Hybrid Switched Capacitor Converters for Efficient and Lightweight Conversion

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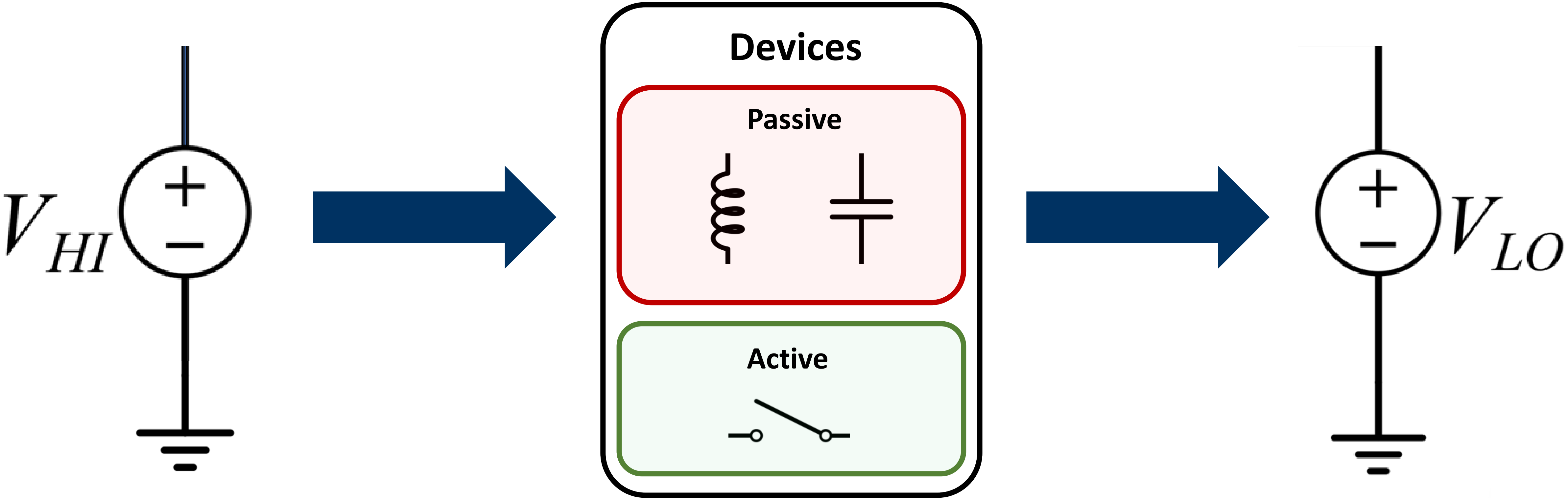
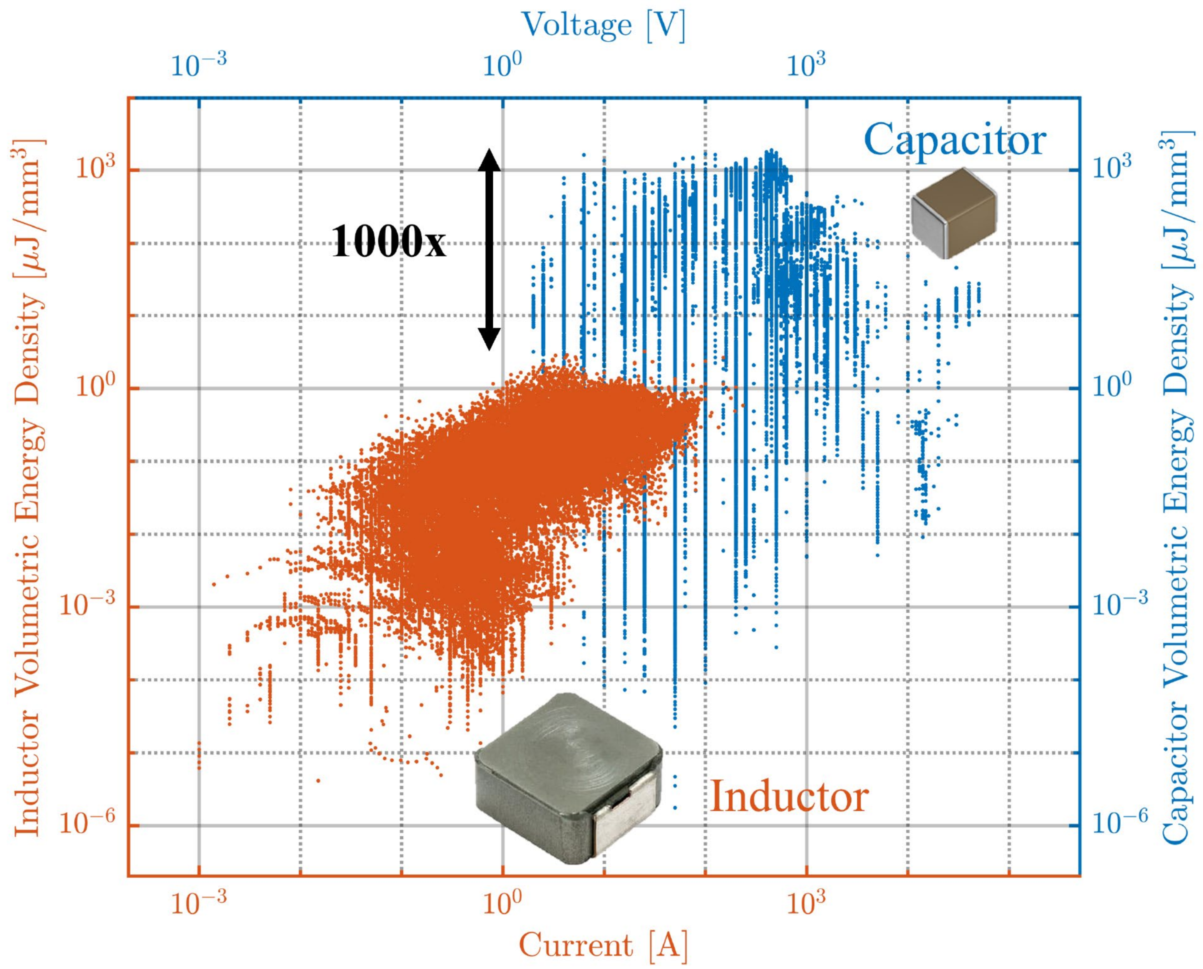
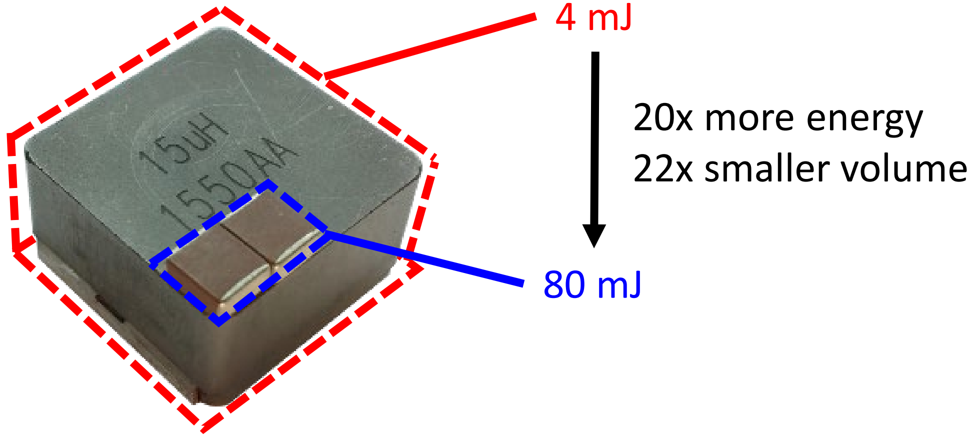
Introduction to Power Electronics



Capacitor-Based Converters



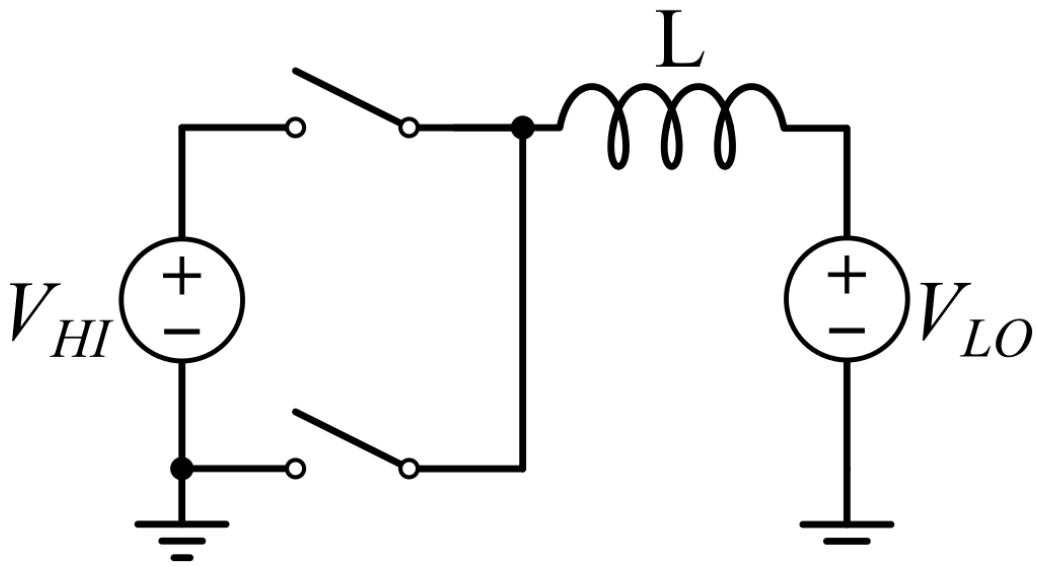
Energy density of multi-layer ceramic capacitors and power inductors [1].



Comparison of energy density between multi-layer ceramic capacitors and inductors.
Note: Components are not to scale but are to relative scale.

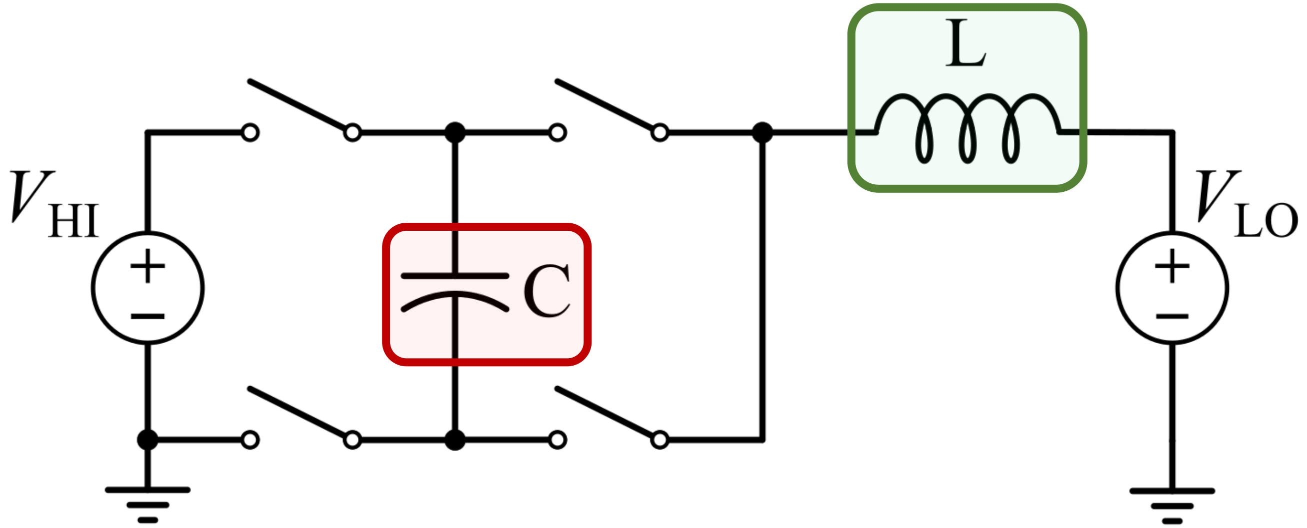
[1] J. Zou, N. Brooks, S. Coday, N. Ellis and R. C. N. Pilawa-Podgurski, “On the Size and Weight of Passive Components: Scaling Trends for High-Density Power Converter Designs,” in 2022 IEEE Workshop on Control and Modeling for Power Electronics (COMPEL), 2022.

Buck Converter



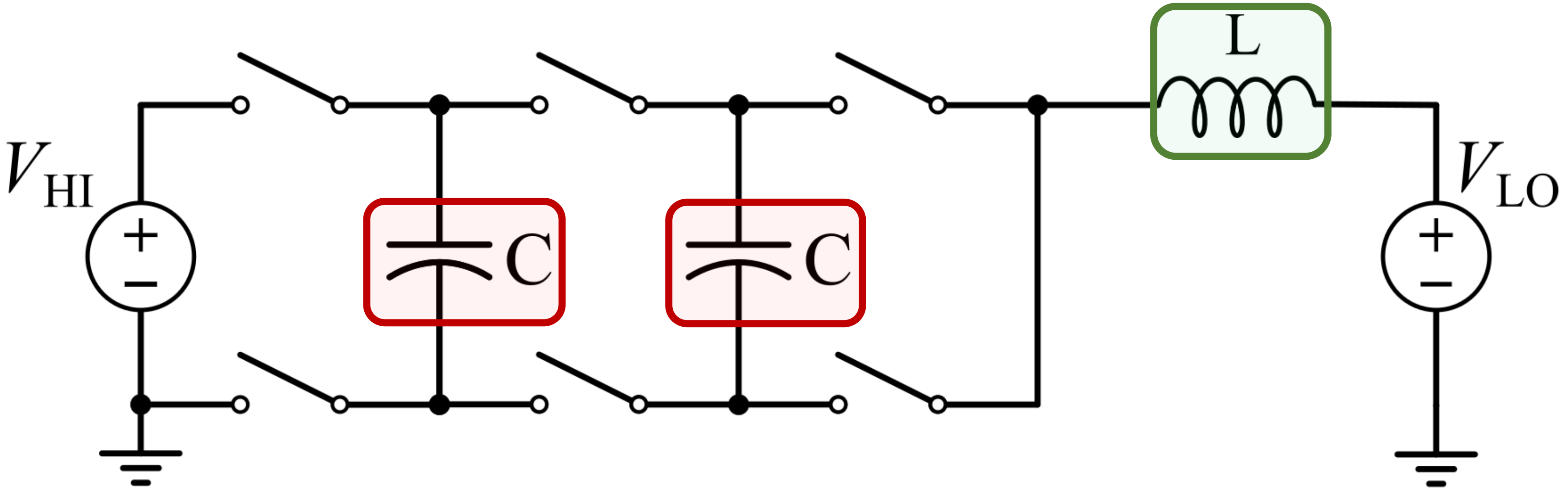
Conventional Buck Converter (a switched-inductor converter).

Hybrid Switched-Capacitor Converter



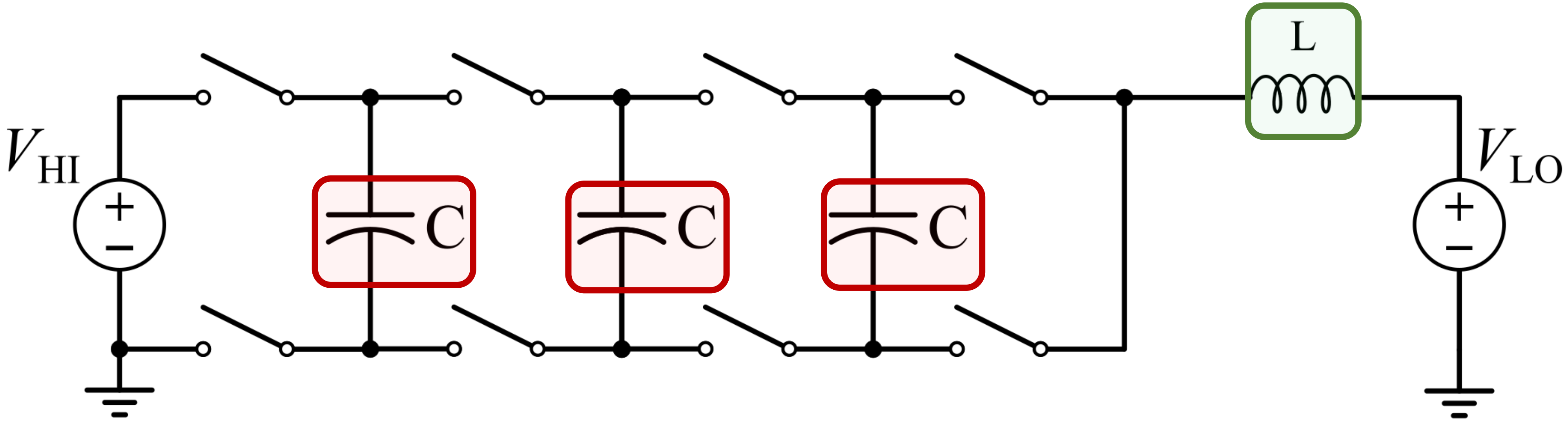
A 2:1 Hybrid Switched-Capacitor Converter.

Hybrid Switched-Capacitor Converter



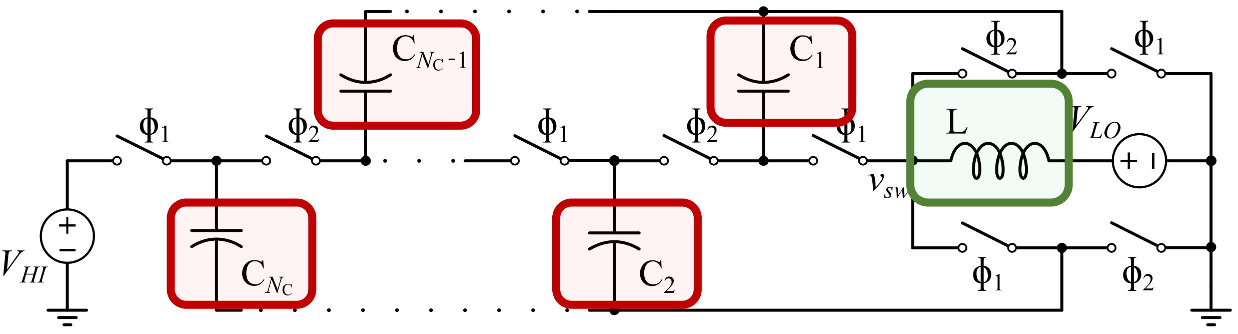
A Hybrid Switched-Capacitor Converter.

Hybrid Switched-Capacitor Converter

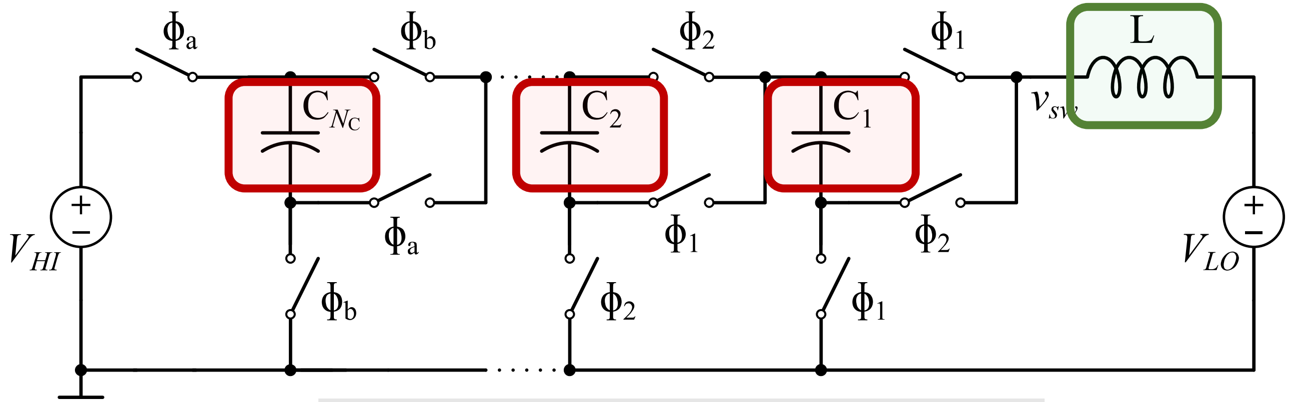


A Hybrid Switched-Capacitor Converter.

Hybrid Switched-Capacitor Topologies

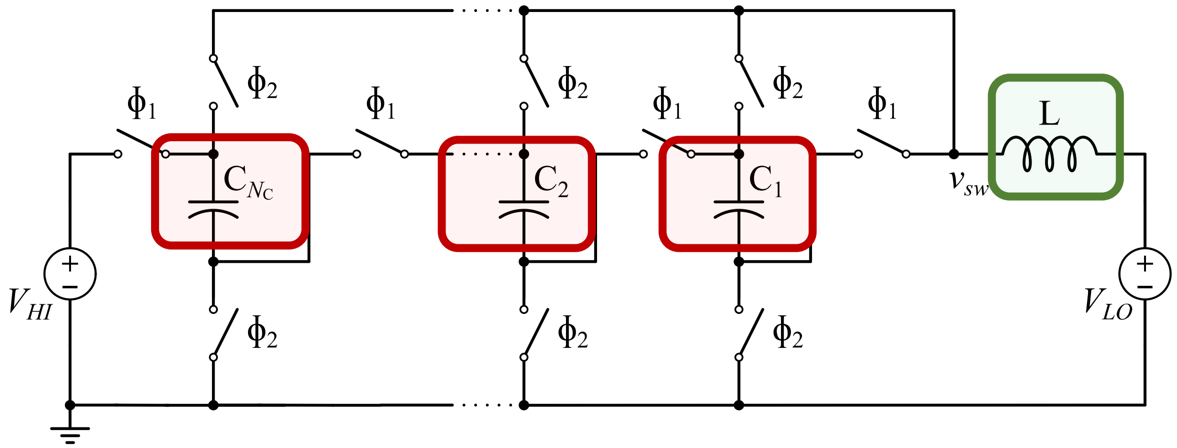


Dickson

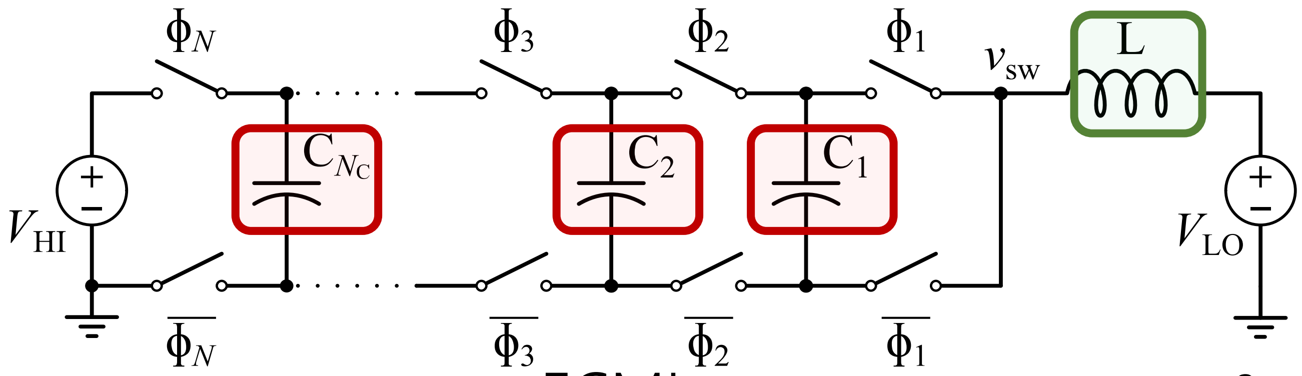


N_C even: a = 1, b = 2 N_C odd: a = 2, b = 1

Fibonacci

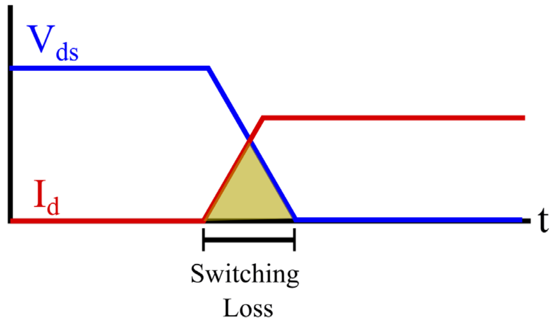


Series-Parallel

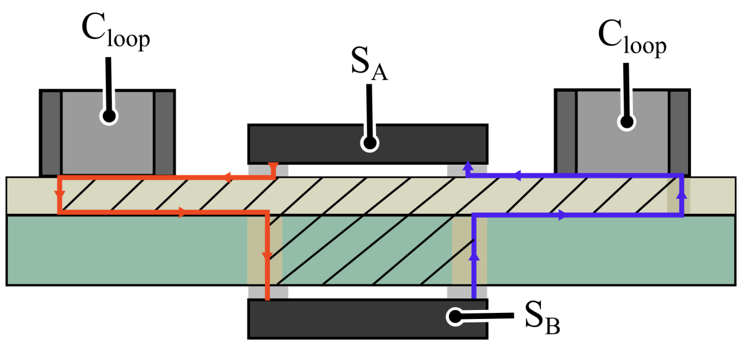


FCML

Implementation Challenges

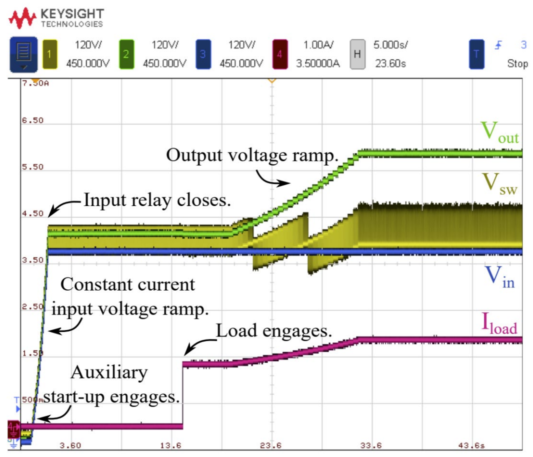


Higher switching losses.

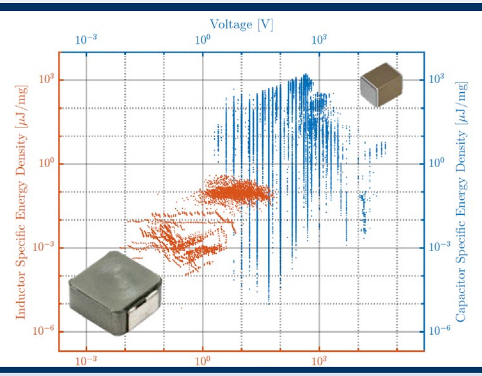


Voltage clearance/creepage.

Challenges



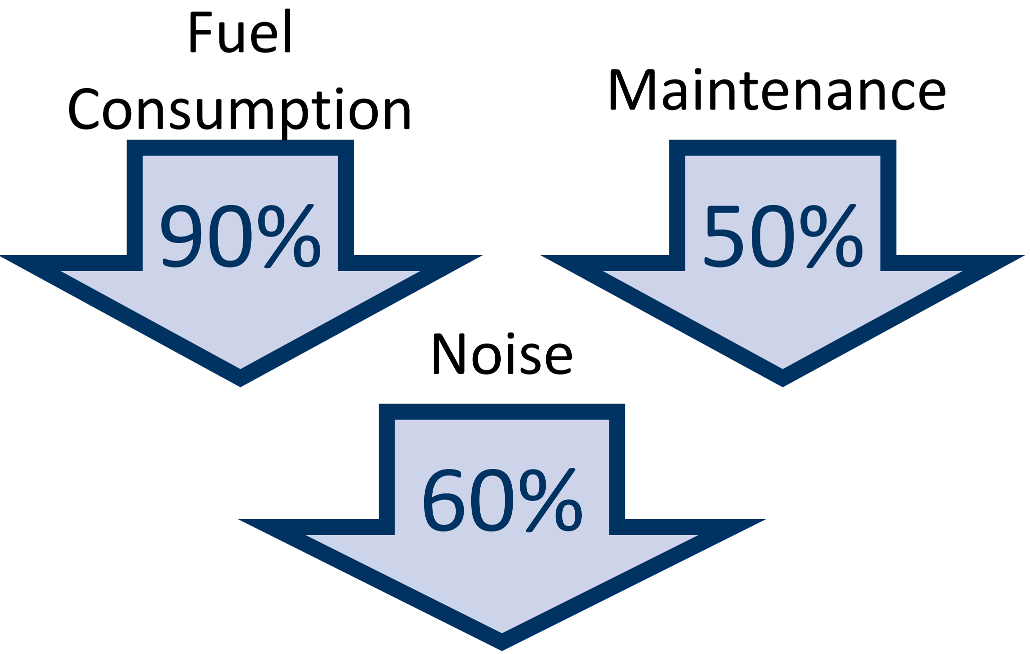
Control techniques.



Component characterization.

Electric Aircraft Benefits

- By 2050 the number of aircraft passengers is expected to triple [1].
- Hybrid electric and eventually fully electric aircrafts offer a solution to reduce emissions and noise from commercial aircrafts [2].



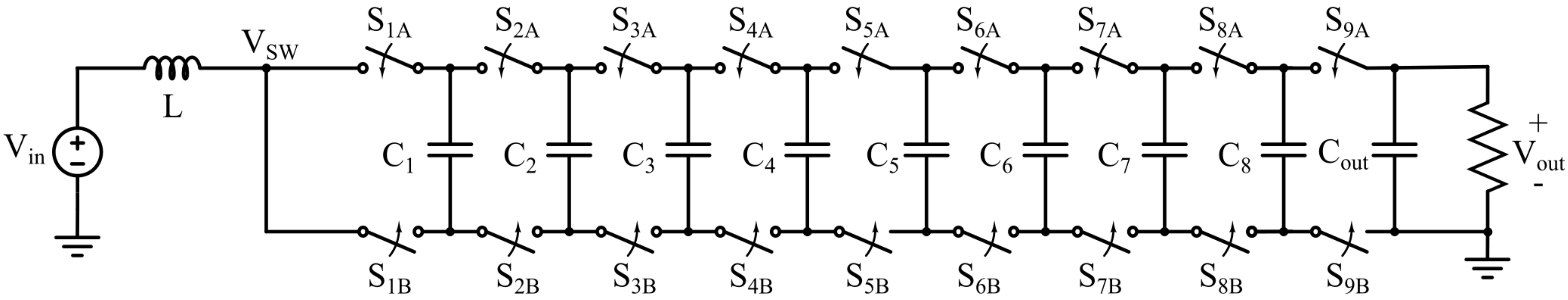
Ampaire set targets Hybrid Electric Flight [3].

NASA's X-57 Maxwell all electric aircraft [4].

Boeing Sugar Volt, parallel hybrid 150 passenger aircraft [5].

[1] J. Overton, "Fact sheet: The growth in greenhouse gas emissions from commercial aviation," 2019.
[2] C. Bowman, et al., "Turbo- and hybrid-electrified aircraft propulsion concepts for commercial transport," AIAA/IEEE EATS, 2018.
[3] Source: Ampaire.
[4] Source: NASA (https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-109.html)
[5] Source: NASA (https://www1.grc.nasa.gov/aeronautics/eap/larger-aircraft/aircraft-configurations-technologies/hybrid-electric/)

10-level FCML Design



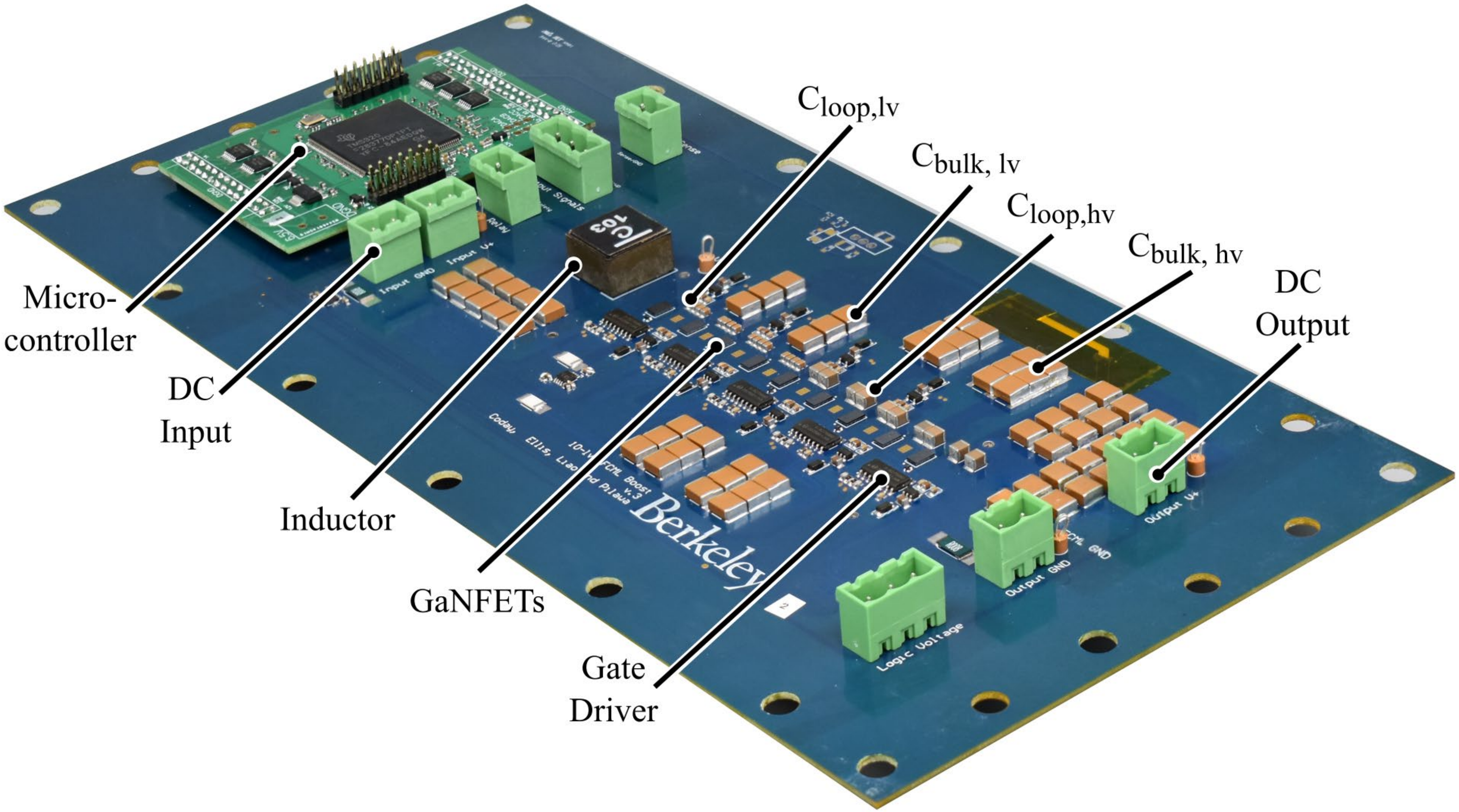
10-level FCML schematic.

Description	Value
Input Voltage	300 V – 700 V
Output Voltage	750 V – 1 kV
Fixed Output Voltage **(Flight)**	750 V
Peak Power	2.5 kW
Fixed Power **(Flight)**	1.6 kW

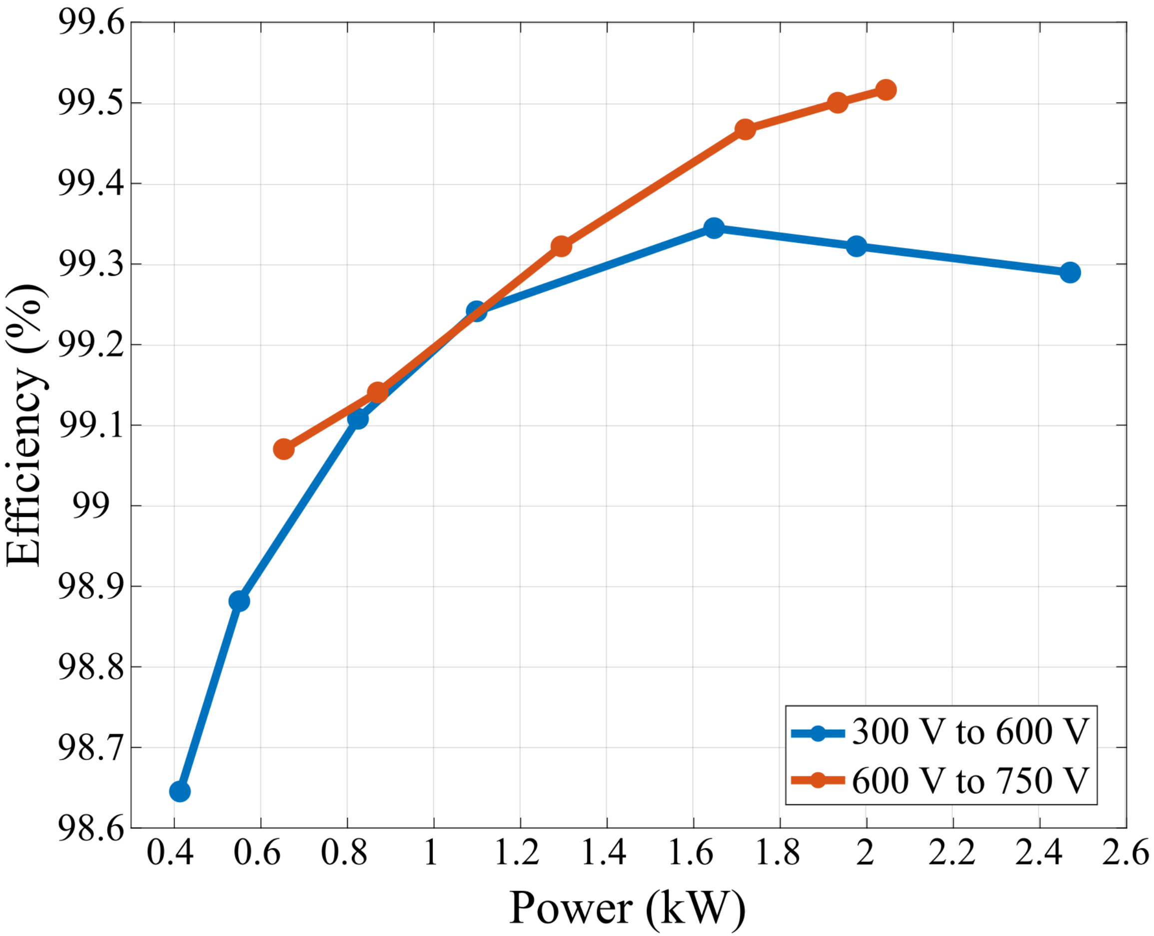
Converter operating parameters.

- Nominal switch stress:
  - 83 V + $\Delta V_{c,fly}$ + overshoot
- EPC2034C GaN FETs
  - 200 V, 48 A
  - Low $R_{ds,on}$: 6 mΩ

Hardware


Micro-
controller
DC
Input
Inductor
GaNFETs
Gate
Driver
$C_{loop,lv}$
$C_{bulk,\ lv}$
$C_{loop,hv}$
$C_{bulk,\ hv}$
DC
Output

FCML Performance



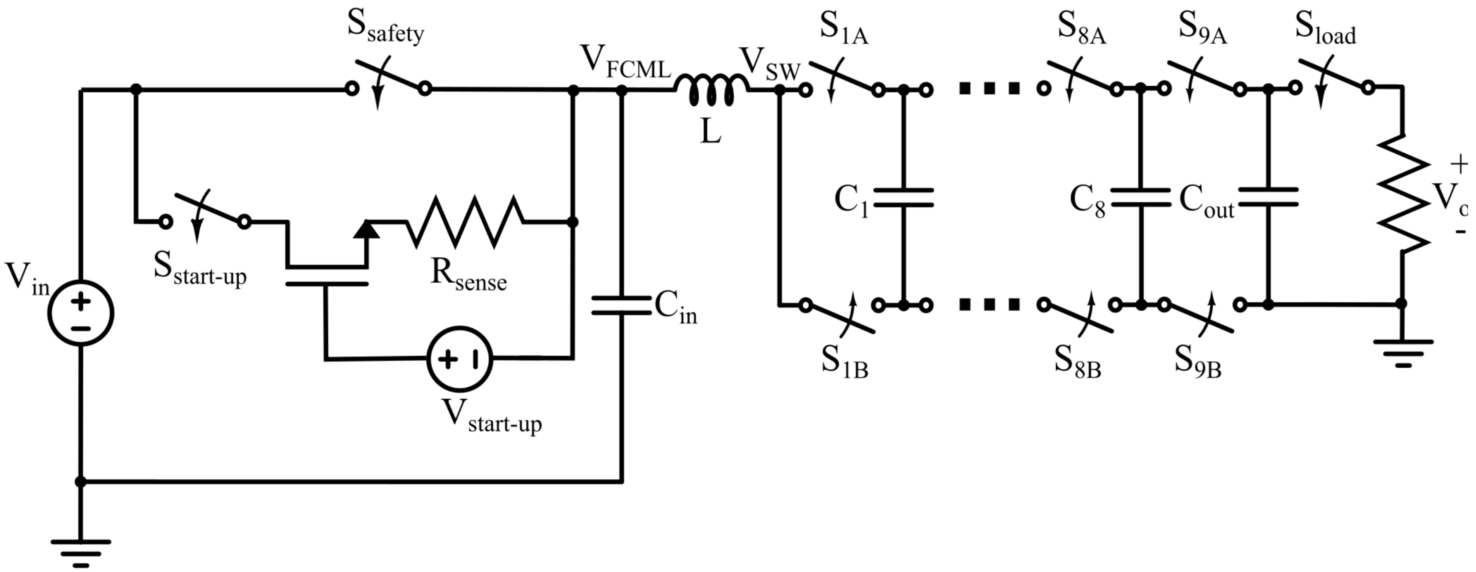
Measured efficiency (including gate drive losses).

FCML performance summary.

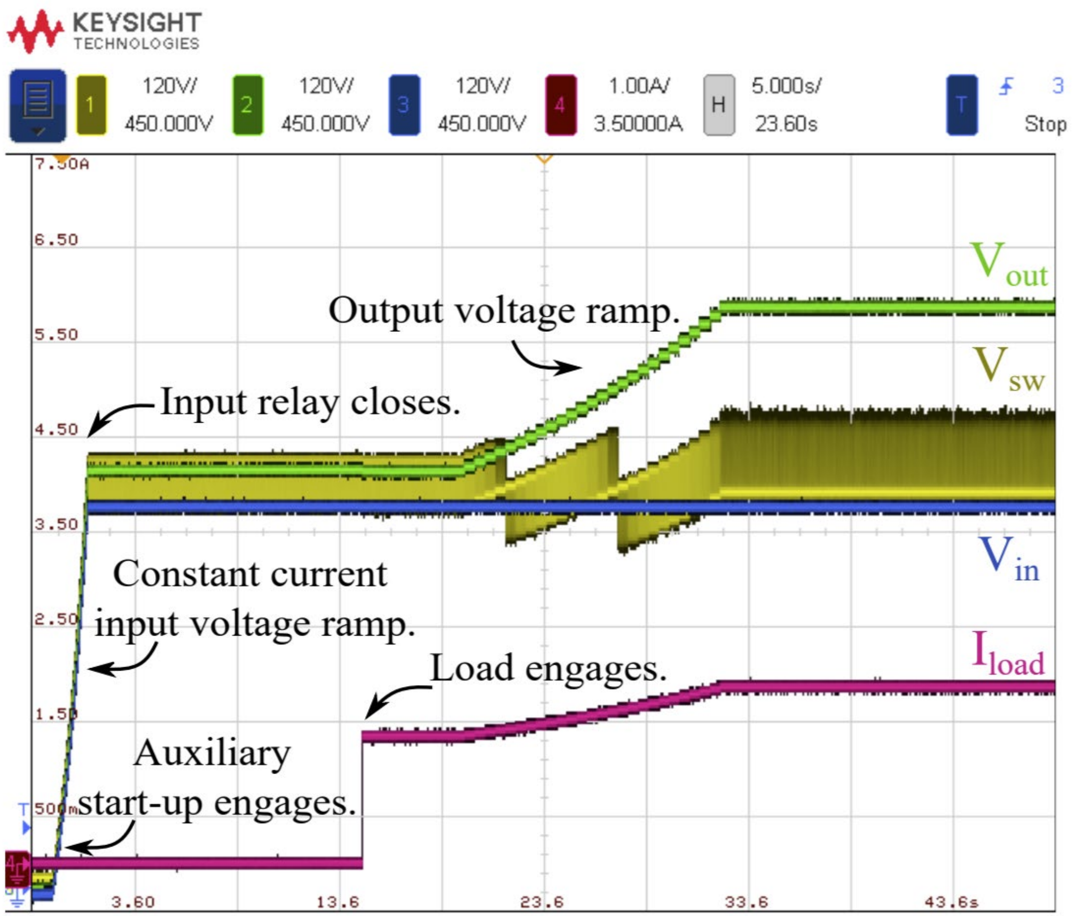
Description	Value
Output Voltage	600 V – 1 kV
f_{sw}	50 kHz
Effective Frequency	450 kHz
Peak Efficiency	**99.52%**
Specific Power Density	**28.3 kW/kg**

Safe Start-up [1]

- New start-up circuit utilizes a constant current source enabled MOSFET to control in-rush current.



Schematic showing constant current path start-up procedure.

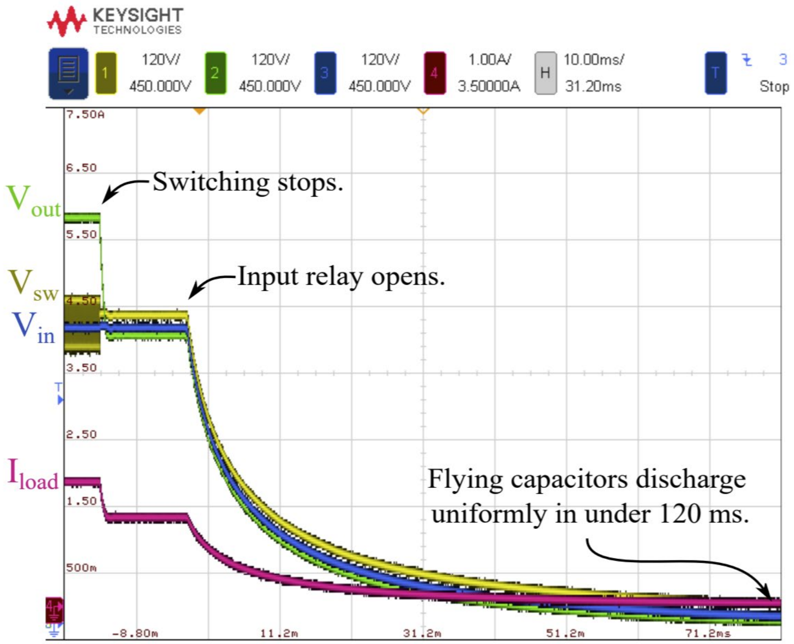


Measured waveforms during start-up, with 550 V input and 750 V output.

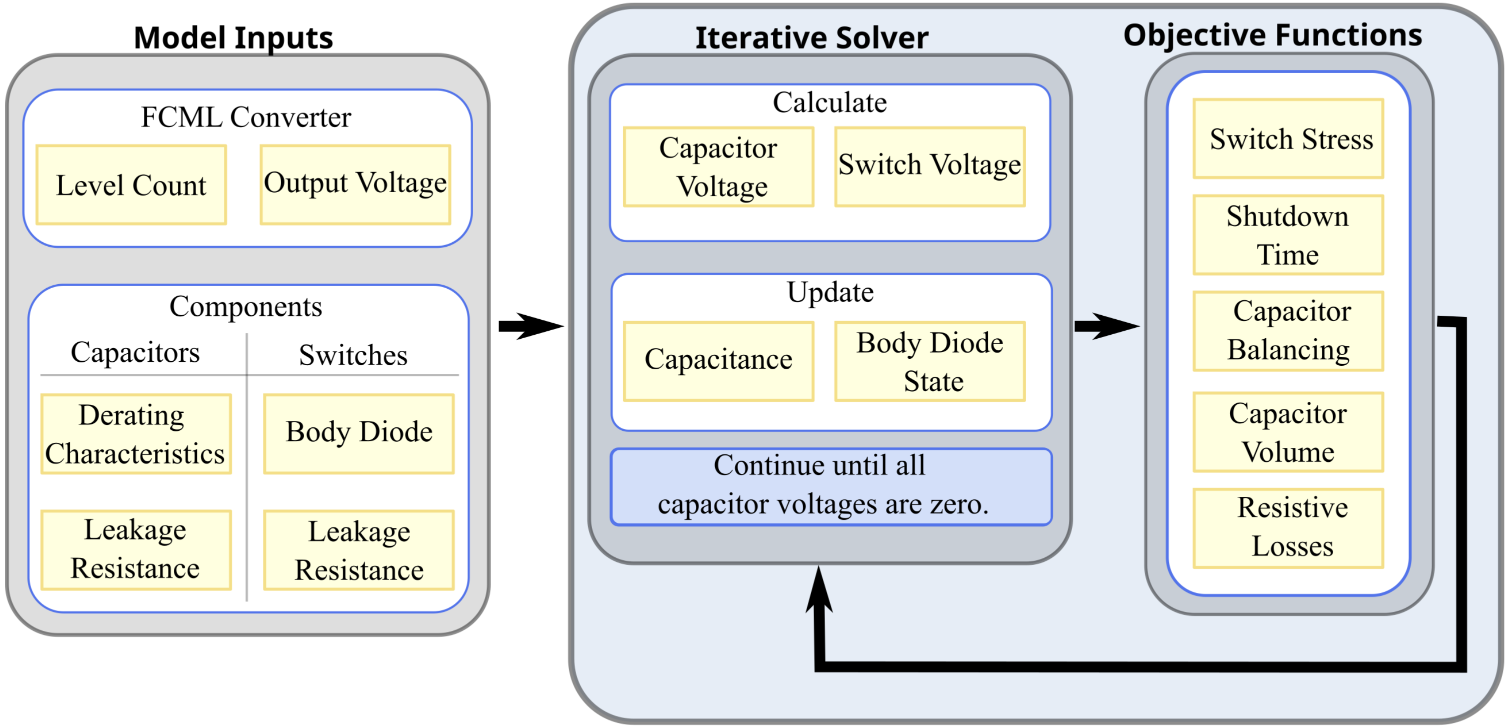
[1] S. Coday, N. Ellis, N. Stokowski, and R. C. N. Pilawa-Podgurski, “Design and Flight Qualification of a Flying Capacitor Multilevel Converter for Electric Aircraft Applications” to appear in IEEE Transactions on Transportation Electrification.

Safe Shutdown [1]

- Without careful design shutdown of capacitor-based converters can result in device failures.
- Developed model allows designers to consider shutdown during design stages and trade-off volume, time and loss.



Experimentally measured **safe** shutdown.



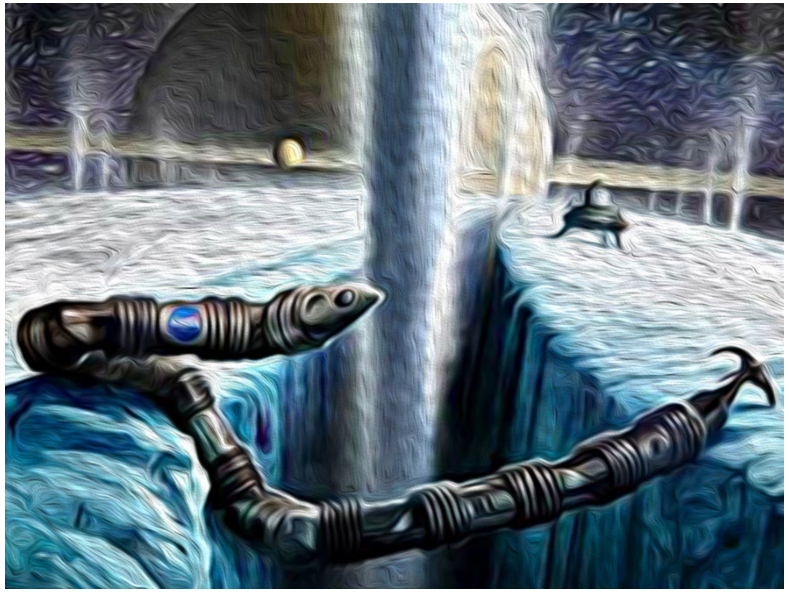
[1] S. Coday, N. M. Ellis and R. C. N. Pilawa-Podgurski, "Modeling and Analysis of Shutdown Dynamics in Flying Capacitor Multilevel Converters," in IEEE Transactions on Power Electronics, doi: 10.1109/TPEL.2023.3285741.

System Integration

Multilevel Converters in Space

- Extreme terrain capable robots will enable further exploration on sites such as pits on the moon and Martian landscape [1].
  - Tethered power systems have been proposed to power these small rovers; however, they require high voltage DC power [2].

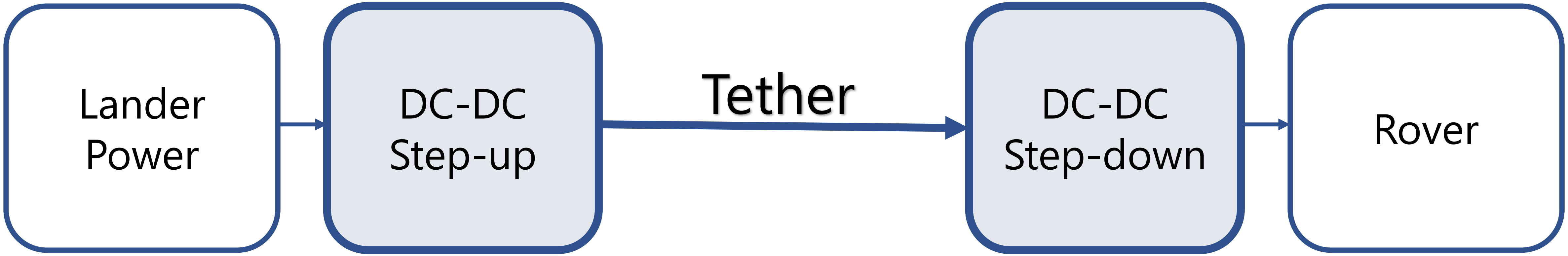
DuAxel with retractable tether [2]



Exobiology Extant Life Surveyor (EELS) Robot- Artist Interpretation [3]

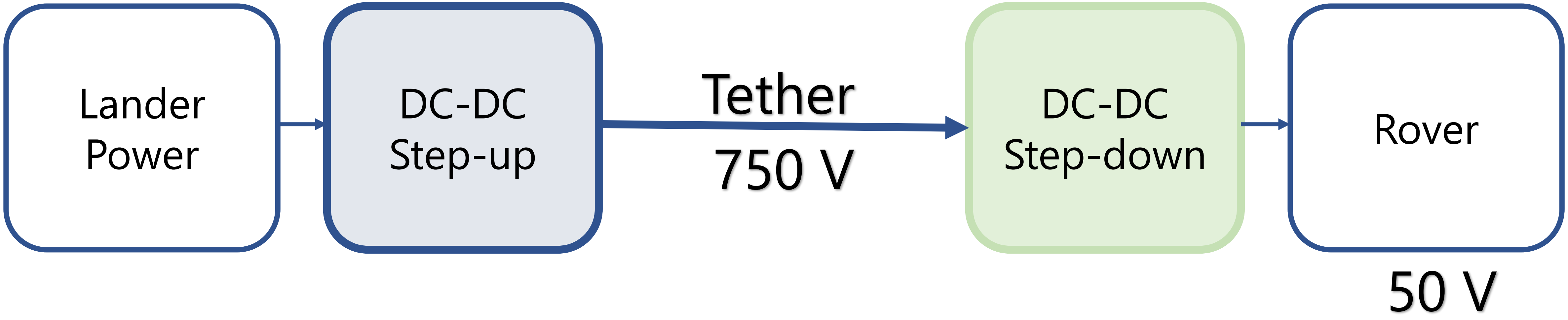
[1] P. McGarey, W. Reid and I. Nesnas, "Towards Articulated Mobility and Efficient Docking for the DuAxel Tethered Robot System," *2019 IEEE Aerospace Conference*, 2019, pp. 1-9.
[2] P. McGarey, T. Nguyen, T. Pailevanian and I. Nensas, "Design and Test of an Electromechanical Rover Tether for the Exploration of Vertical Lunar Pits," *2020 IEEE Aerospace Conference*, 2020, pp. 1-10.
[3] K. Carpenter and M. Cable. "Exobiology Extant Life Surveyor (EELS) Robotic Architecture." https://www.kiss.caltech.edu/lectures/2019_EELS.html

Multilevel Converters in Space



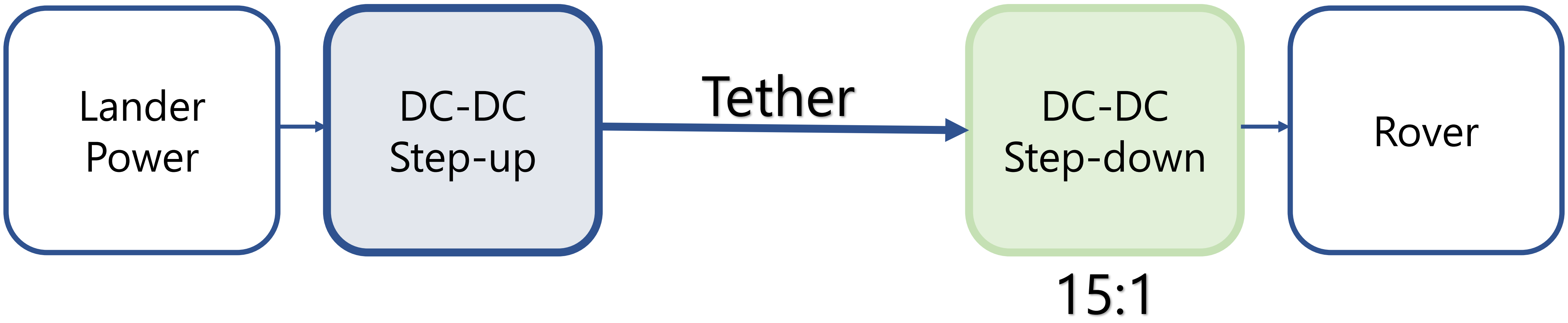
Multilevel Converters in Space

- ❑ Withstand radiation of the harsh space environment.



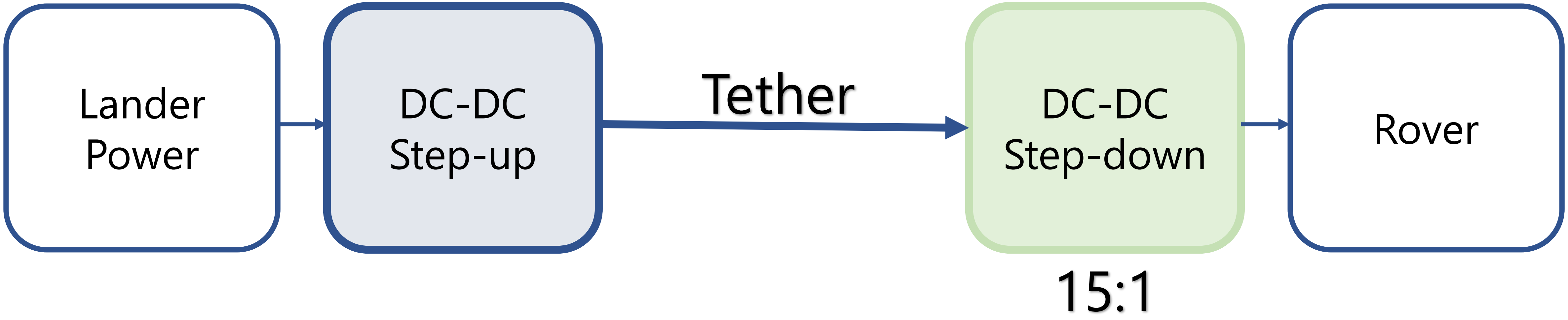
Multilevel Converters in Space

- ❑ Withstand radiation of the harsh space environment.
- ❑ Capable of high voltage step-down conversion ratio.



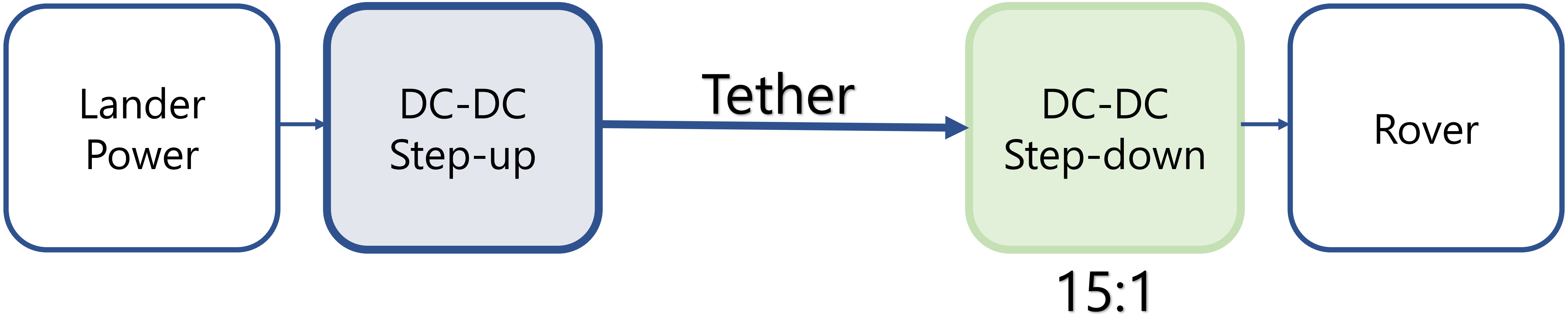
Multilevel Converters in Space

- ❑ Withstand radiation of the harsh space environment.
- ❑ Capable of high voltage step-down conversion ratio.
- ❑ Regulation of output voltage.



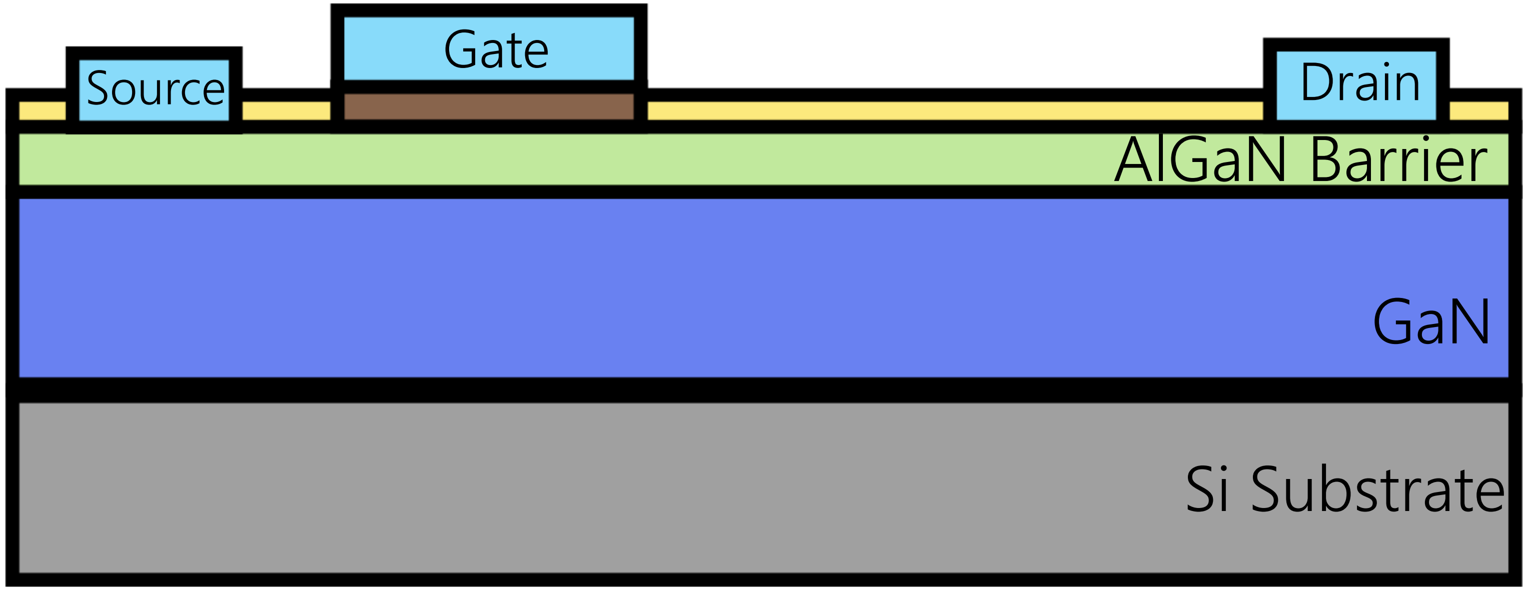
Multilevel Converters in Space

- Withstand radiation of the harsh space environment.
- Capable of high voltage step-down conversion ratio.
- Regulation of output voltage.
- Light-weight and compact design.



Design Challenges

- ✓ Withstand radiation of the harsh space environment.
- ❑ Capable of high voltage step-down conversion ratio.
- ❑ Regulation of output voltage.
- ❑ Light-weight and compact
- Due to their device structure, GaN devices have been shown to withstand radiation better than traditional silicon devices [1][2].

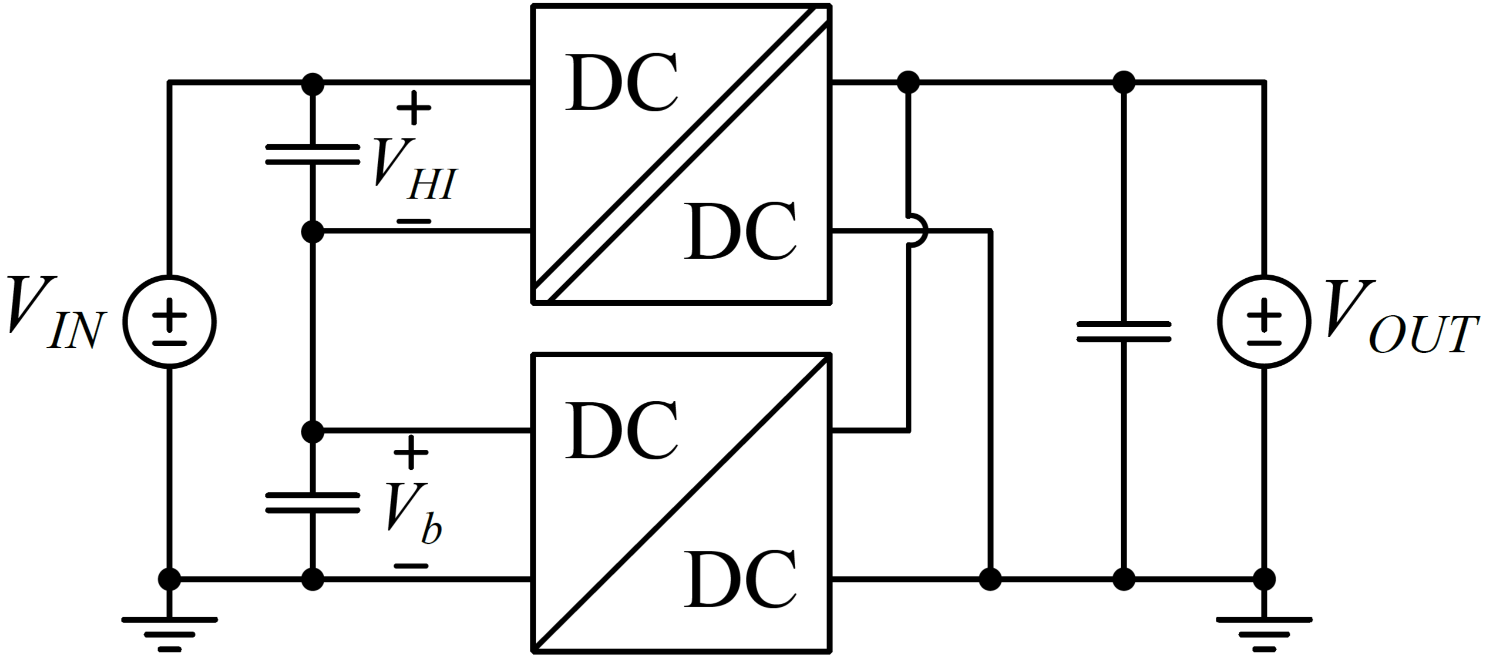


Enhancement mode GaN Transistor.

[1] M. Zafrani and A. Lidow, GaN in Space Applications, Power Electronics Europe, Issue 6 2020.
[2] S. Coday, A. Barchowsky, and R. C. N. Pilawa-Podgurski, "A 10-level GaN-based Flying Capacitor Multilevel Boost Converter for Radiation-Hardened Operation in Space Applications," in 2021 IEEE Applied Power Electronics Conference and Exposition (APEC), 2021.

Design Challenges

- ✓ Withstand radiation of the harsh space environment.
- ✓ Capable of high voltage step-down conversion ratio.
- ❑ Regulation of output voltage.
- ❑ Light-weight and compact design.



Partial Power Processing (PPP) Structure [1]

[1] C. Li, Y. E. Bouvier, A. Berrios, P. Alou, J. A. Oliver, and J. A. Cobos, “Revisiting ’Partial Power Architectures’ from the ’Differential Power’ Perspective,” in 2019 20th Workshop on Control and Modeling for Power Electronics (COMPEL), 2019, pp. 1–8.

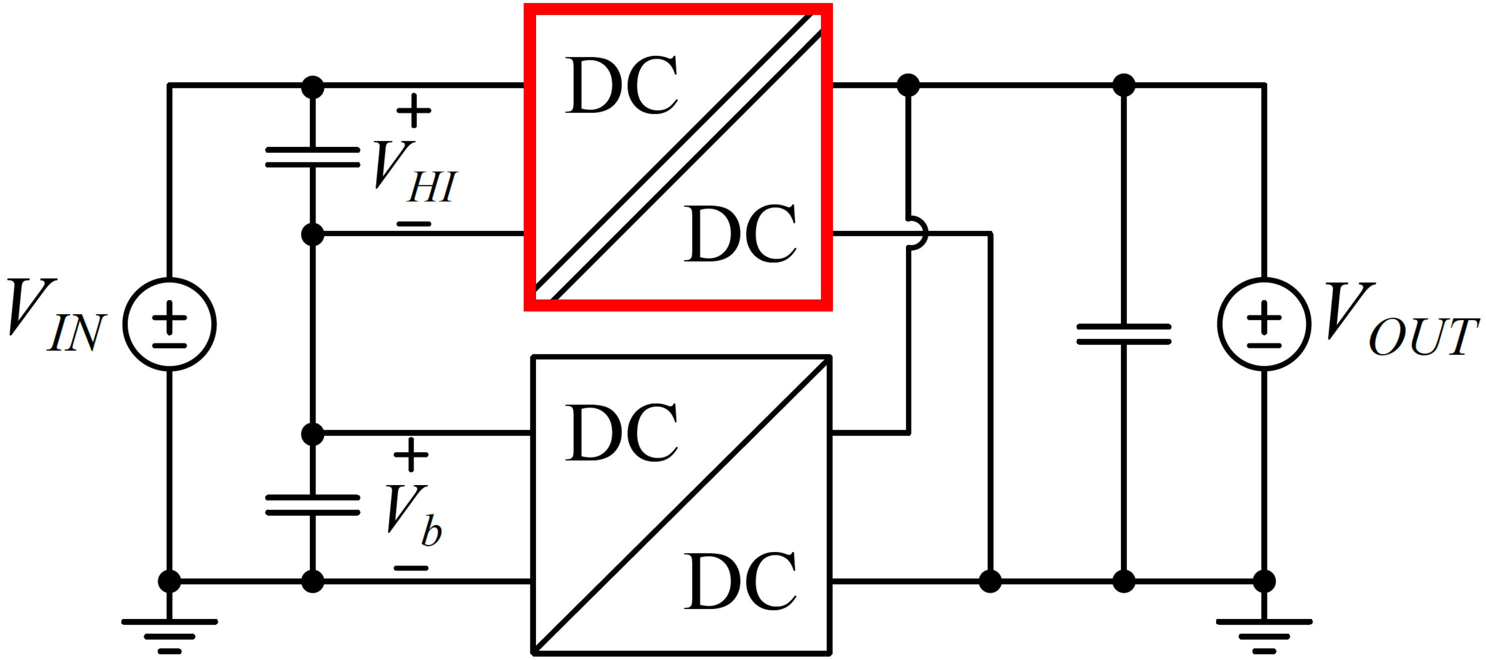
Design Challenges

✓ Withstand radiation of the harsh space environment.

✓ Capable of high voltage step-down conversion ratio.

❑ Regulation of output voltage.

❑ Light-weight and compact design.



Partial Power Processing (PPP) Structure [1]

- Fixed-ratio converter with high efficiency and power density.
- Processes the majority of the power.

[1] C. Li, Y. E. Bouvier, A. Berrios, P. Alou, J. A. Oliver, and J. A. Cobos, “Revisiting ’Partial Power Architectures’ from the ’Differential Power’ Perspective,” in 2019 20th Workshop on Control and Modeling for Power Electronics (COMPEL), 2019, pp. 1–8.

Design Challenges

- ✓ Withstand radiation of the harsh space environment.
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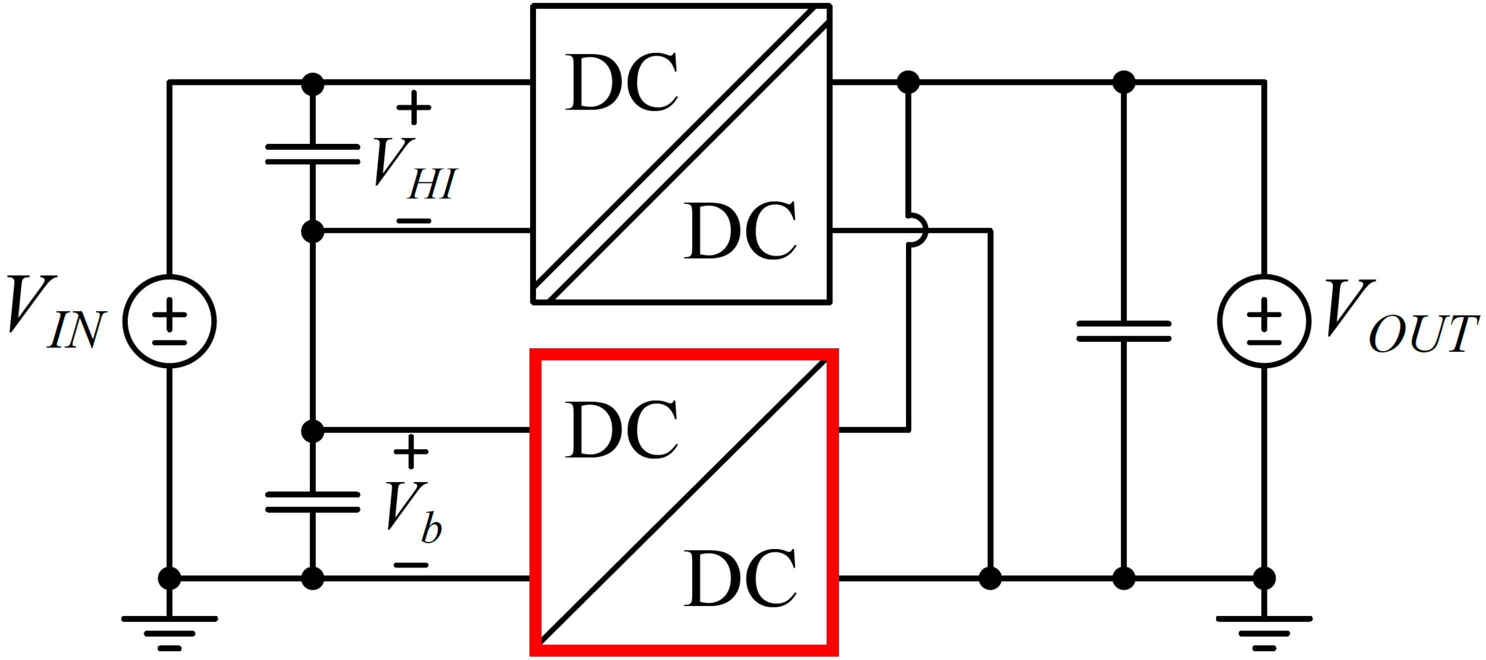
- ✓ Regulation of output voltage.
- ❑ Light-weight and compact design.



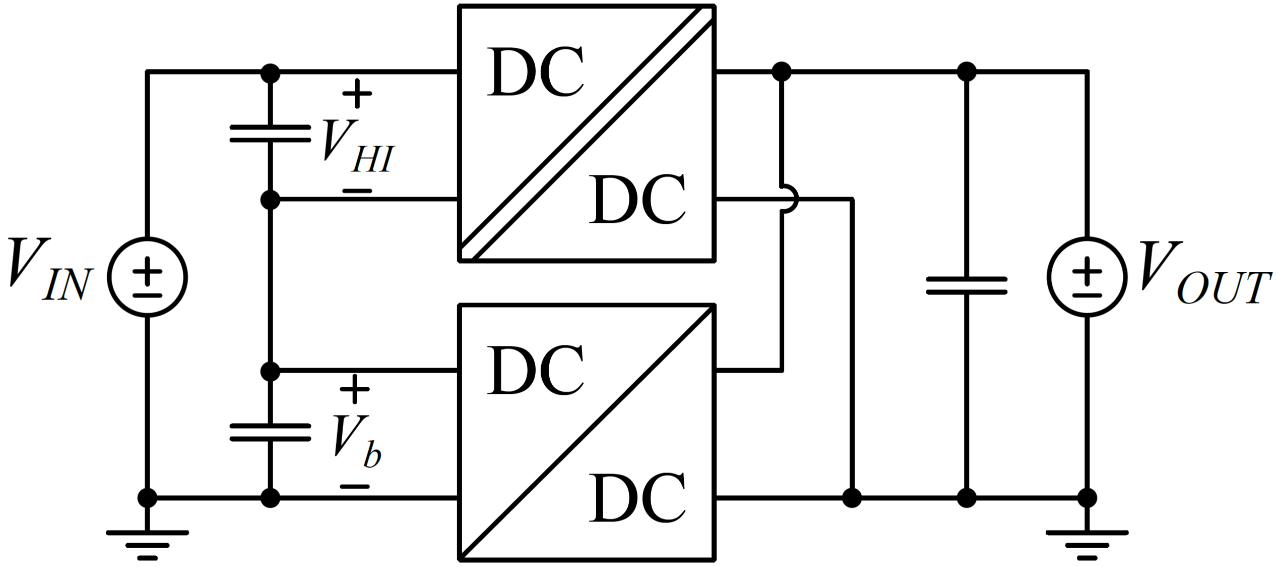
Partial Power Processing (PPP) Structure [1]

- Regulating converter allows for varying input/output voltage requirements.
- Processes minimum power to provide regulation.

[1] C. Li, Y. E. Bouvier, A. Berrios, P. Alou, J. A. Oliver, and J. A. Cobos, “Revisiting ’Partial Power Architectures’ from the ’Differential Power’ Perspective,” in 2019 20th Workshop on Control and Modeling for Power Electronics (COMPEL), 2019, pp. 1–8.

Design Challenges

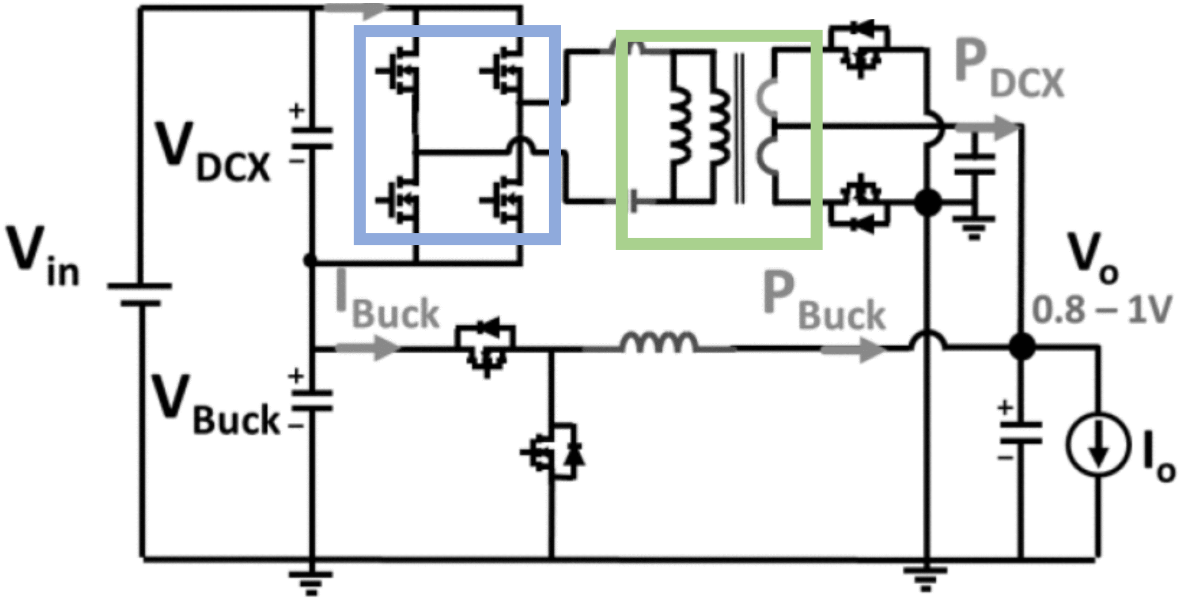
- ✓ Withstand radiation of the harsh space environment.
- ✓ Capable of high voltage step-down conversion ratio.
- ✓ Regulation of output voltage.
- ❑ Light-weight and compact design.



Partial Power Processing (PPP) Structure [1]

High voltage stress.

Magnetic isolation.



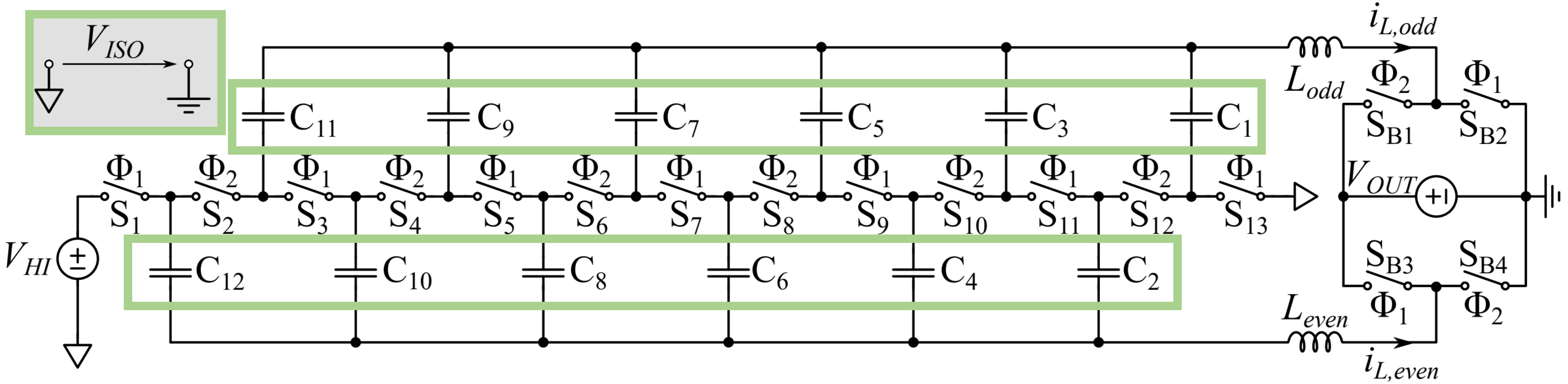
Sigma converter for 48:1 conversion [1].

[1] M. H. Ahmed, C. Fei, F. C. Lee, and Q. Li, “Single-Stage High-Efficiency 48/1 V Sigma Converter With Integrated Magnetics,” IEEE Transactions on Industrial Electronics, vol. 67, no. 1, pp. 192–202, 2020.

Design Challenges

- ✓ Withstand radiation of the harsh space environment.
- ✓ Capable of high voltage step-down conversion ratio.
- ✓ Regulation of output voltage.
- ❑ Light-weight and compact design.

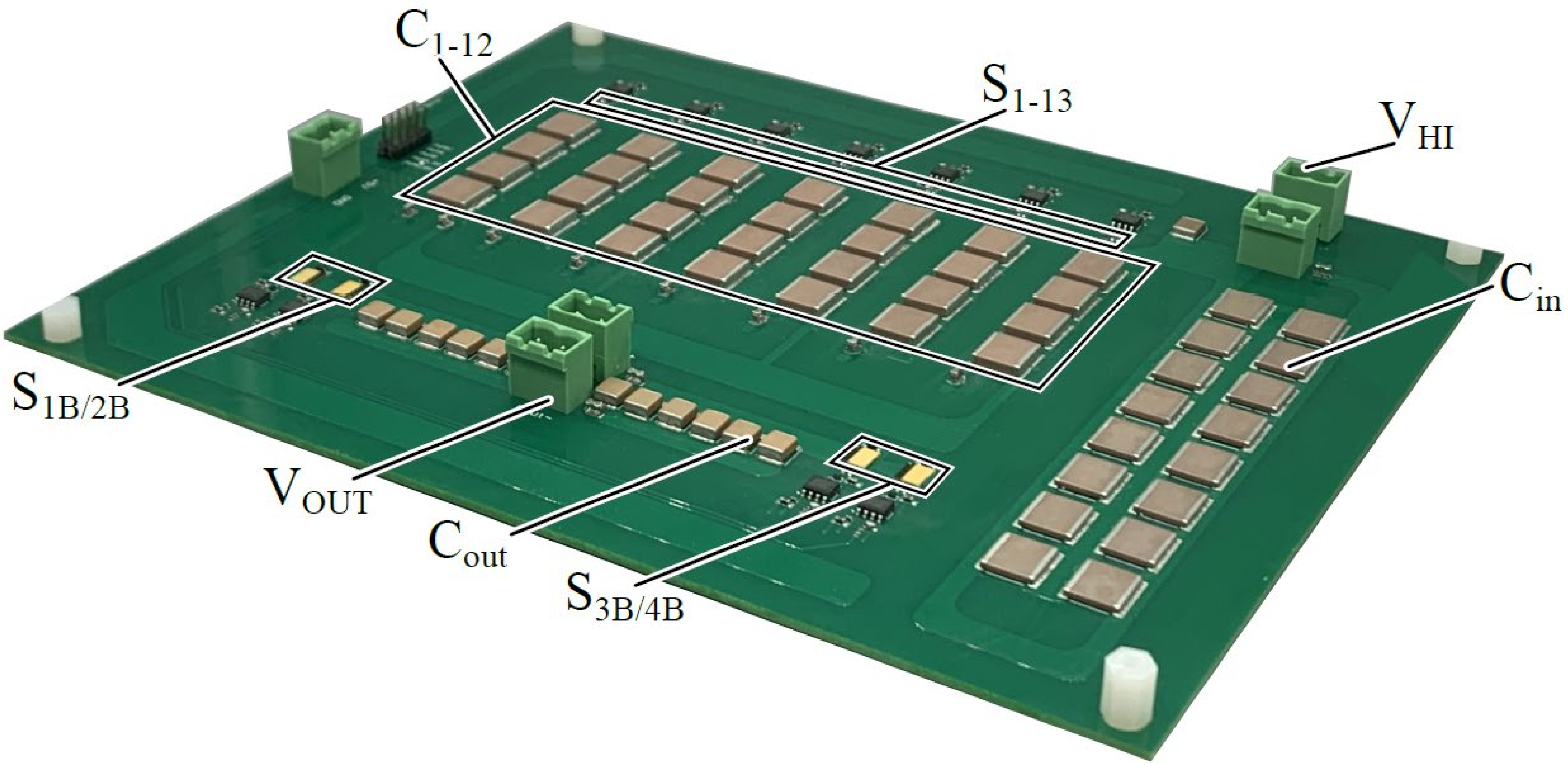
$$V_{ds,max} = \frac{1}{6} \cdot V_{HI}$$



Dual Extended LC-tank 12:1 Converter [1]

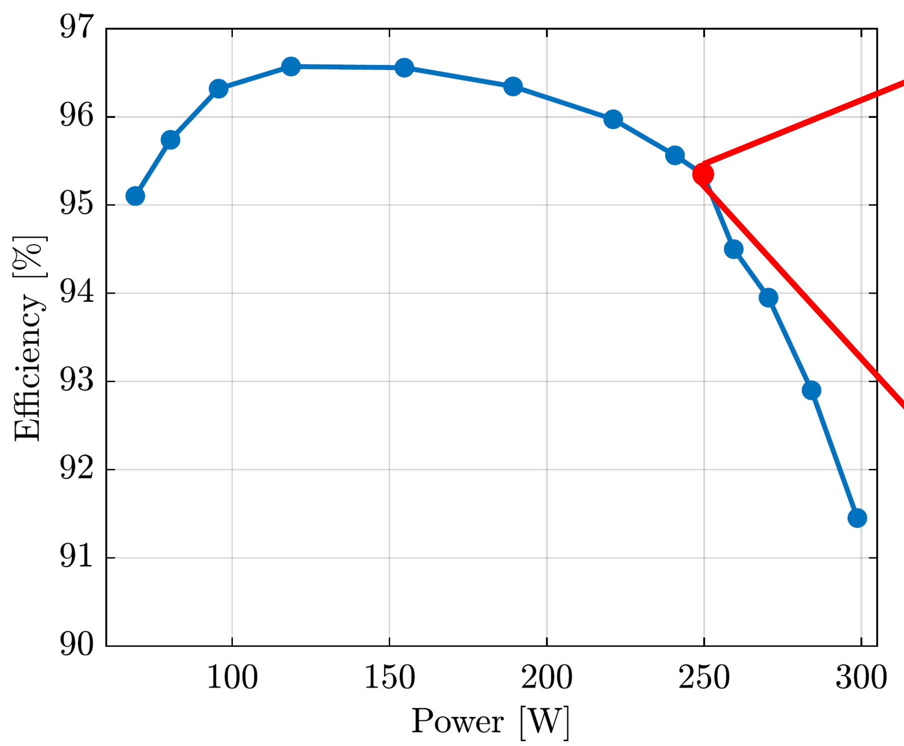
[1] A. Jackson, N. M. Ellis and R. C. N. Pilawa-Podgurski, "A Capacitively-Isolated Dual Extended LC-tank Hybrid Switched-Capacitor Converter," 2022 IEEE Applied Power Electronics Conference and Exposition (APEC), 2022, pp. 1279-1283.

Hardware Prototype

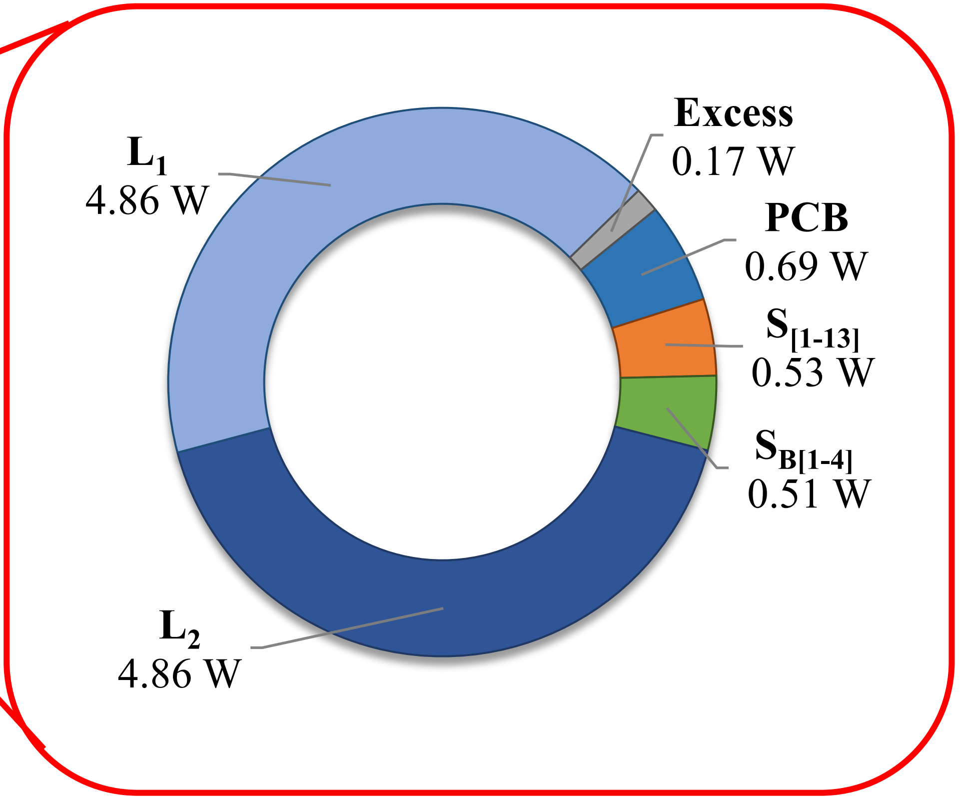


Dickson Converter Performance

- Dickson converter peak efficiency is measured at 96.6%, with a fixed conversion ration of 12:1.



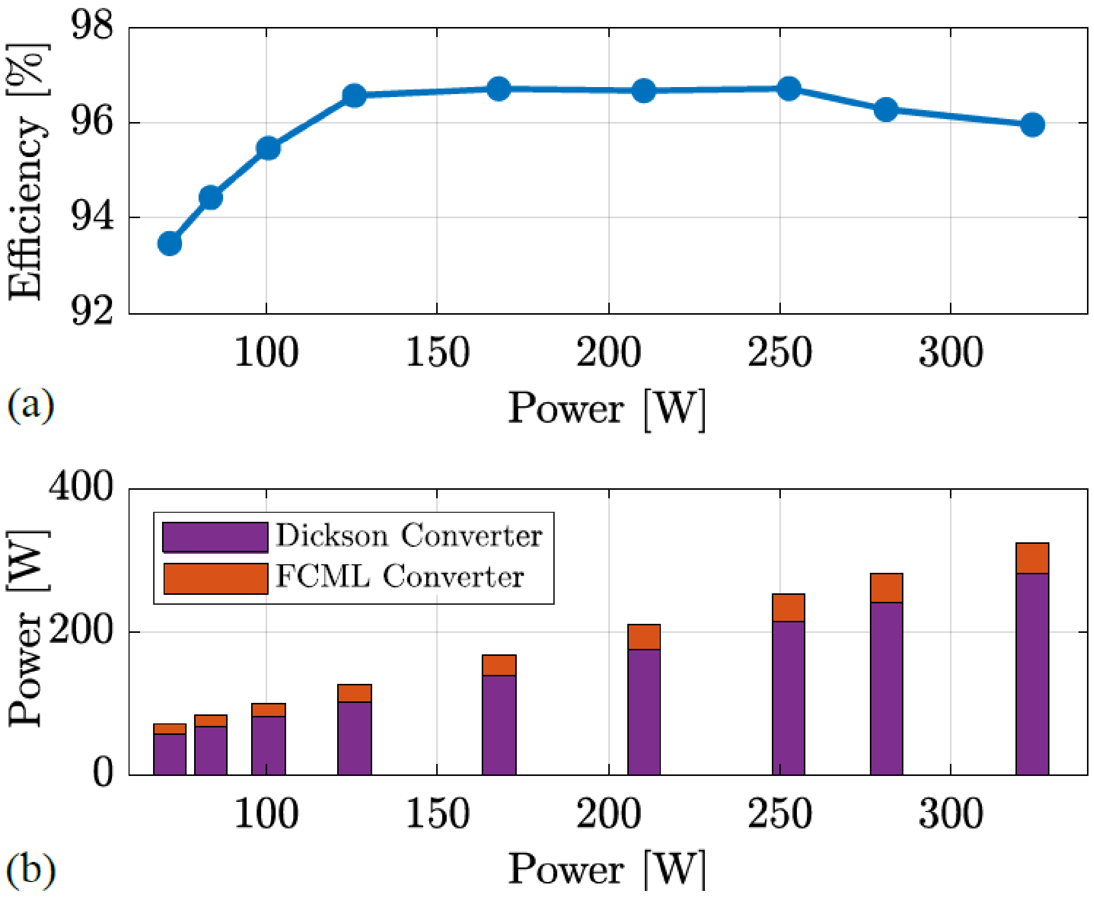
Measured efficiency for 12:1 fixed conversion.



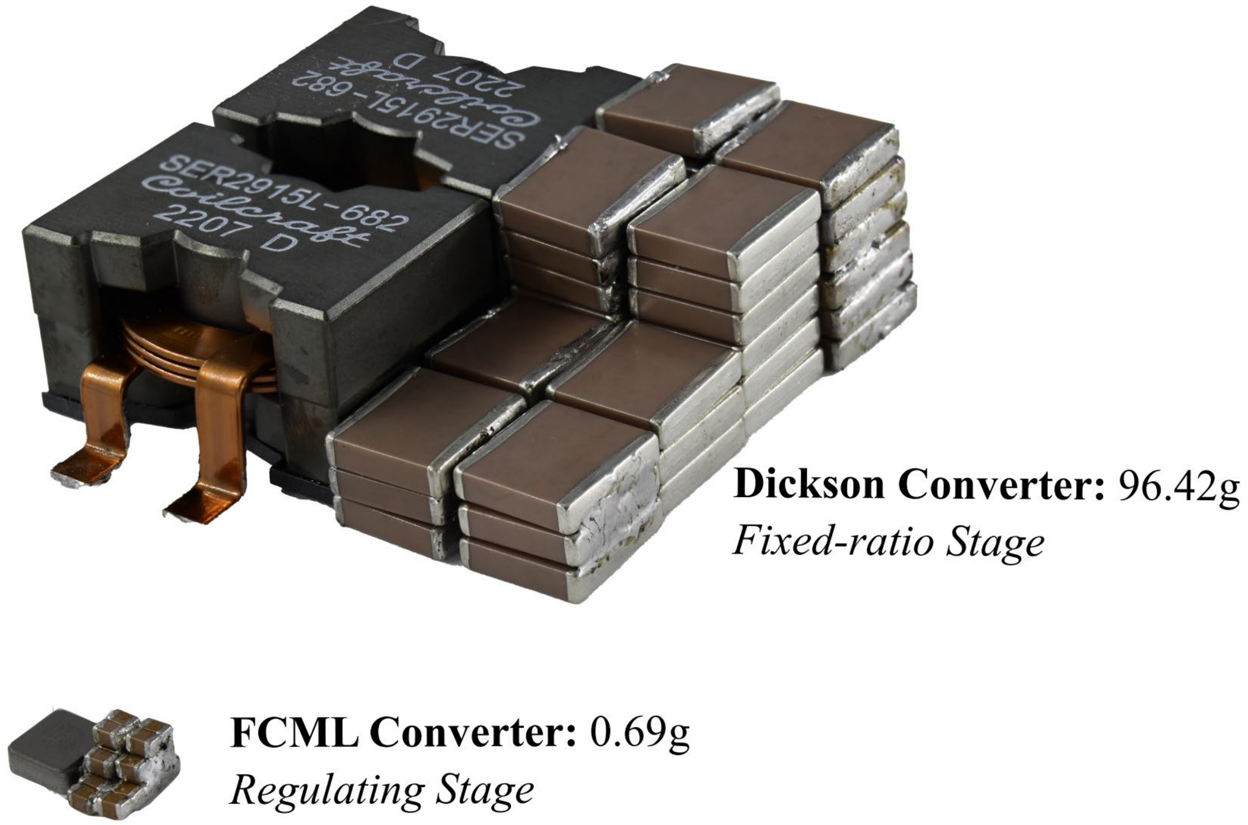
Loss breakdown for capacitively isolated Dickson.

[1] S. Coday, E. Krause, M. Blackwell, N. Ellis, A. Barchowsky, and R. C. N. Pilawa-Podgurski, "Design and Implementation of a GaN-based Capacitively-Isolated Hybrid Switched-Capacitor Dickson Converter for Space Applications," in 2023 IEEE Applied Power Electronics Conference and Exposition (APEC), 2023.

Full System Performance



(a) Measured efficiency of full composite converter operating at $V_{IN} = 750\ V$ and $V_{OUT} = 50\ V$. (b) A breakdown of the portion of output power delivered by the Dickson converter and FCML converter.



Passive component weight breakdown for PPP converter.

Composite Converter Summary

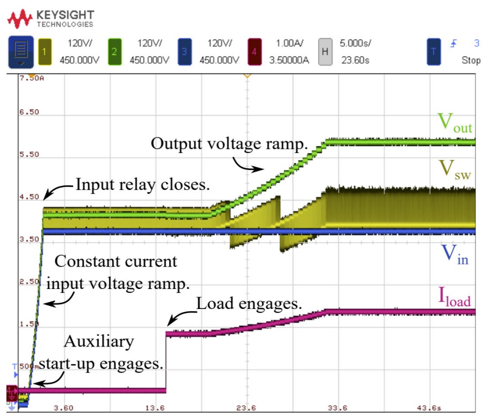
- Proposed Partial Power Processing (PPP) hybrid switched capacitor converter for space exploration.
- Optimization method provides framework for minimizing converter mass for both regulating and resonant style hybrid switched-capacitor converters.

Dickson Converter: 96.42g
Fixed-ratio Stage

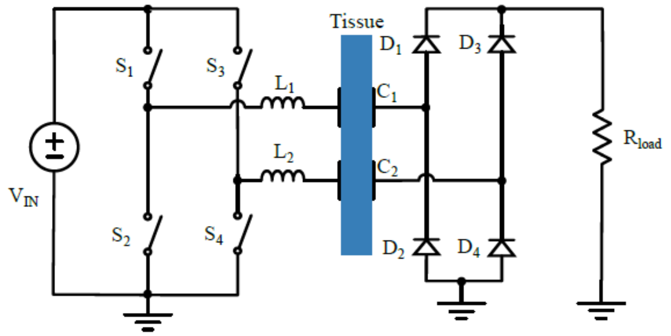
FCML Converter: 0.69g
Regulating Stage

Passive component weight breakdown for PPP converter.

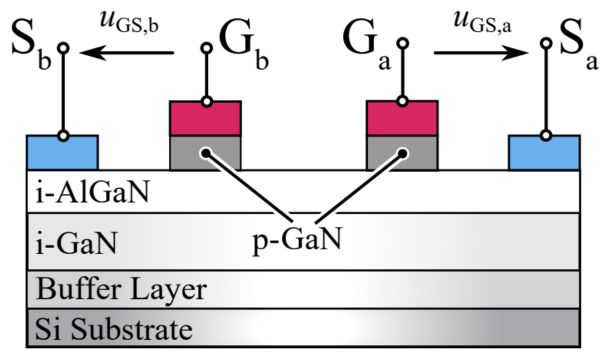
Future Research



Practical Control for Robust Operation.



Novel Applications for Capacitor-based Converters



Implementation of novel devices.

Next-Generation Hybrid Switched-Capacitor Converters

Berkeley | EECS
Electrical Engineering and Computer Sciences

BPEC
Berkeley Power & Energy Center

Coday
Research Group

JPL

Jet Propulsion Laboratory
California Institute of Technology

arpa·e

CHANGING WHAT'S POSSIBLE

AMPAIRE