Converter Topologies for Large Conversation Ratios: A Story from SI, SC to Hybrid Architectures

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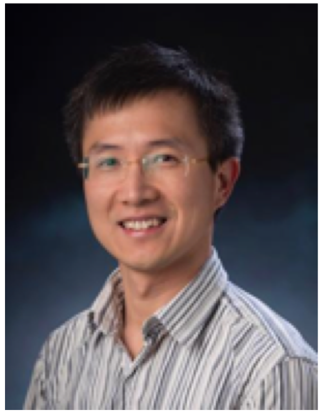

- **Ph.D.** **UC Berkeley** **2013**
- **M.S.** **KAIST, Korea** **2006**
- **B.S.** **HUST, Hanoi, Vietnam** **2003**

- **Prior experience:**
  - Lion Semi., San Francisco, CA 2012 – 2015 (shipping millions to large smart phone makers)
  - Rambus, Sunnyvale, CA 2012
  - Intel, Beaverton, OR 2009
  - Oracle, Santa Clara, CA 2008
  - JDA Tech., Korea 2004 – 2007
  - VAST, Vietnam 2002 – 2004

iPower3Es

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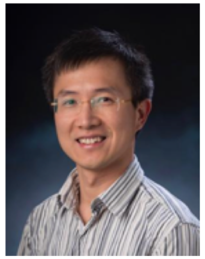
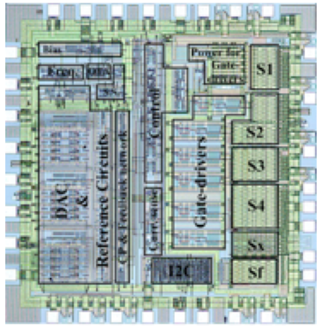
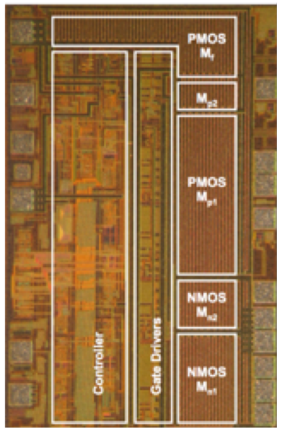
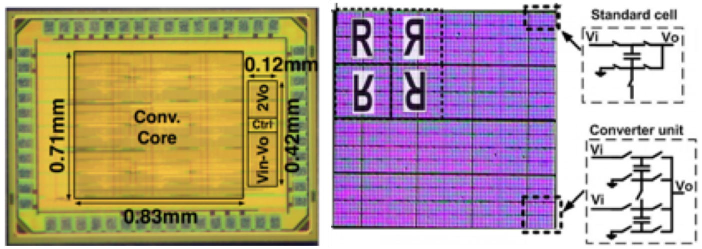


SIMO

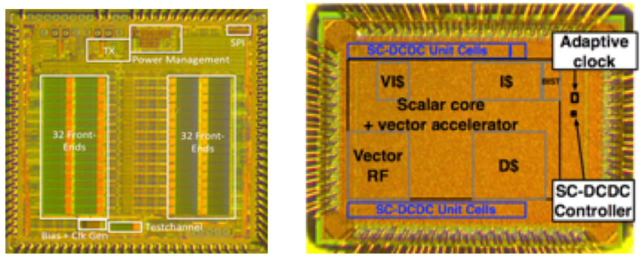




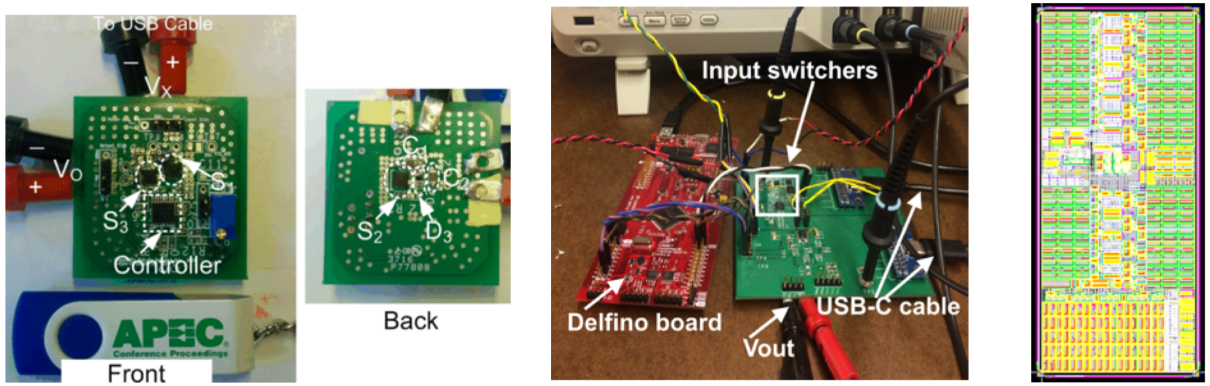
SC



Energy-efficient systems

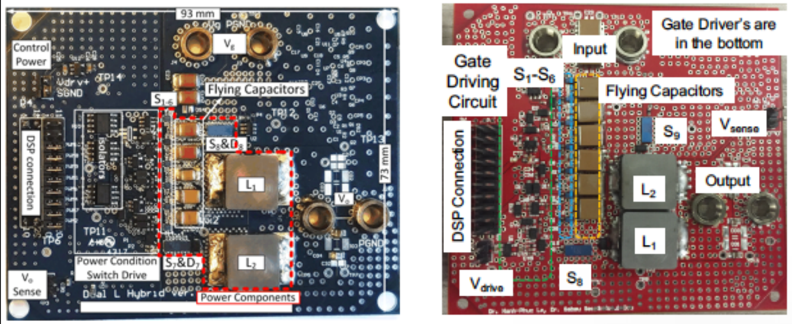


Smart-Cable (Hybrid) Converters



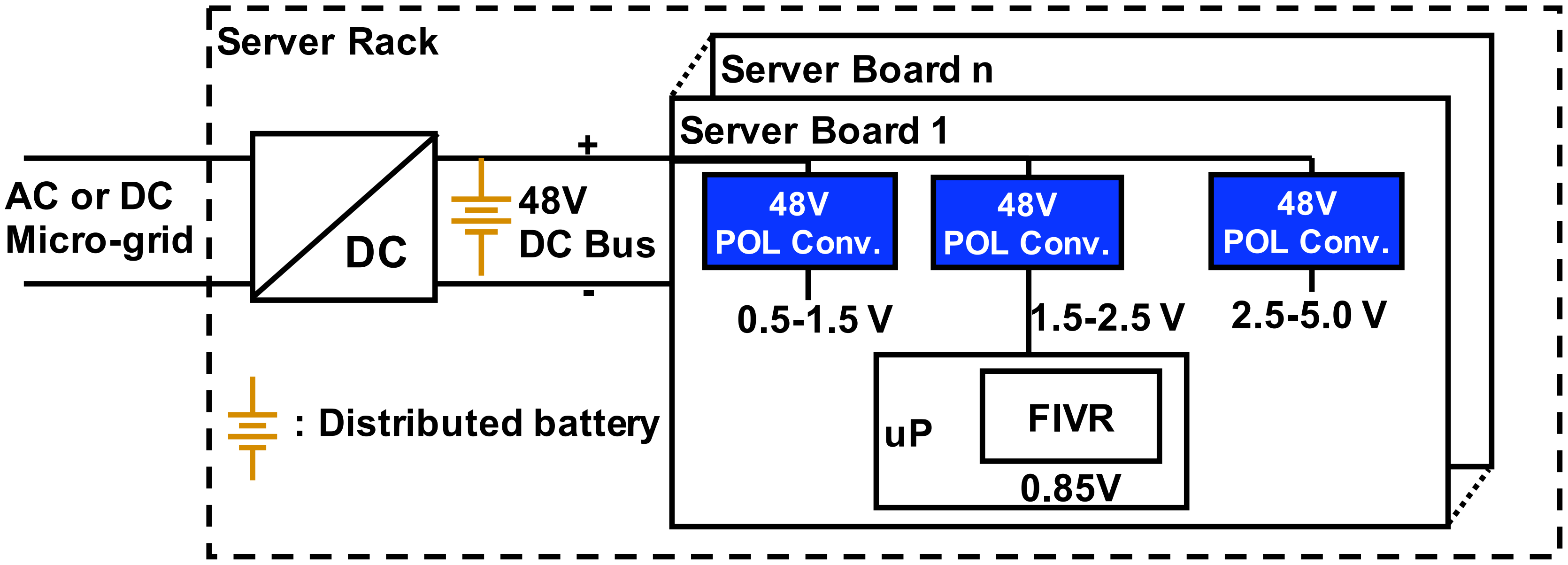
1 @ APEC '17, 2 @ COMPEL '18, 1 @ ISSCC '19

Hybrid, High-voltage



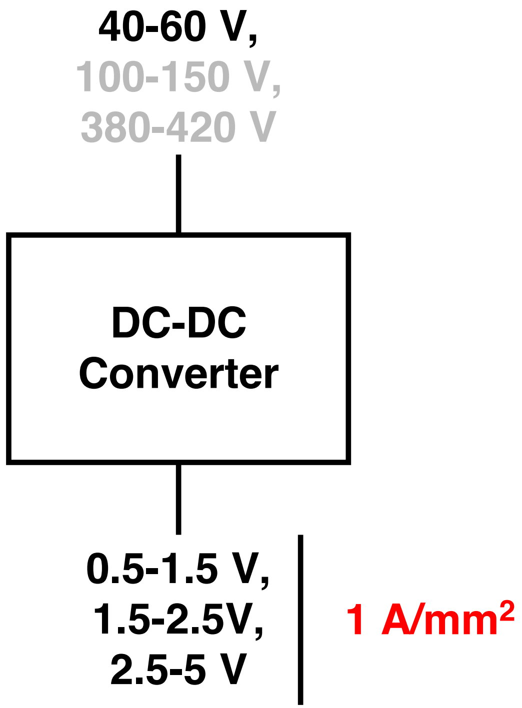
2 @ ECCE '18, 3 @ APEC '19

The Need for Advanced DC-DC Converter



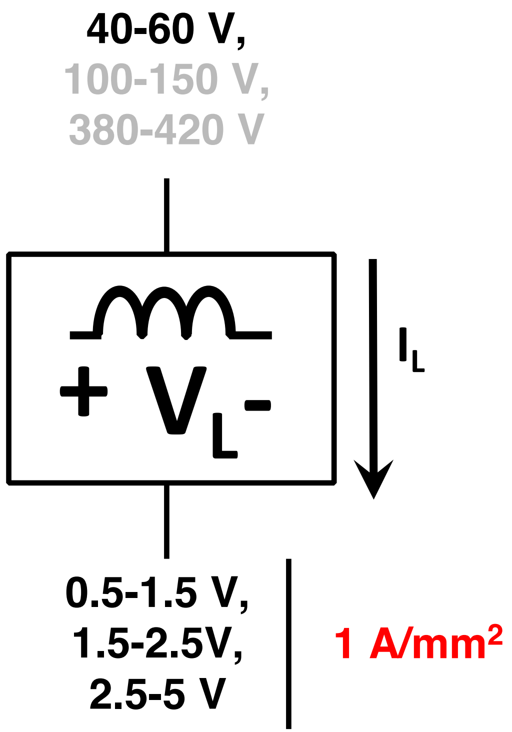
- **Global data traffic for data centers increases exponentially:**
  - 2 EB (2013) → 20 EB (2018) → 100 EB (2023)
  - ~73 billion kWh (2020), or ~$7.3 billion cost of electricity in the U.S. alone
- **~15% power consumption lost over conversion stages and delivery.**

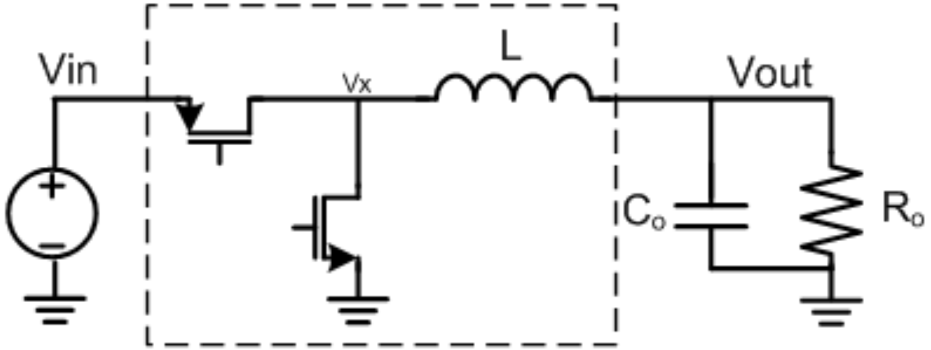
Key Requirements for the "Magical" Converter(s)

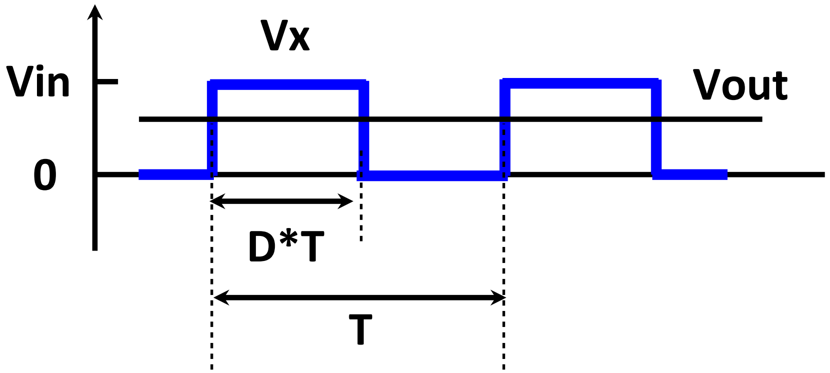


- **Large conversion ratios, e.g. 48-to-1**
- **High input voltage, >40V**
- **Large current density, 1 A/mm^2**
- **High efficiency, >95%**
- **Wide regulation range (wide input/output voltages)**
- **Scalable for both larger and smaller current**
  - Granular power supply (miniaturized converter unit)
- **Reliable**
  - More integration
- **Low cost**
  - More integration and miniaturization

Converter Magic 1 – Switched Inductor (Buck)





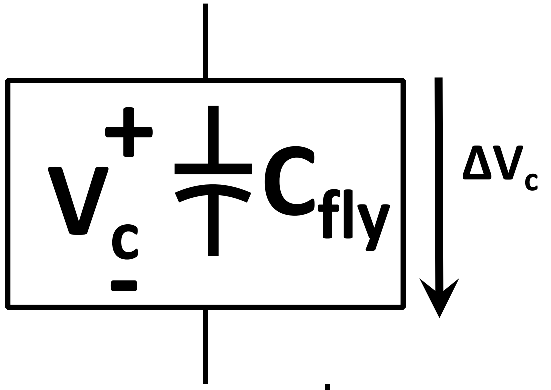


$$Vout = D * Vin$$

- Transfer charge in form of current in inductor
- High efficiency for fine regulation
- **Require switches with large breakdown → high $R_{ds,ON}$**
- **Difficult/expensive integrated inductor**
- **Not easy to scale**

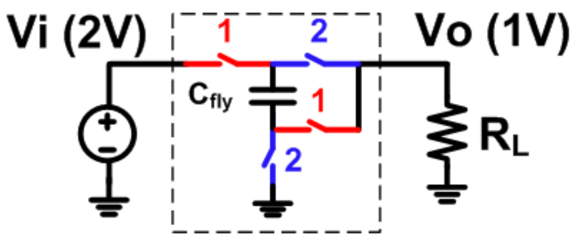
Converter Magic 2 – Switched Capacitor (SC)

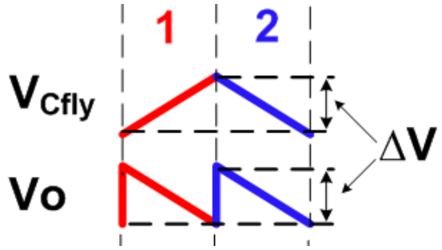
40-60 V,
100-150 V,
380-420 V



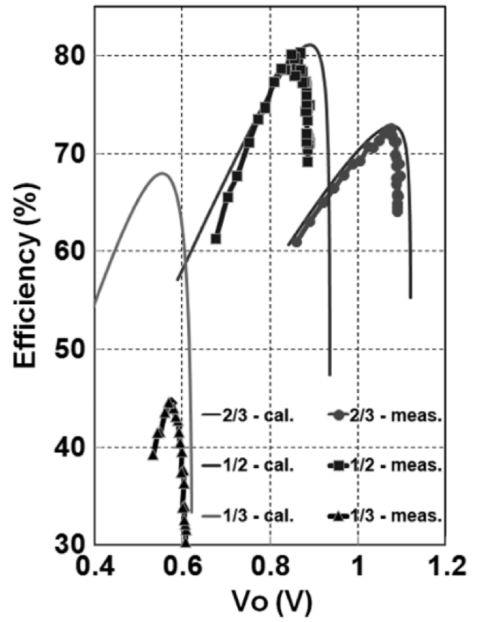
0.5-1.5 V,
1.5-2.5V,
2.5-5 V

1 A/mm²





- **Transfer charge in form of cap. voltage ripple**
- **No bulky magnetic → can be integrated and scalable**
- **Integrated capacitors are readily available**
  - MOS, MIM, MOM, deep-trench capacitors
- **Small and inexpensive**
  - Trend to use more capacitors to reduce stress on inductors
- **Problem in fine regulation efficiency**

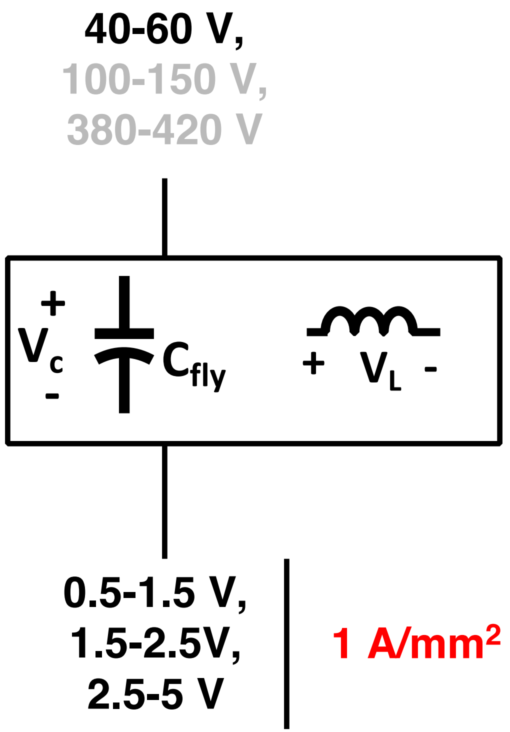


Ref: Le, et al., ISSCC 2010

- **~80% efficiency @ 0.9 A/mm²**
- **Linear efficiency degradation**
  - **hard charging**

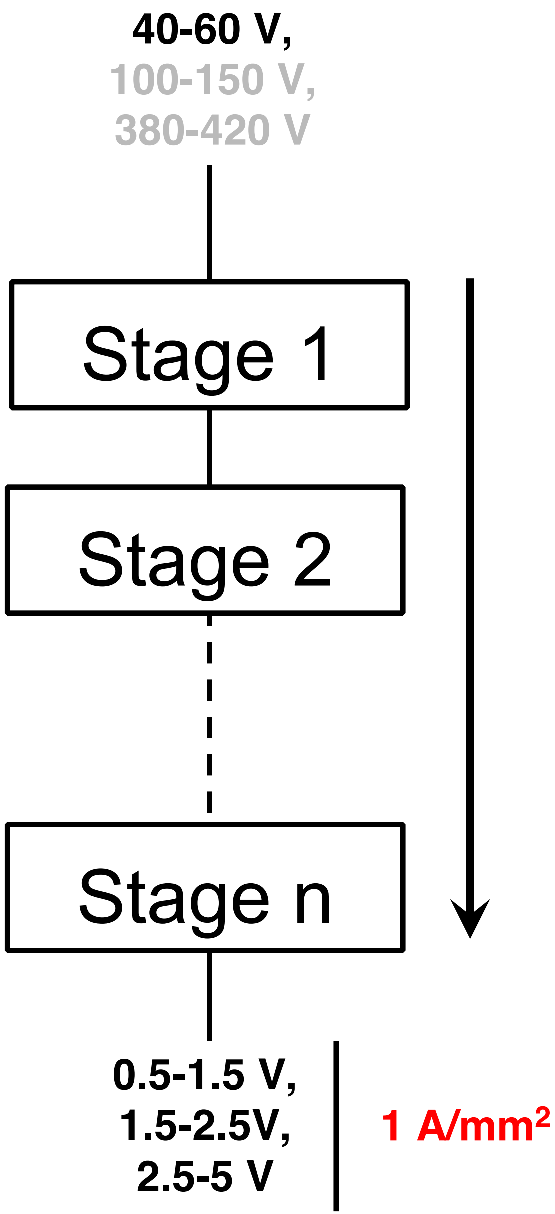
- **Products: TI, Intel, Dialog, Lion Semiconductor, etc**

Converter Magic 3 – Hybrid Architecture



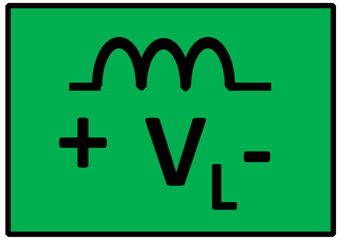
- **SC stage blocks large portion of V_{in}**
  - Only need to handle small voltage ripple
- **Flying inductor blocks a fraction of voltage**
  - Support fine regulation
- **Efficient use of both passive components**
  - Can support large conversion ratios

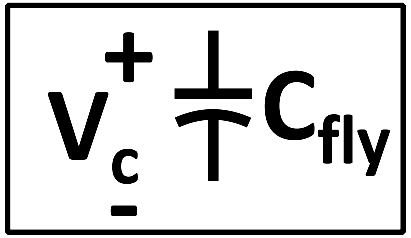
Hybrid Converter Architecture – Overview



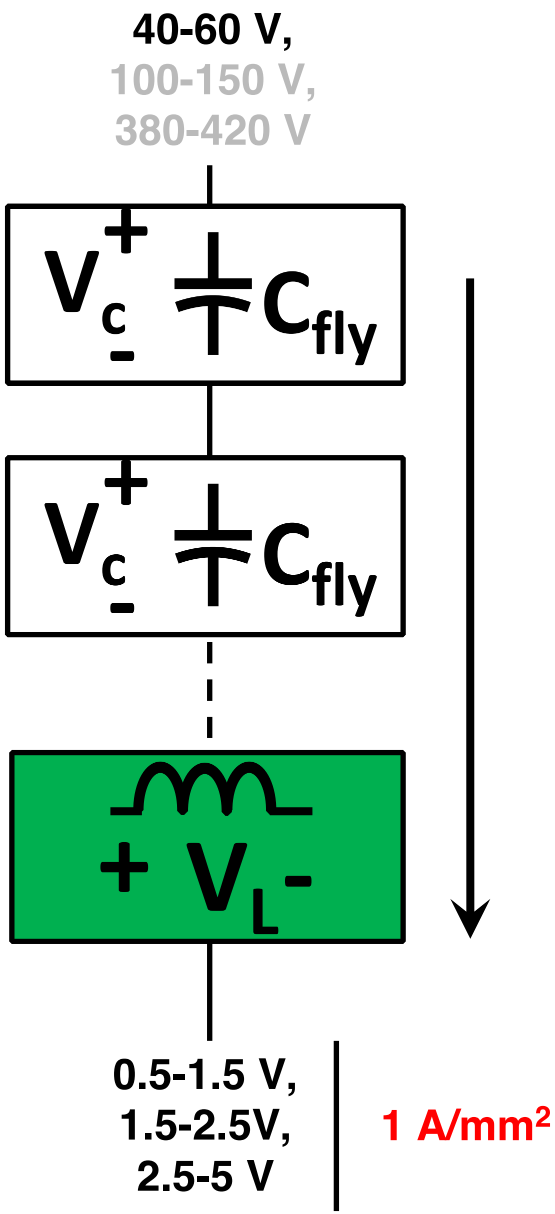
- **Key challenge:**
  - Efficient conversion with large ratios
  - Fine voltage regulation

- **Want to have multiple stages**
  - Use both inductors and capacitor stages
    - Capacitor: block the voltage
    - Inductor: soft-charge capacitors, can be smaller and more integrated





Hybrid Converter Architecture – Overview



- **Key challenge:**
  - Efficient conversion with large ratios
  - Fine voltage regulation
- **Want to have multiple stages**
  - Use both inductors and capacitor stages
    - Capacitor: block the voltage
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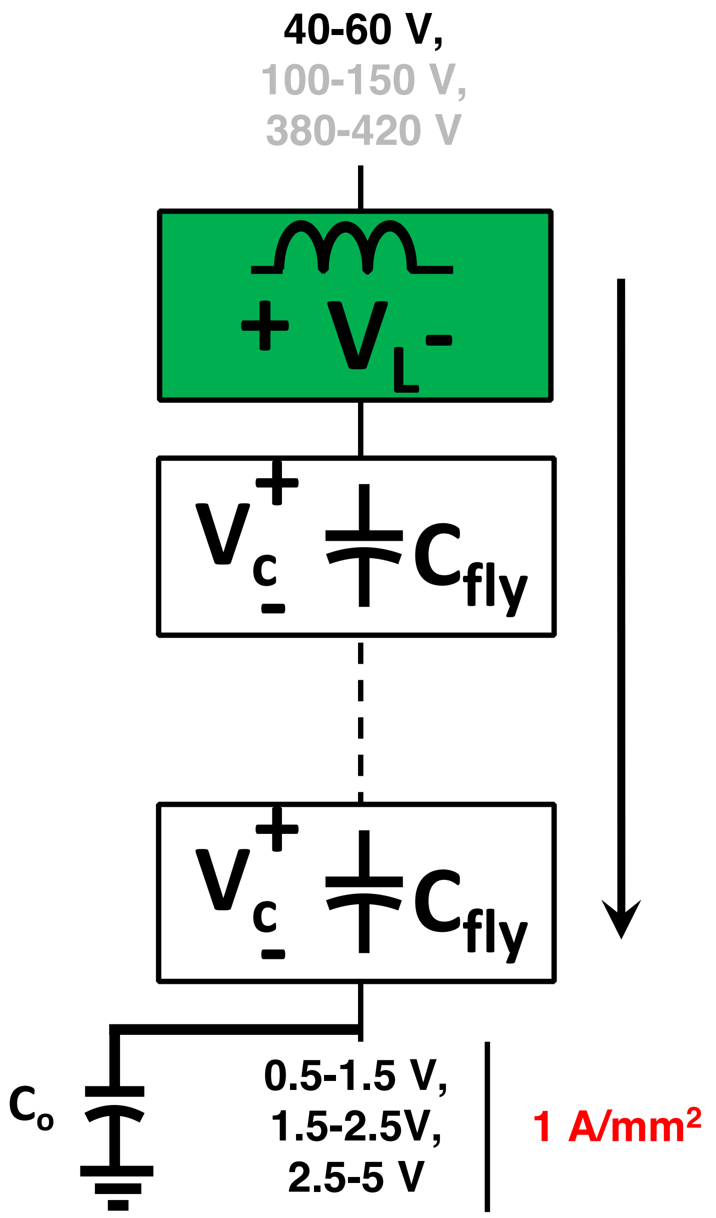
- **Option:**
  - Inductors at the output: convenient but inductor carry output currents

Hybrid Converter Architecture – Overview



- **Key challenge:**
  - Efficient conversion with large ratios
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- **Want to have multiple stages**
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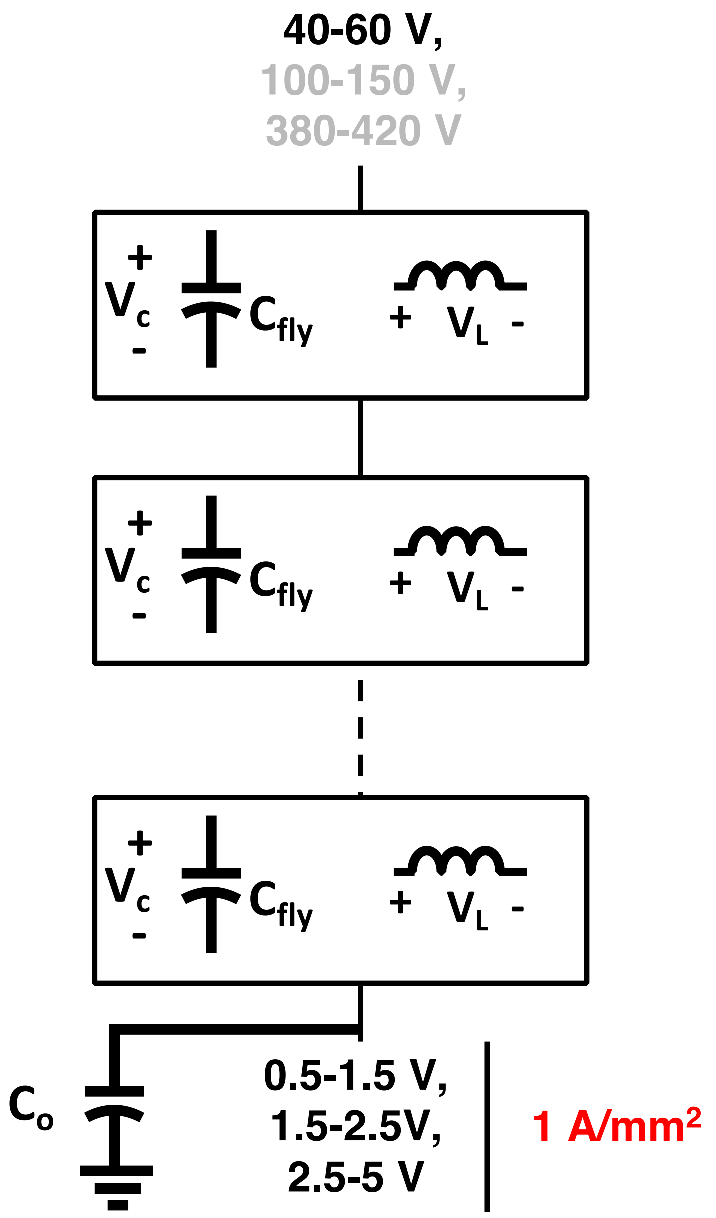
- **Option:**
  - Inductors at the output: convenient but inductor carry output currents
  - Inductors at the input: inductor only handles input current, but capacitor could hard charge with output capacitor

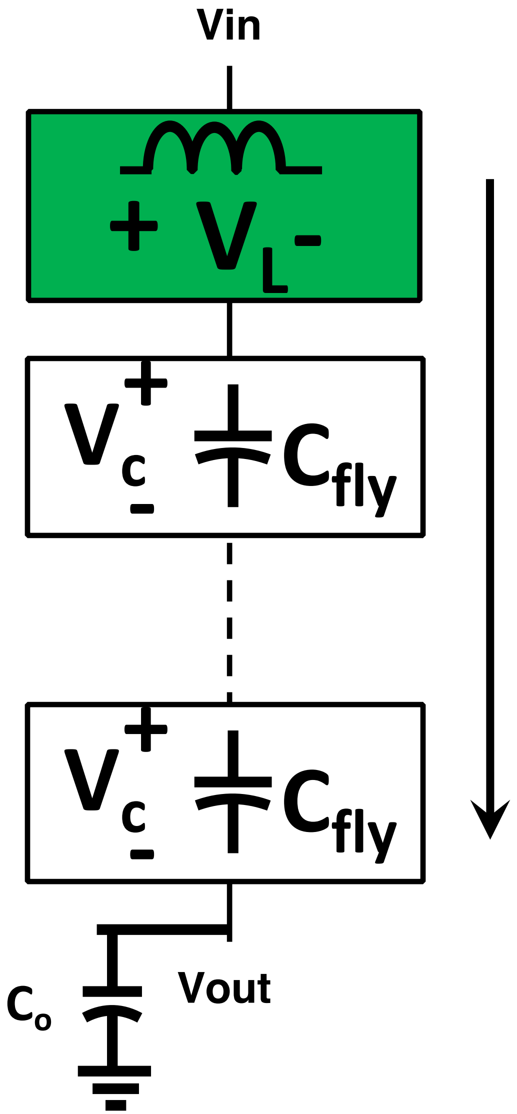
Hybrid Converter Architecture – Overview



- **Key challenge:**
  - Efficient conversion with large ratios
  - Fine voltage regulation
- **Want to have multiple stages**
  - Use both inductors and capacitor stages
    - Capacitor: block the voltage
    - Inductor: soft-charge capacitors, can be smaller and more integrated
- **Option:**
  - Inductors at the output: convenient but inductor carry output currents
  - Inductors at the input: inductor only handles input current, but capacitor could hard charge with output capacitor
  - Resonant operation with both inductor and capacitors

Key: the stages need to work together!

Hybrid Converter – Inductor First (S-Hybrid)



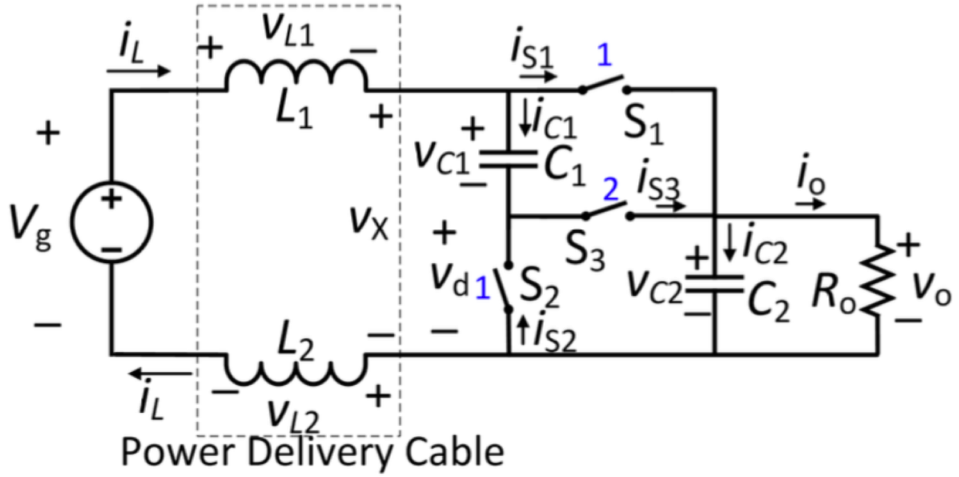
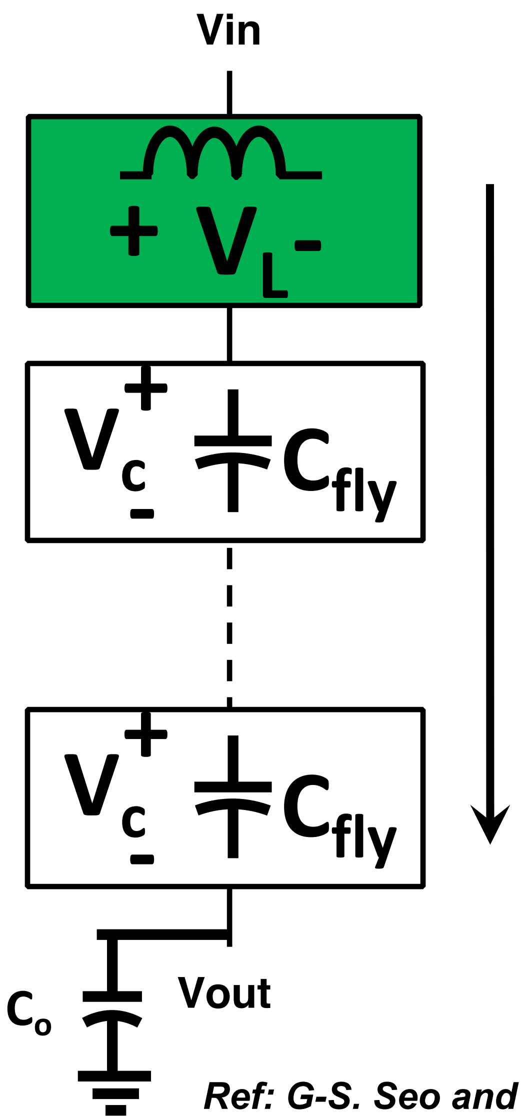
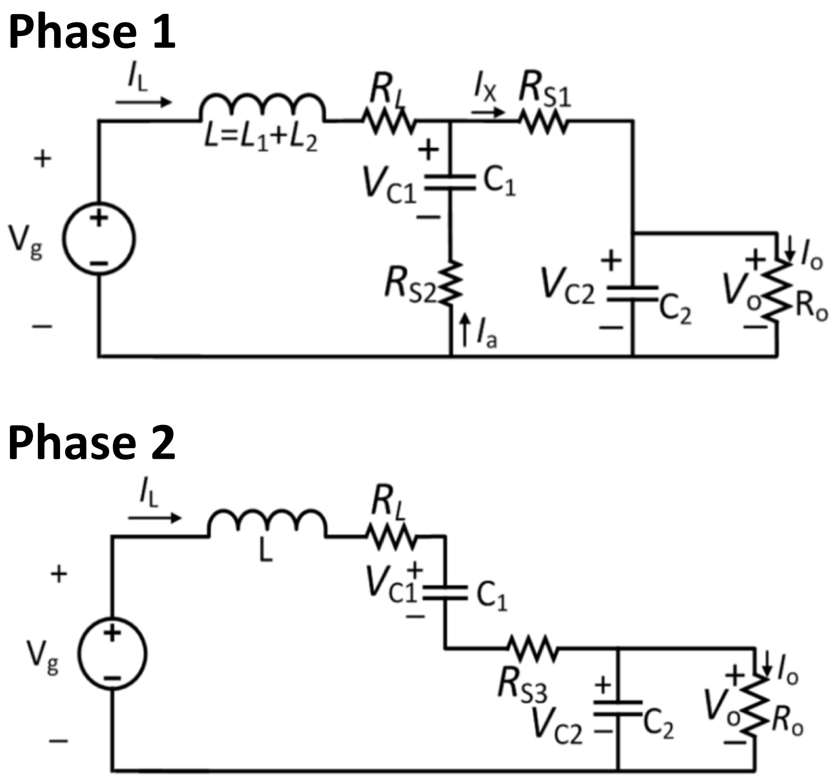


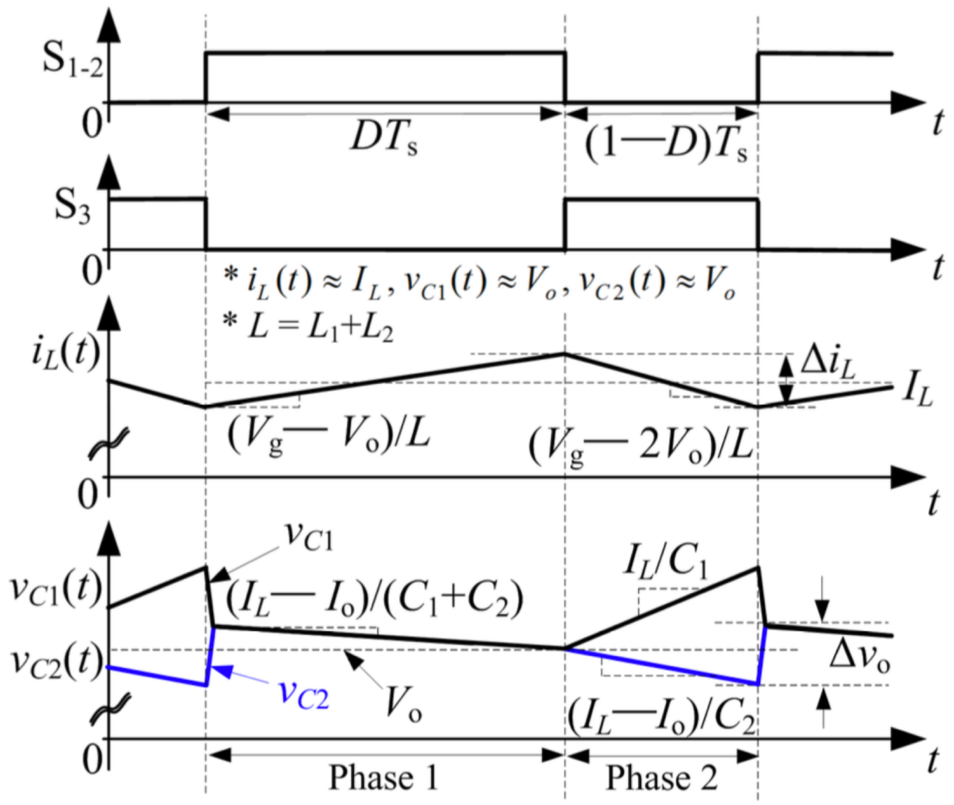
Fig. 3. Schematic of the S-Hybrid step-down converter.

- **Ref: G-S. Seo and H-P. Le @ APEC & COMPEL 2017**
- **Inductor at the input**
  - Step-down operation with synchrosnous SC network
  - Application-aware and environment-aware design:
    - Battery charger application: use USB cable for inductors

S-Hybrid Converter Operation



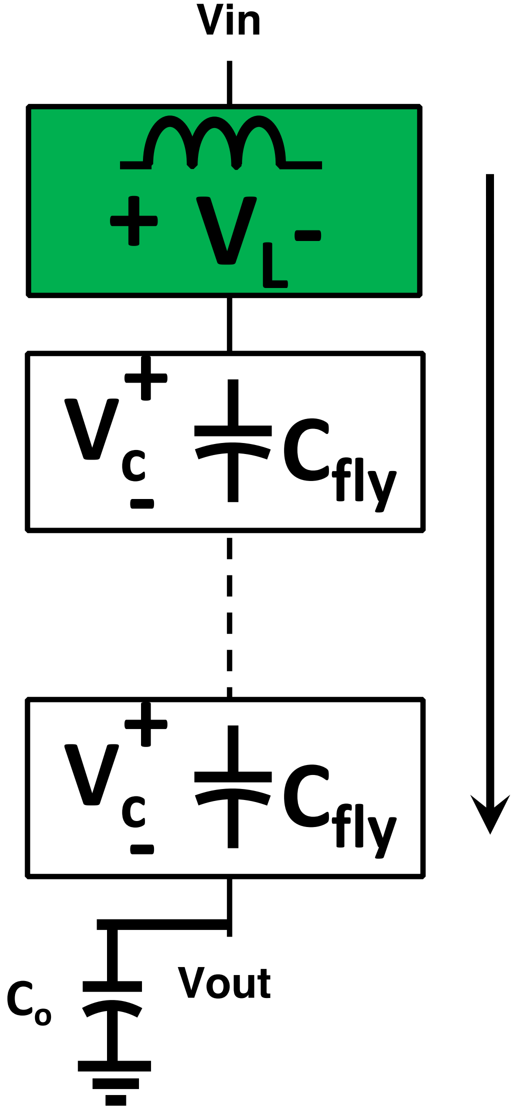


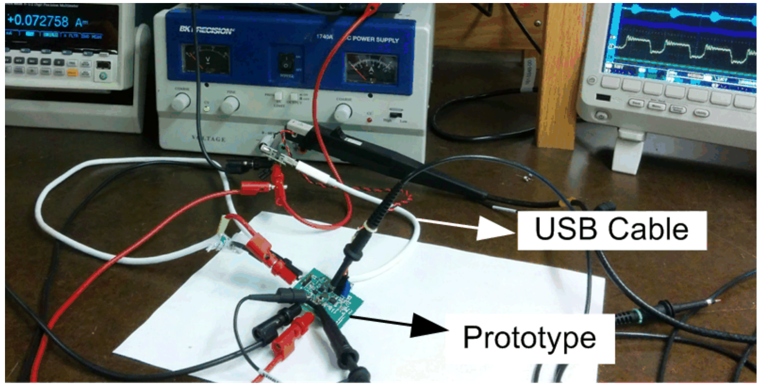


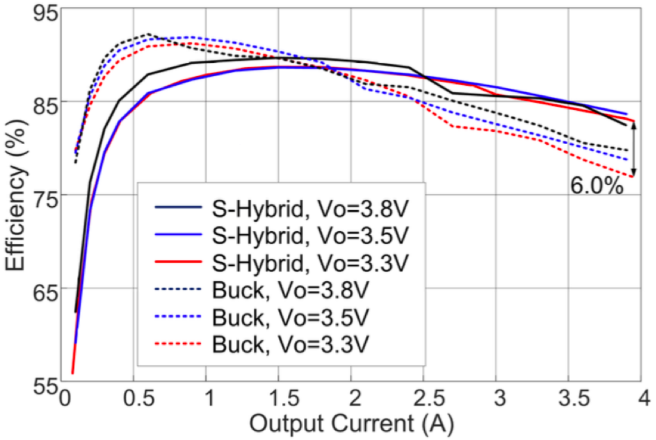
- **Soft charging in Phase 2**
- **But still hard charging in Phase 1**

Ref: G-S. Seo and H-P. Le @ APEC & COMPEL 2017

Hybrid Converter – Inductor-First Designs







- **S-Hybrid topology @ *APEC & COMPEL 2017***
  - Improve 6% efficiency (31.6% loss reduction) at 15 W power for USB charger

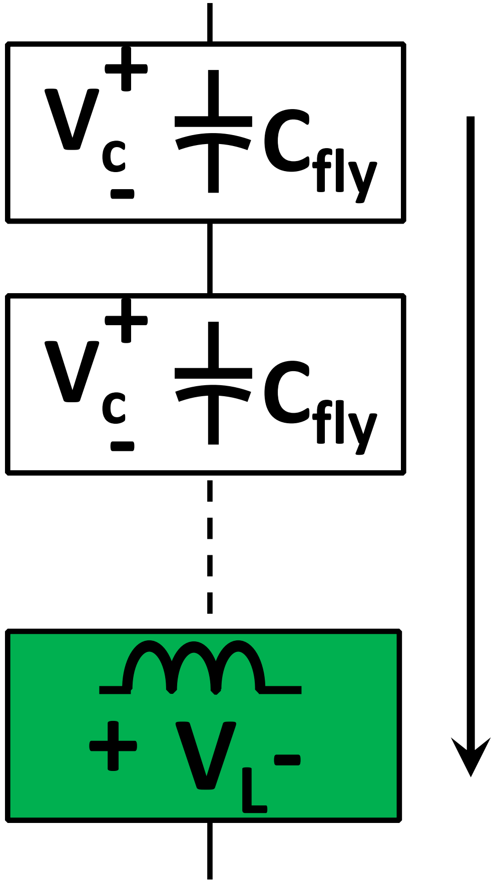
Covered unpublished materials
(To be presented at ISSCC 2019)

- **Superior integrated version with 9V input.**
  - Proved operations and performance
  - Simultaneous data communication over the cable

(ISSCC 2019)

Hybrid Converter – Capacitor First (DIHC Family)

40-60 V,
100-150 V,
380-420 V



0.5-1.5 V,
1.5-2.5V,
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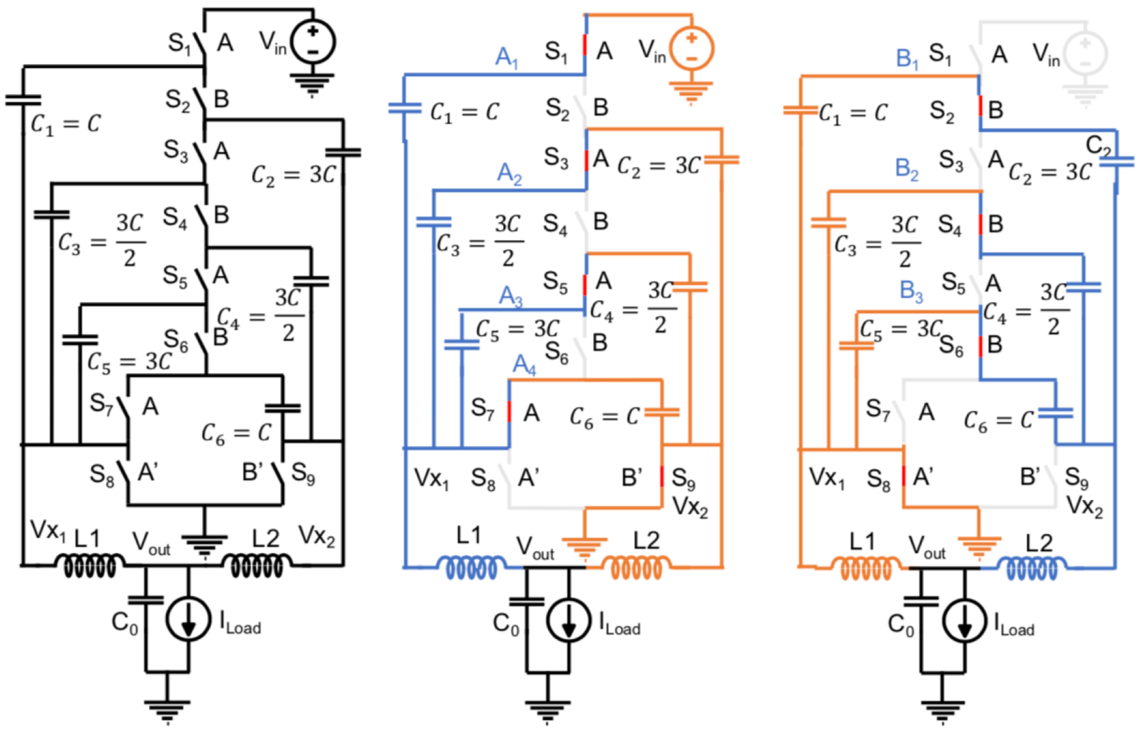
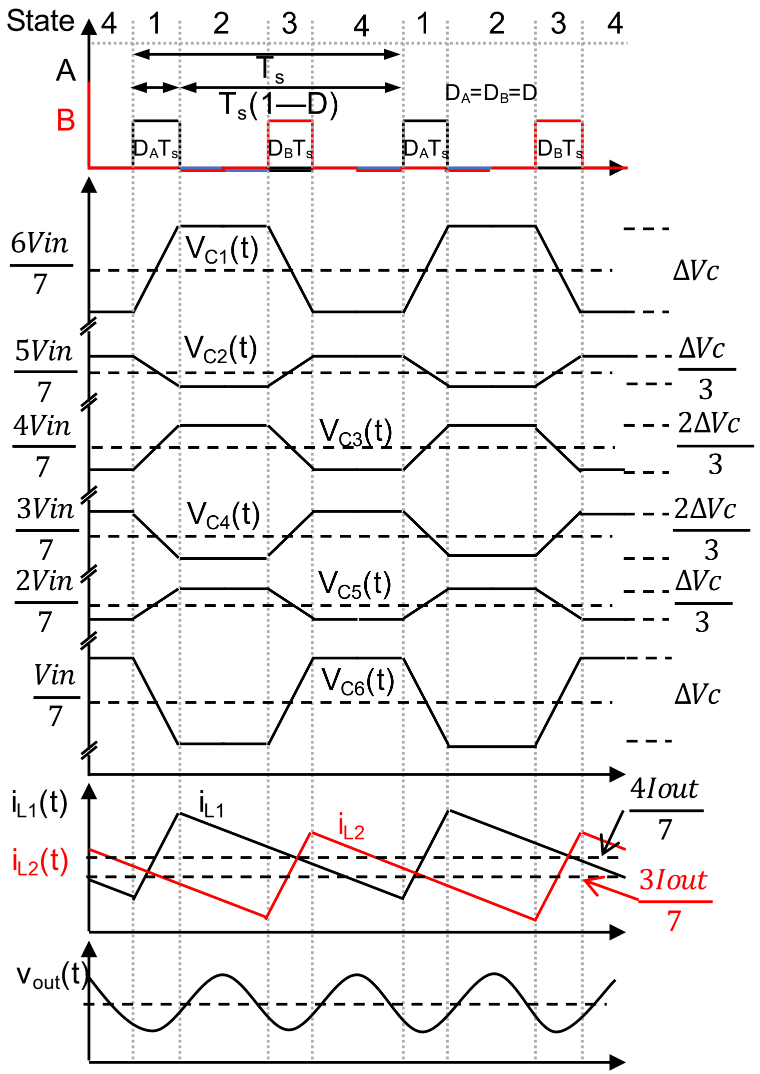
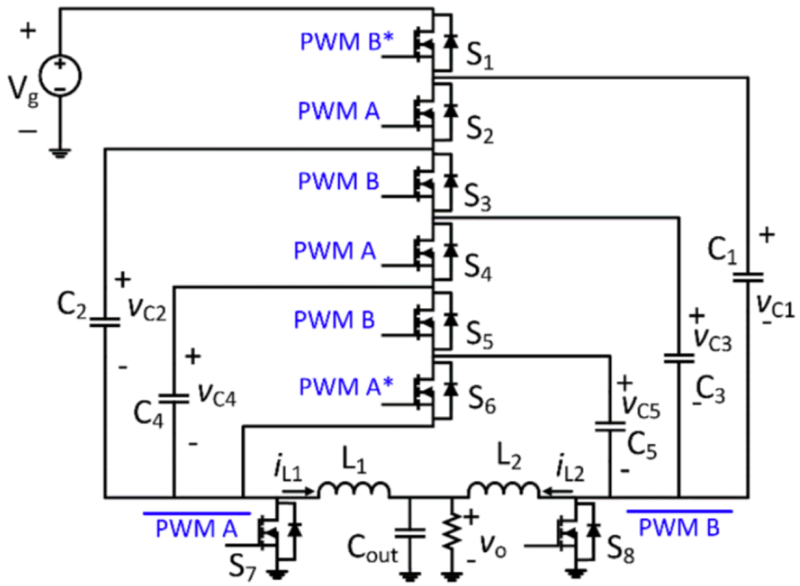
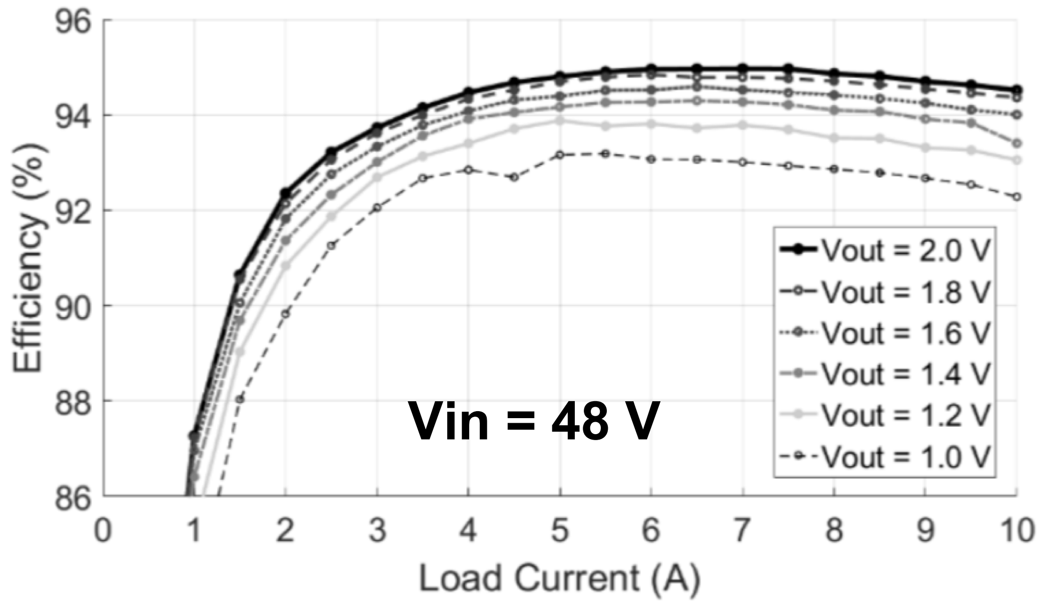


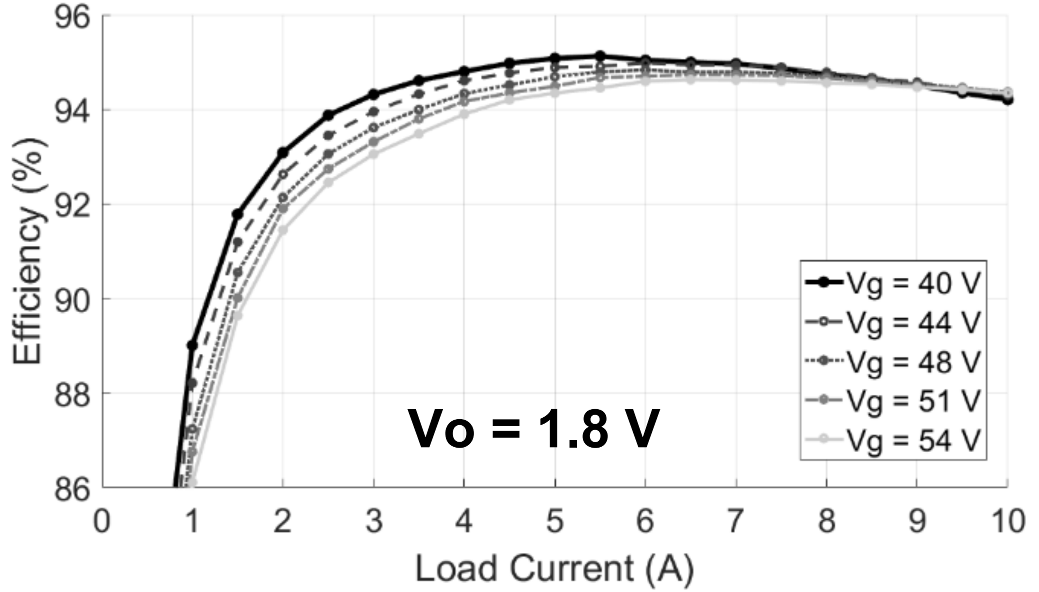


- **Dual inductors hybrid converter:**
  - One charges and one discharges the SC network
- **Ref: R. Das, T. Xie, G-S. Seo, and H-P. Le @ ECCE 2018 (2 papers), APEC 2019 (3 papers)**

iP1 - DIHC 1 (Even-Level) – Data Center VRM

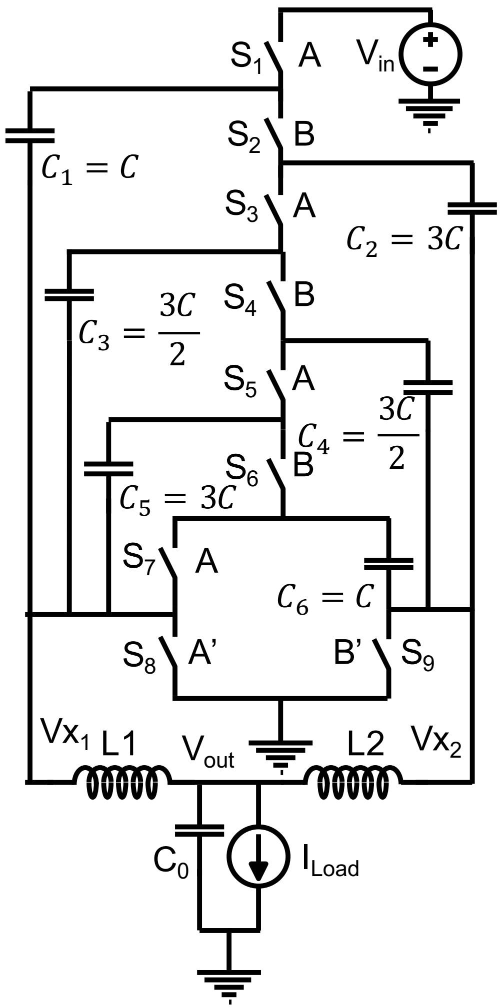


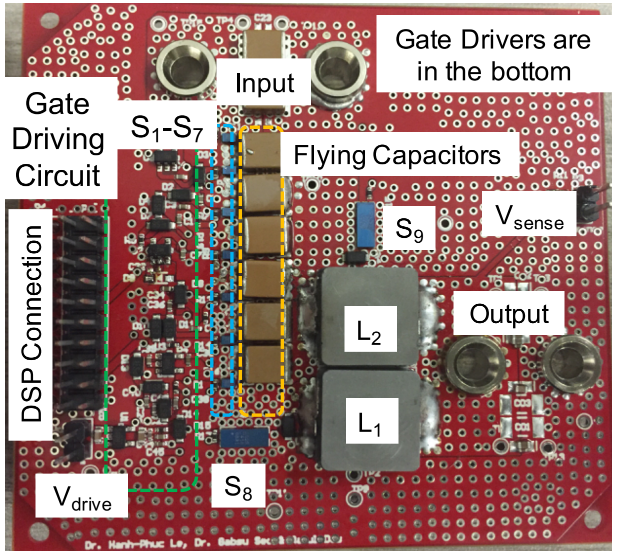


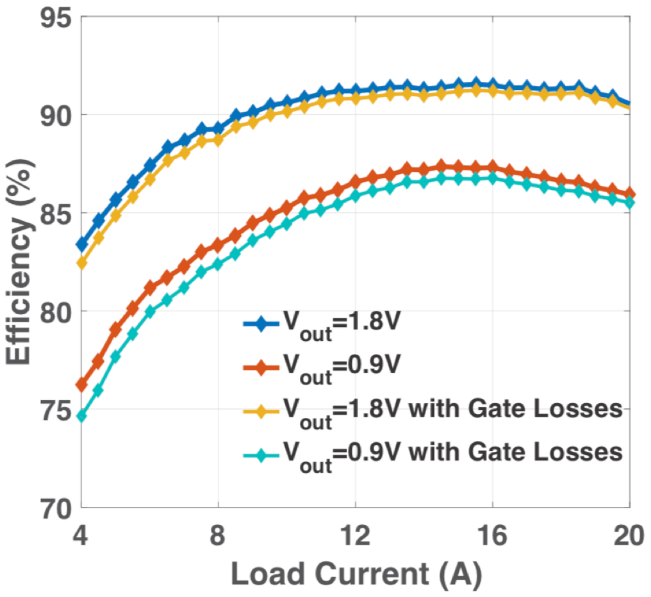


- **48V to 1.8V (norminal)**
  - 40-54V to 1-2V
- **>95% peak efficiency**
- **Split phase control to avoid hard charging**
- **Ref: G-S. Seo, R. Das, H-P. Le @ ECCE 2018**

iP2 - DIHC 2 (Odd-level) – Capacitor First, Extreme Conversion







- **Extreme conversion ratios:**
  - 87.3% from 120V to 0.9V (130:1) at 15A load
  - 91.5% from 120V to 1.8V at 15A load (66.7:1)

- **Ref: R. Das, G-S. Seo, and H-P. Le @ ECCE 2018**

iP3 - Multiphase Dual Inductor Hybrid Converter (MPDIHC)

- **2 inductors,**
- **5 capacitors,**
- **6 phases**

- **Individual charging and discharging phase for capacitors**
  - Completely remove hard charging
  - But high side switches need to handle full inductor currents.

- **92.1%, 48V-to-1.8V @4A**

Covered unpublished materials
(To be presented at APEC 2019)

APEC 2019

iP4 - Multi-Phase Multi-Inductor Hybrid Converter

Covered unpublished materials
(To be presented at APEC 2019)

- 3 inductors, 5 capacitors, 6 levels, 3 charging phases
- 80-W 95%-Efficient 48V-to-1V/2V

Covered unpublished materials

iP5 - Dual-Phase Multi-Inductor Hybrid Converter

Covered unpublished materials
(To be presented at APEC 2019)

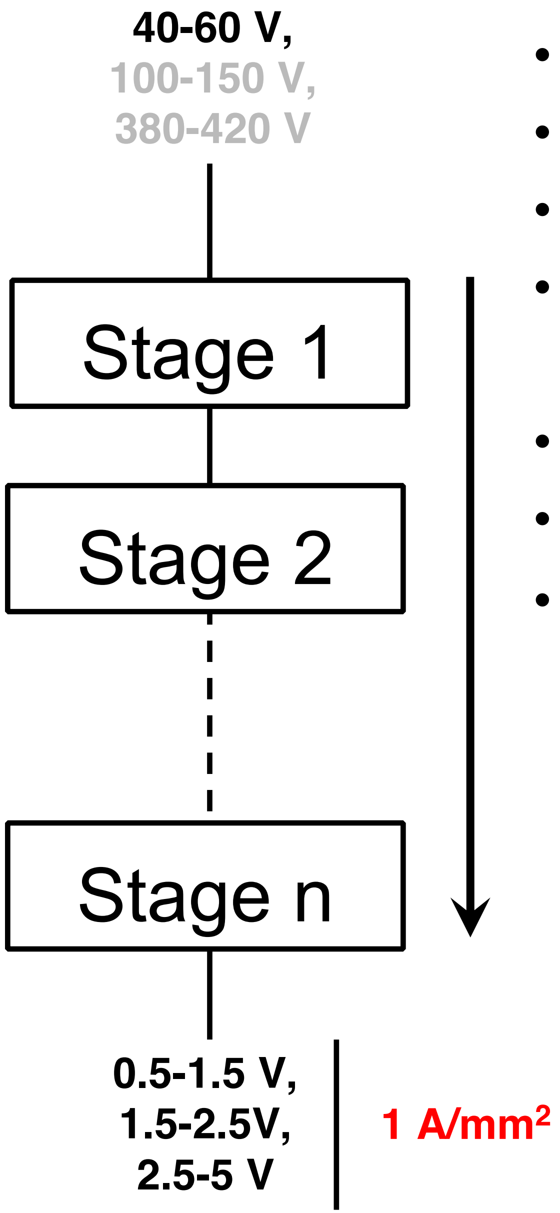
- 4 inductors, 3 capacitors, 4 levels, 2 charging phases

- 90W, 92%, 48V-to-1.6V

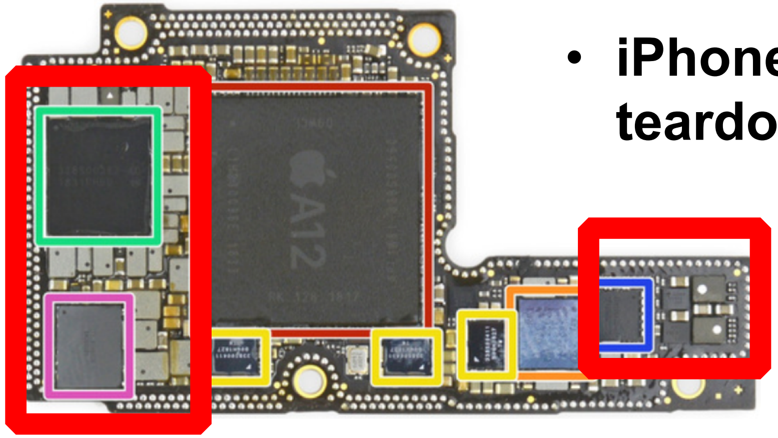
Covered unpublished materials

APEC 2019

What's Next?



- More advanced hybrid converter topologies will come!
- They will cover large conversion ratios.
- They can support cover "impossibly" large current density.
- Multiple stages
  - But these stages have to **work together synchronously as one** for efficiency.
- Inductors and capacitors will be integrated!
- Power switches (GaN or more advanced MOS) will be more integrated!
- The whole converter will be **integrated …**
  - … as everything else has been!



- **iPhone XS teardown**

- **4 unpublished papers was included in this talk!**

iPower3Es

Thank you!

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