/GRM155B31A225KE95%23.html)
Coilcraft XAL6030-102ME (https://www.coilcraft.com/pdfs/xal60xx.pdf)

Why not only use Capacitors?

- ❑ Capacitors store energy very effectively but energy transfer is inefficient
- ❑ Charge-Sharing losses grow with larger ΔV
- ❑ Need large C to achieve high efficiency

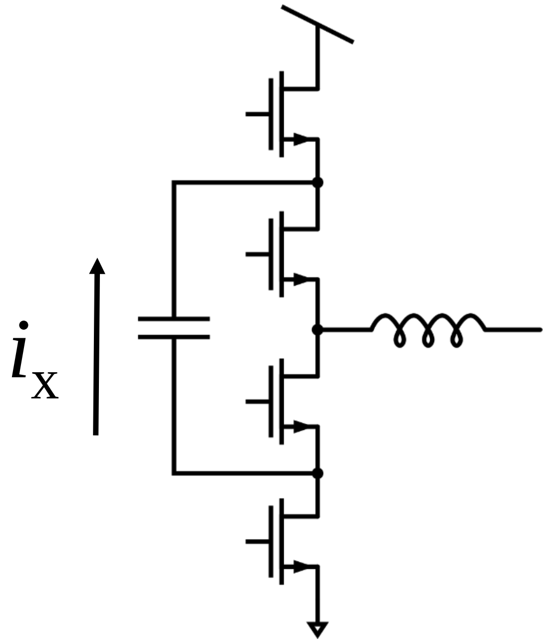
➢Cannot achieve high Power Density and High efficiency

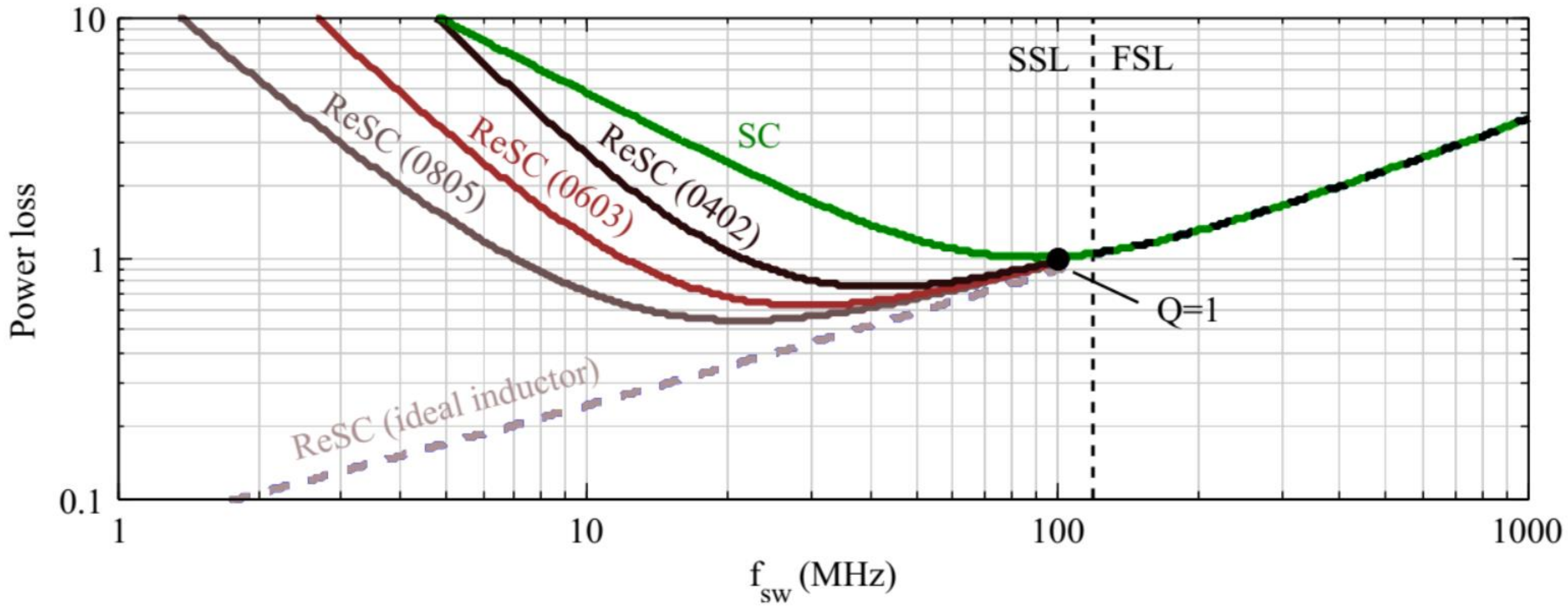


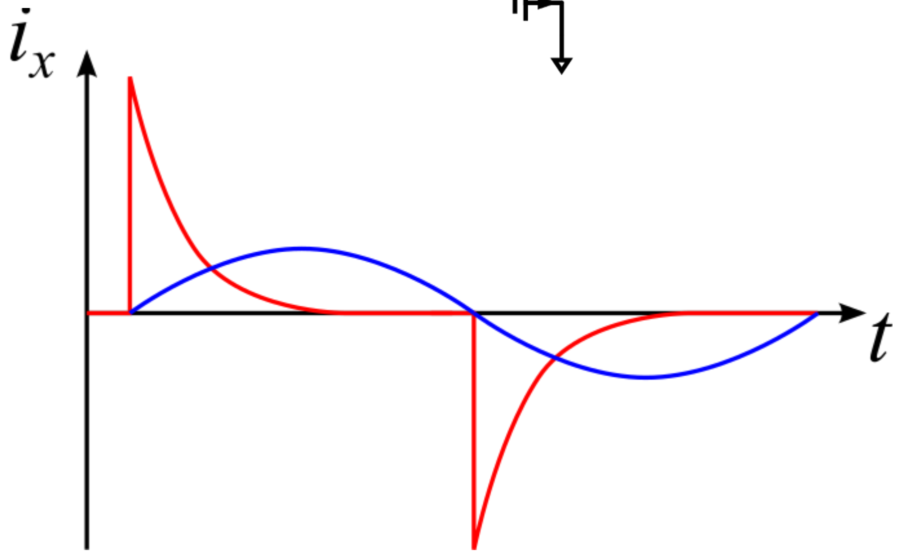


Resonant Switched-Capacitor

- Can charge/discharge capacitors through inductors
- Resonant charge transfer eliminates charge-sharing losses
- Very small inductor enough to achieve significant improvement





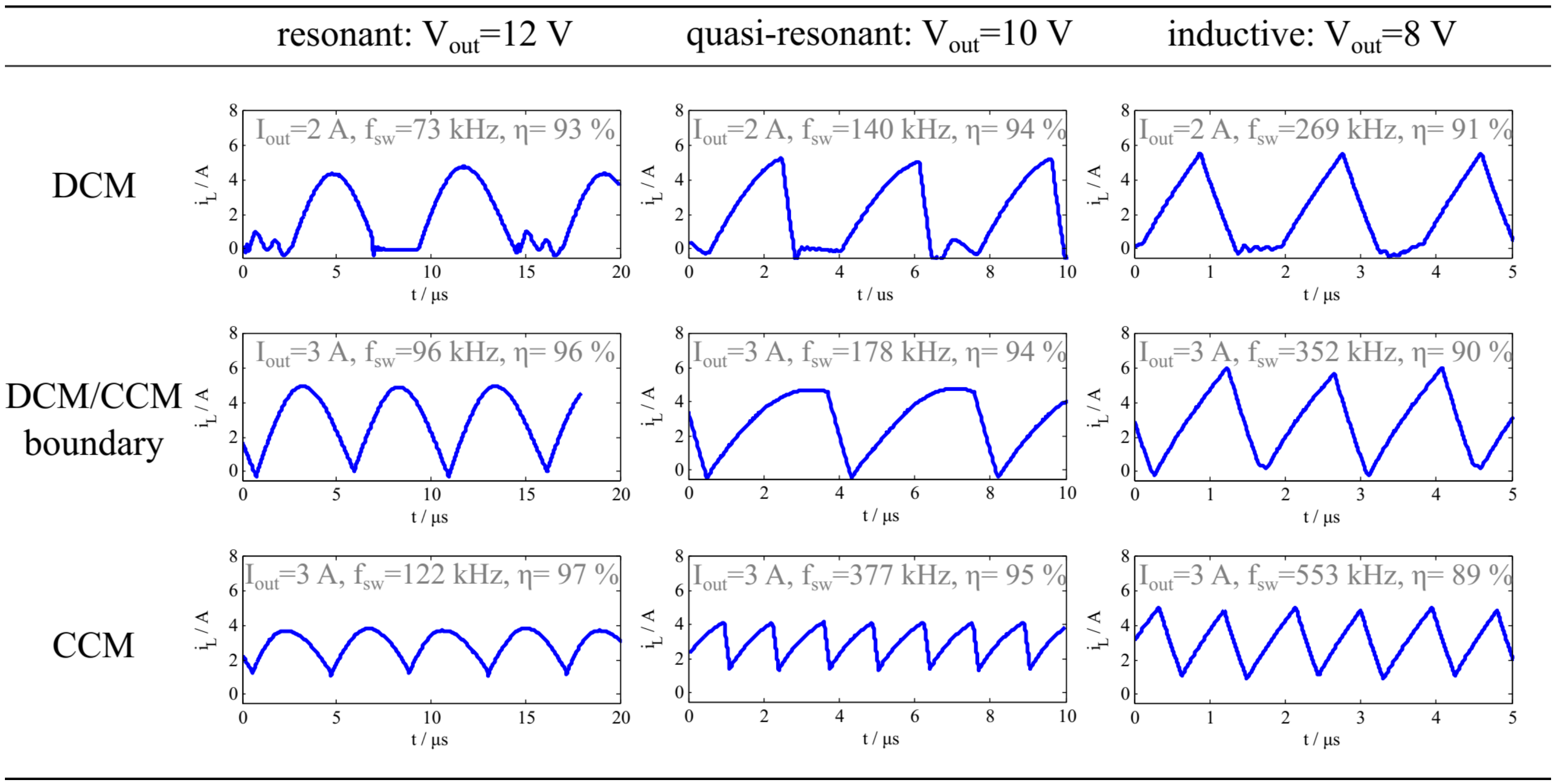


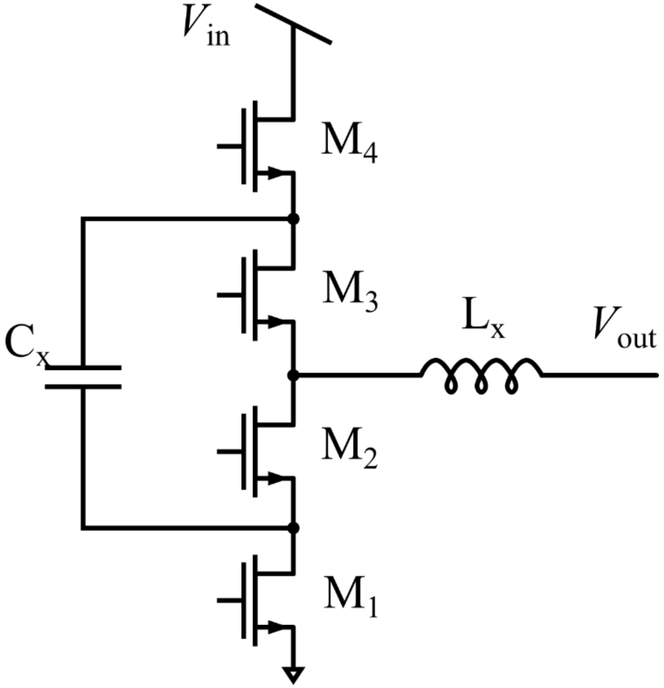
Source: C. Schaef, J. Rentmeister and J. T. Stauth, "Multimode Operation of Resonant and Hybrid Switched-Capacitor Topologies", TPEL. 2018

Beyond Resonant – Multimode Operation

- A hybrid converter can be operated in different modes
- Operating mode determined by conversion ratio and frequency
- Continuous range from resonant to inductive

Inductor current waveforms for 3L buck converter in different operating modes:





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Hybrid Topology Spectrum

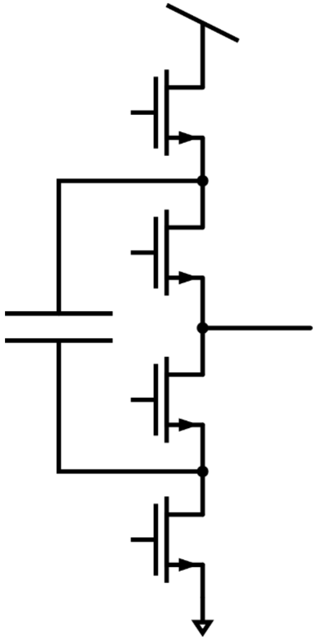
Switched Capacitor

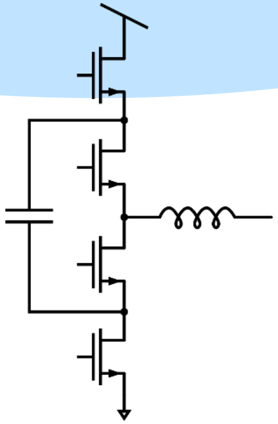
Buck

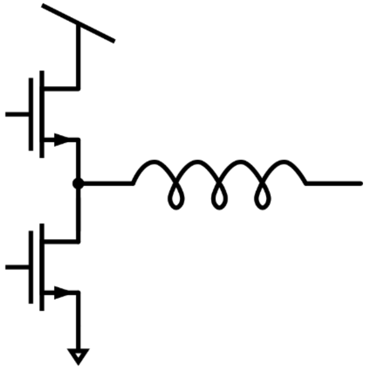
Regulation capability →

Resonant | Quasi-Resonant | Inductive

← Power Density & Efficiency



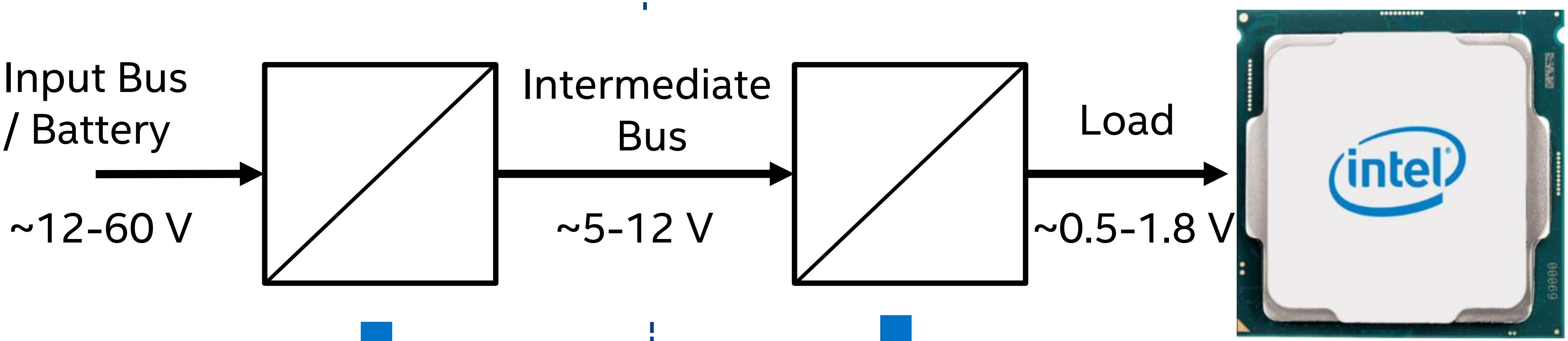




Where do they fit?

Conversion Stage
- Fixed ratio
- High efficiency (98%+)

Regulation Stage
- Fast transient response
- Small footprint

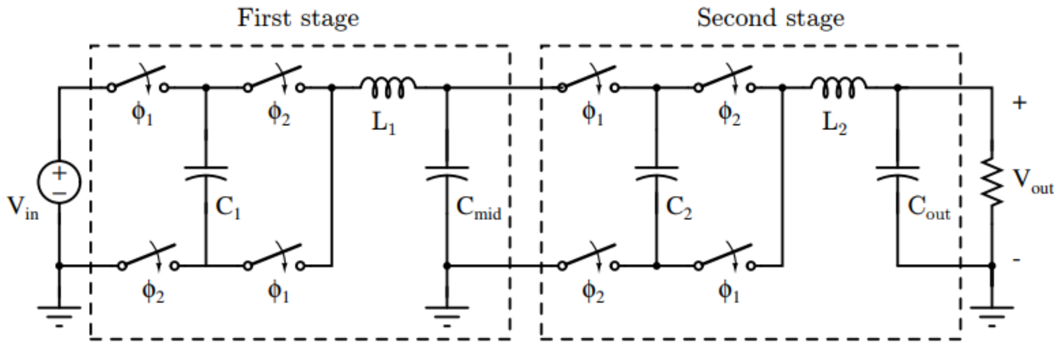


Resonant SC

Inductive Hybrid

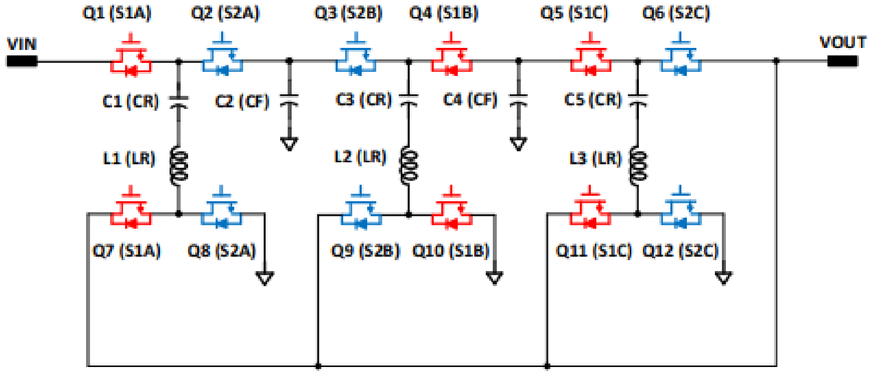
Examples – Fixed Ratio

Resonant Doubler
Ye (UCB), APEC 2018[1]



48 to 12 V	
Switching Frequency	105 kHz
Power Density	1750 W/in^3
Peak Efficiency	98.9 %
Max Load Efficiency	98 %

Resonant Switched Tank
Jiang (Google), APEC 2018[2]



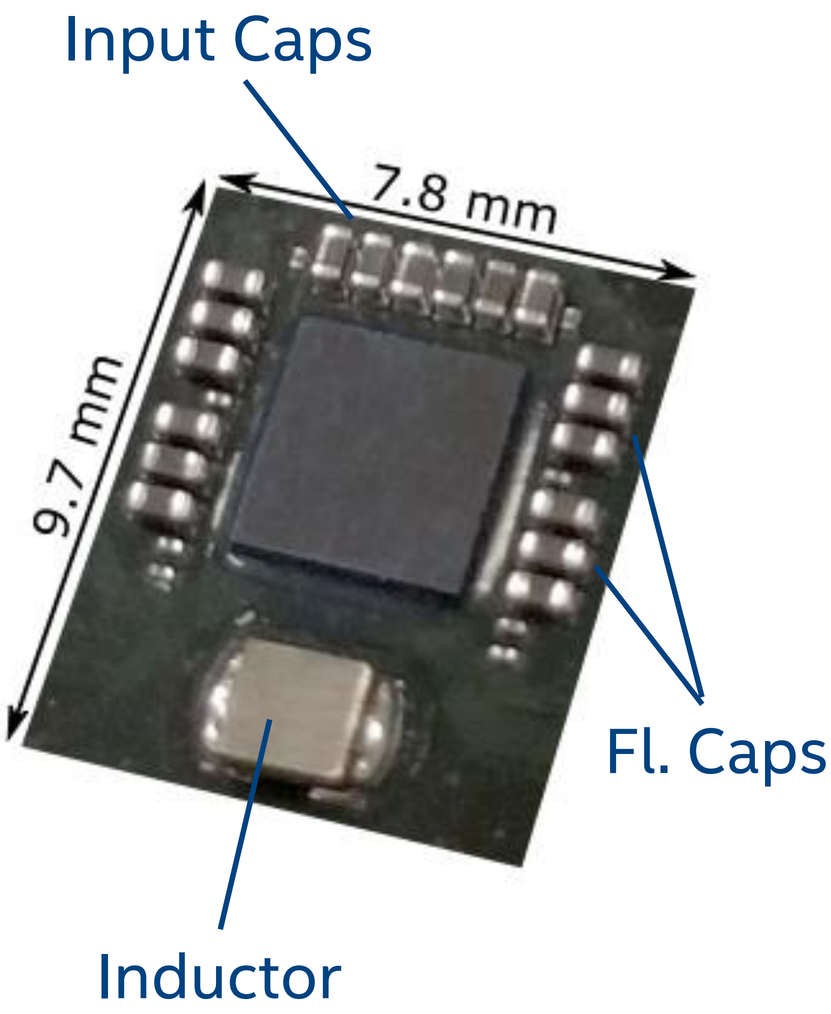
54 to 13.5 V	
Switching Frequency	320kHz
Power Density	500 W/in^3
Peak Efficiency	99 %
Max Load Efficiency	97.5 %

[1] 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
[2] S. Jiang, C. Nan, X. Li, C. Chung and M. Yazdani, "Switched tank converters," APEC 2018

Regulation Stage Example- 4L FCML

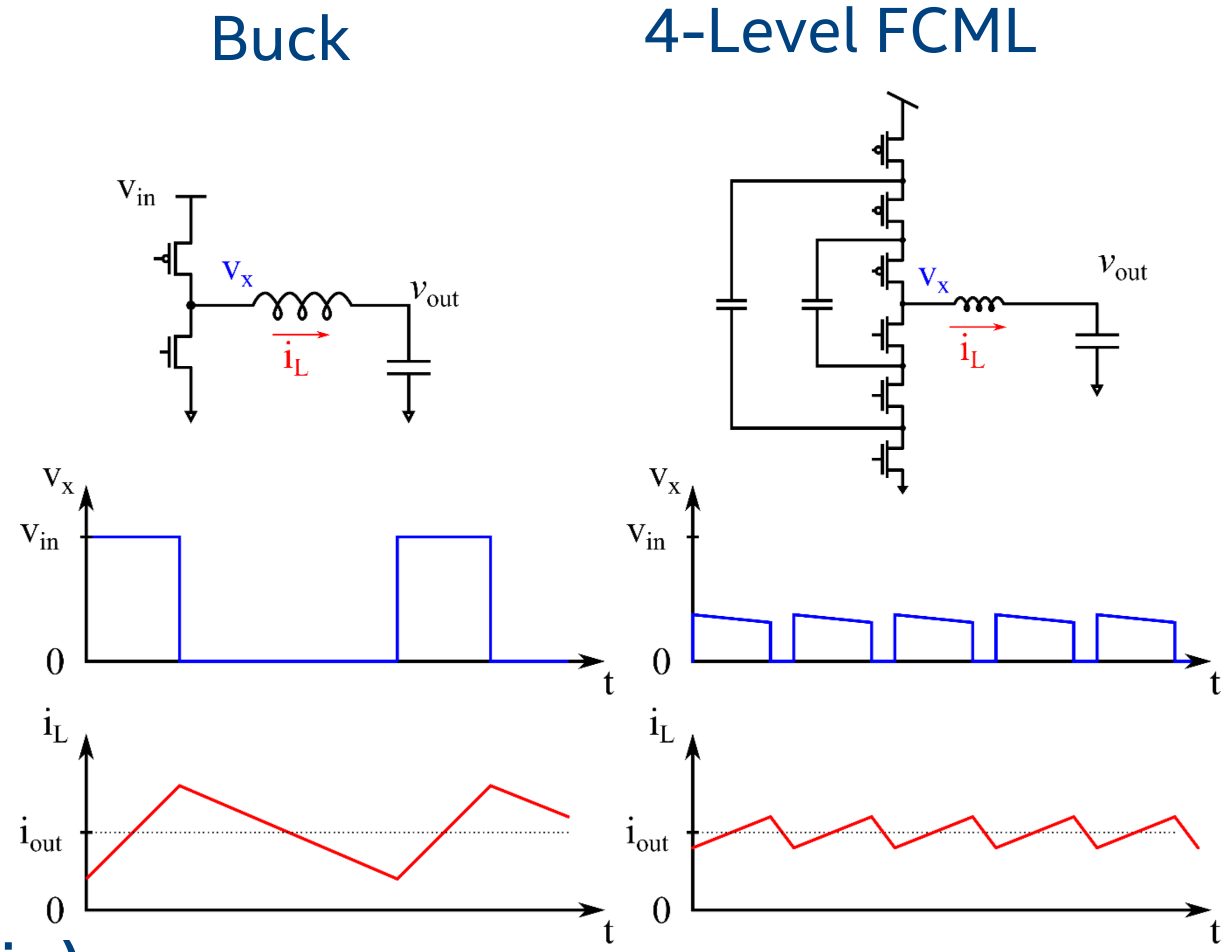
- Integrated Design in 22nm FFL
  - 4L powerstage
  - gate drivers with nested bootstrapping
- All passives on package

Vin	5 V
Iout	10A
Freq.	5 MHz
Size	7.8x9.7x1.2 mm
Package	4L FCCSP (coreless)
Capacitors	6x0402 2.2µF (C_{x1},C_{x2}, C_{in}) 01005 220nF (C_{bs1-6})
Inductor	2512 10 nH



Flying Capacitor Multi-level Converter

- ❑ Use of flying capacitors to produce additional voltage levels
- ❑ 4-Level FCML: 0,1/3, 2/3, 1 V_{in}
- ❑ Each Switch only block 1/3 V_{in}
- ❑ 3x Frequency multiplication

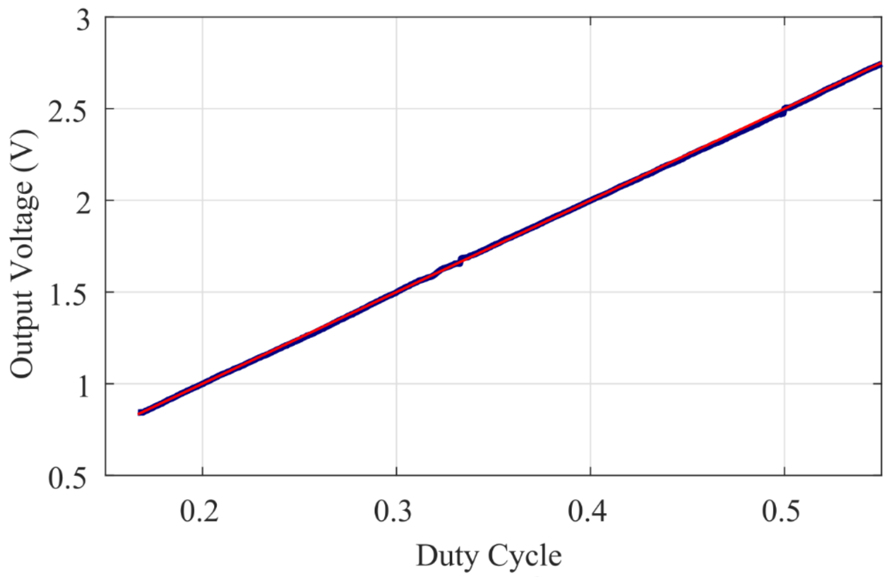


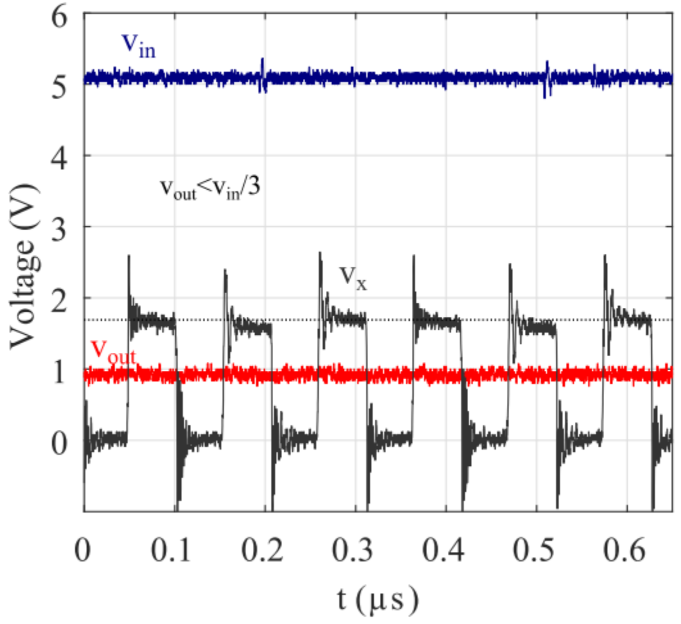
Main benefits

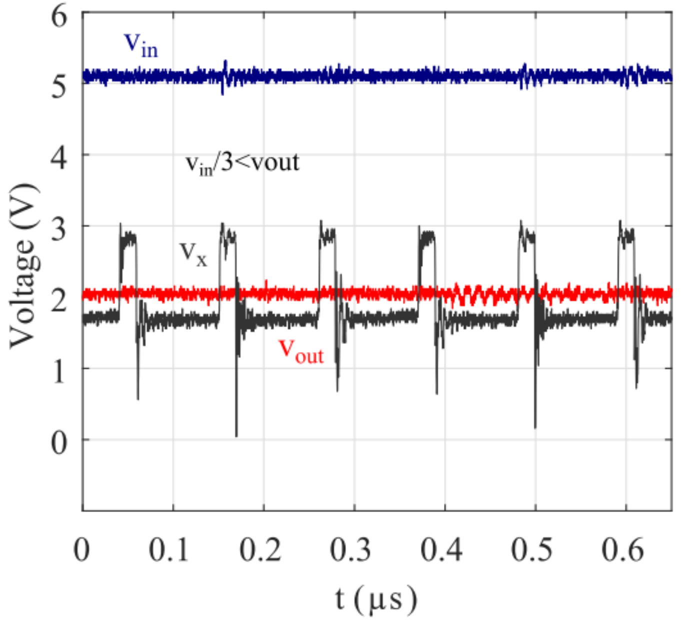
- ➤Reduced Vs stress on inductor
- ➤Switching Frequency multiplication
- ➤Equally rated devices
- ➤Continuous conversion ratio (0 to Vin)

PWM-based Operation

- ❑ 3-phase PWM with 120deg phase shift
- ❑ Switching frequency equals 3x of PWM frequency
- ❑ PWM duty cycle allows continuous control of output voltage
  - ➢ Conventional duty-cycle control
  - ➢ Improved transient response due to higher switching frequency and smaller inductance

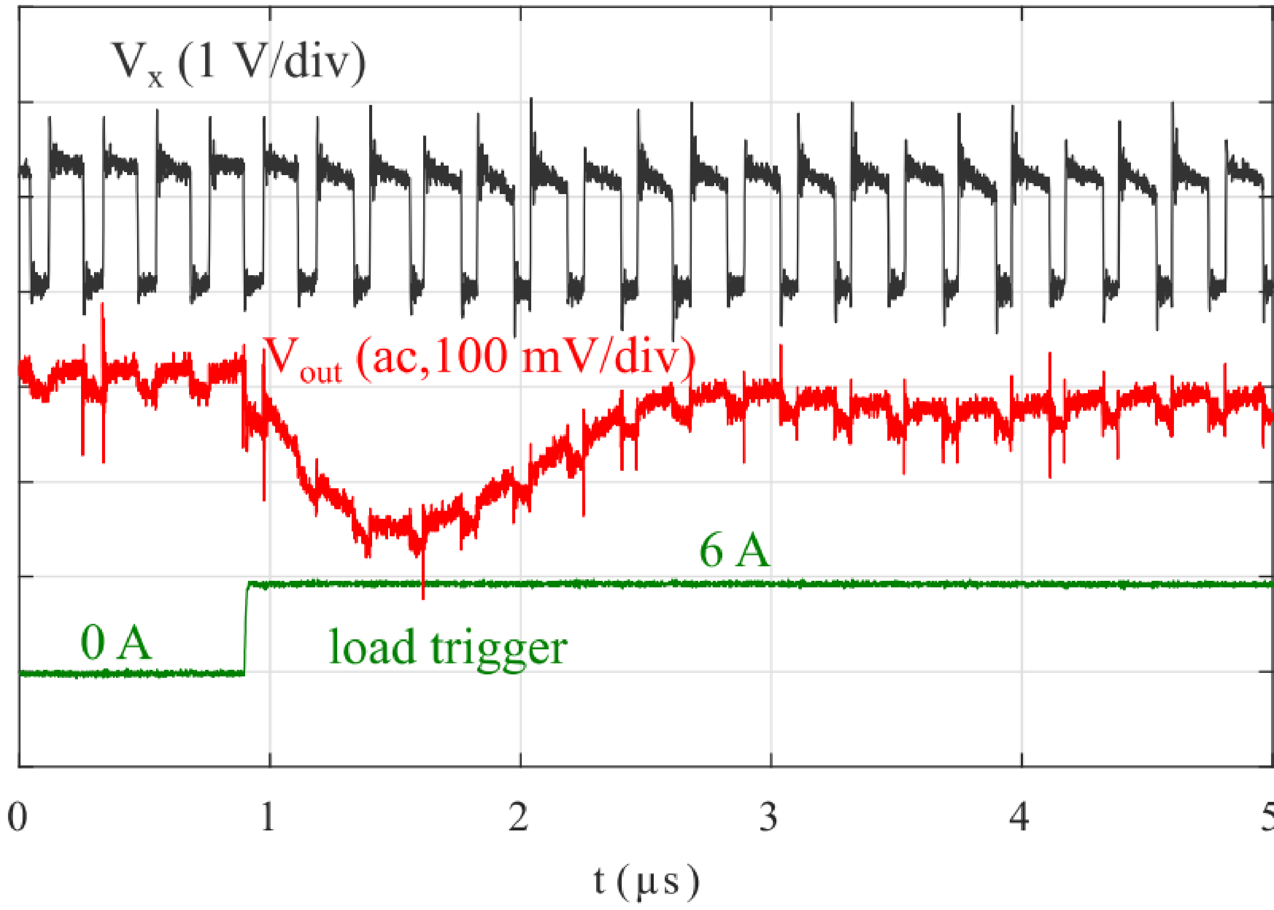






Closed-loop transient response

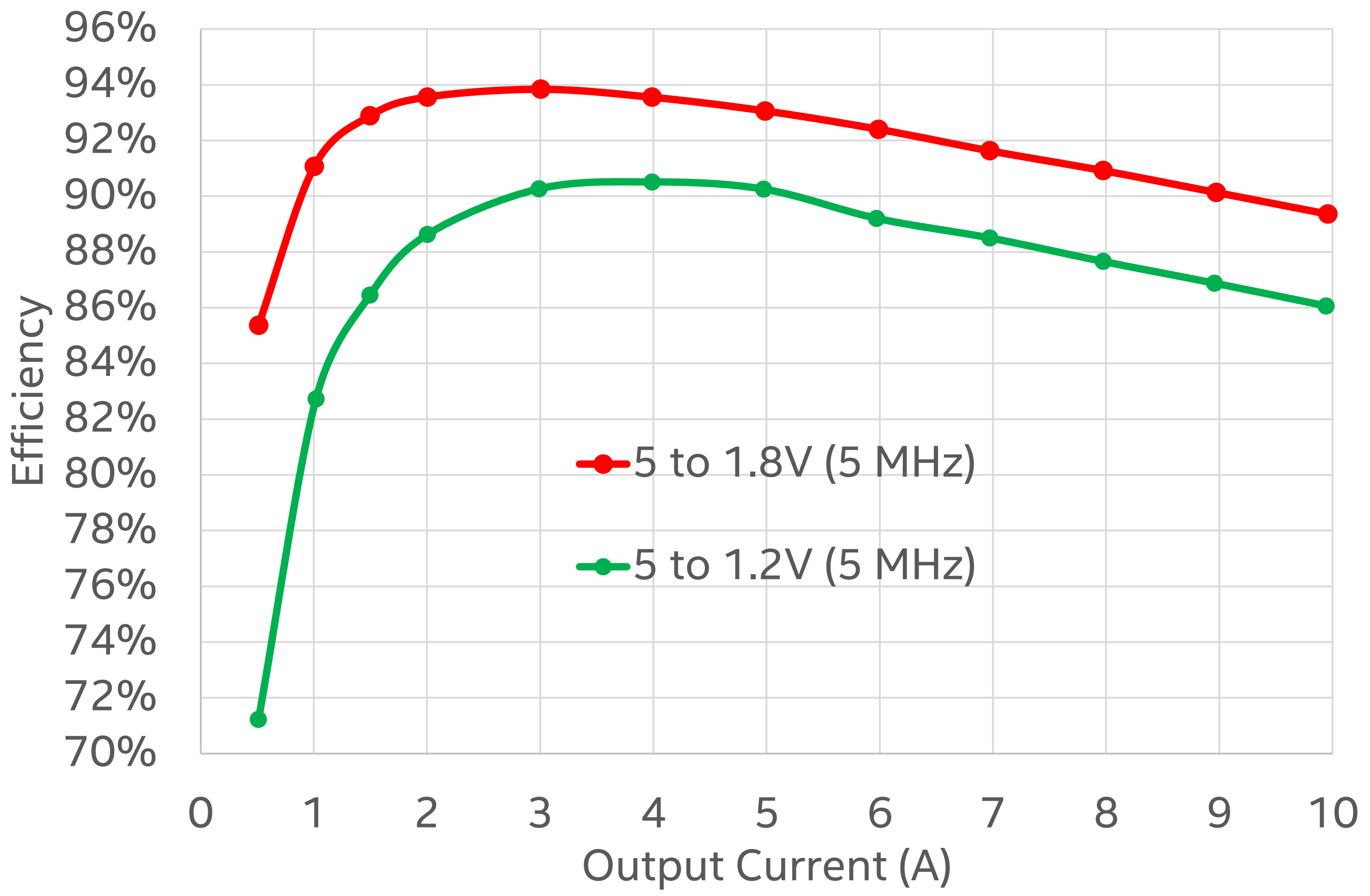
- ❑Feedback implemented with digital Type III controller
- ❑Closed-loop response to 6A load transient measured
- ❑Output decoupling < 20 μF
- ❑Demonstrates transient response improvement possible with hybrid approach compared to buck



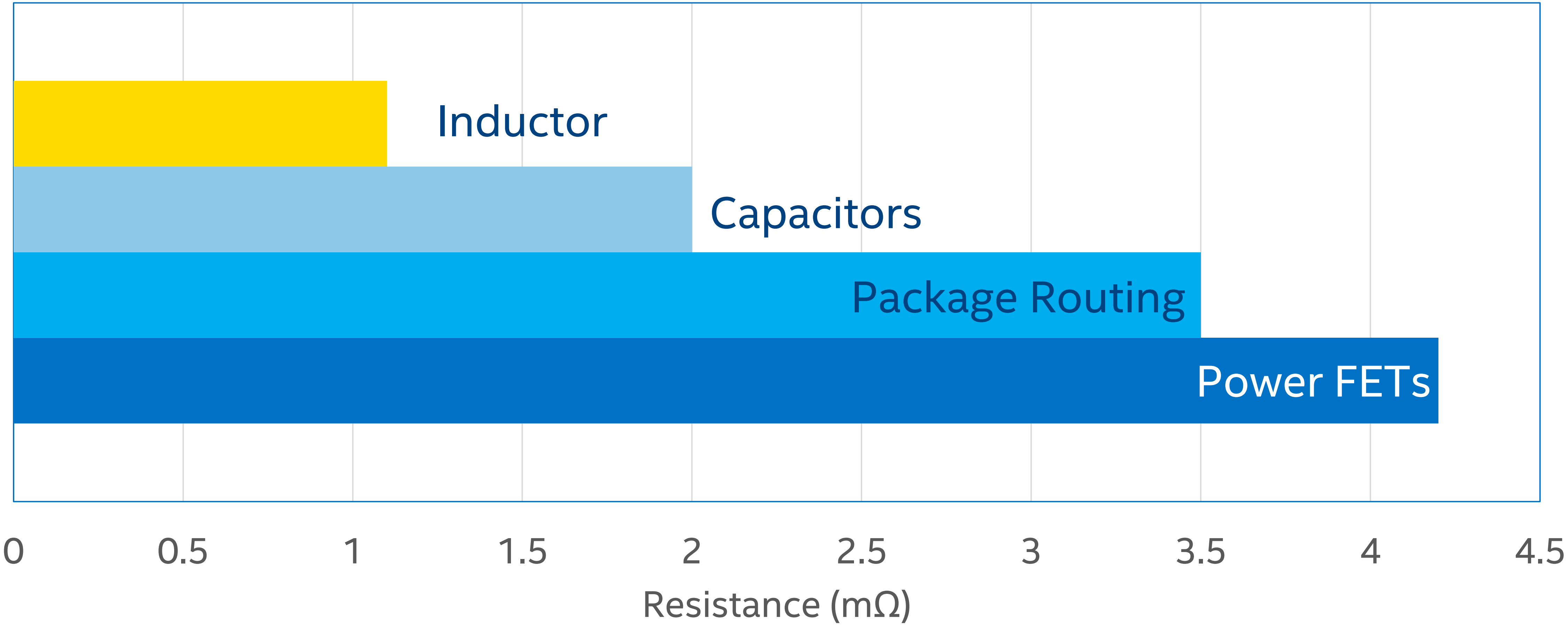
Efficiency Measurements

- ❑Efficiency measured for 5 to 1.8 and 1.2 V
- ❑Peak efficiency of 93.8 % at 3A load
- ❑Over 90% maintained up to 9A

➢High Efficiency with order-of-magnitude lower inductance



Resistance contributions



- ➢ Package routing significant contributor
- ➢ Advances in 3D packaging technology will bring further improvement

Hybrid Regulators - Practical challenges

- Control
  - Several phase-shifted PWMs
  - Capacitor balancing loops
- Gate-driving
  - Supply generation with nested/cascaded bootstrapping
  - Level shifting to different domains
- Packaging
  - On-package capacitor placement
  - Package routing parasitics

Summary

- Hybrid topologies can address many of the challenges in compute platform power delivery today
- A Range of fixed-ratio and regulated converters with great performance metrics have been demonstrated
- Integrated designs most attractive to manage complexity and deliver competitive cost
- Advancements in packaging critical to realize full performance potential

Thank You!