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Demystifying Capacitive Isolation in High-Efficiency DC-DC Converters

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Agenda

01 | Motivation and Context

02 | Principles of Capacitive Isolation

03 | Converter Topologies

04 | Design Considerations and Challenges

05 | Experimental Validation

06 | Outlook and Research Opportunities

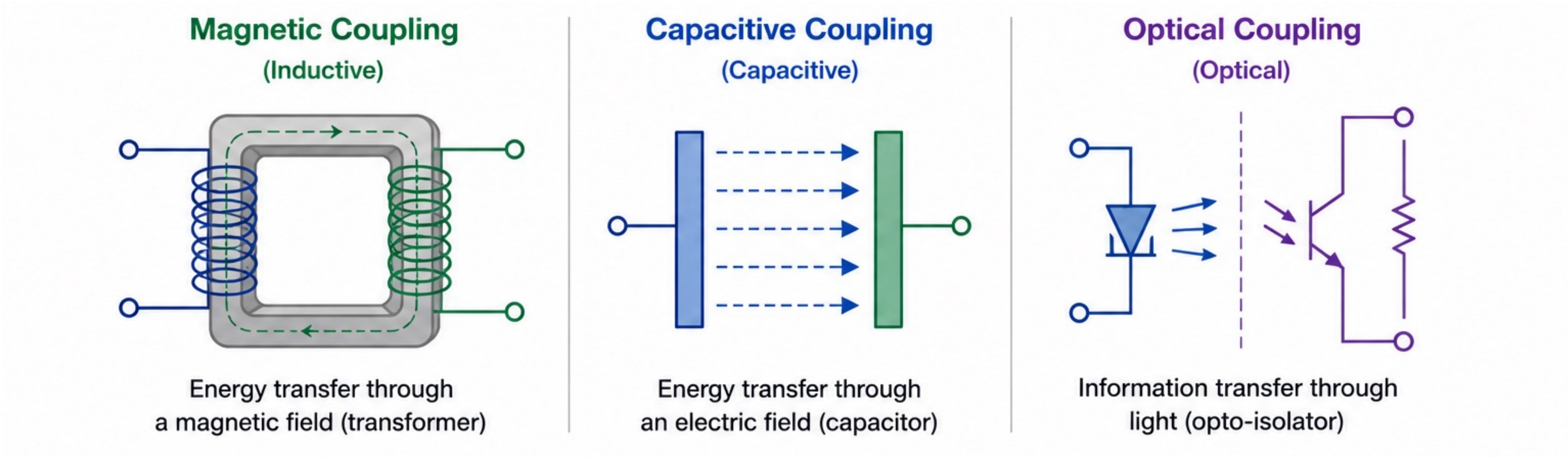
01

Motivation and context

Galvanic isolation fundamentals

Galvanic isolation enables power flow among circuits that must be disconnected

This physical disconnection prevents dc and high-speed transients, but **energy or information can still be transferred** using different coupling mediums



Why isolation matters?

1 HUMAN SAFETY

- Protects users from hazardous voltages
- Isolation prevents electric shock and ensures compliance with safety standards

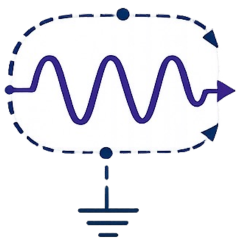
Isolation protects people

2 EQUIPMENT PROTECTION

- Prevents fault propagation between subsystems
- Simplifies protection coordination and improves system reliability

Isolation protects equipment

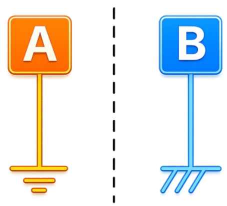
3 COMMON-MODE NOISE MITIGATION



- Breaks common-mode current paths
- Improves EMI/EMC performance and helps meet regulatory limits

Isolation improves EMC performance

4 FUNCTIONAL INDEPENDENCE

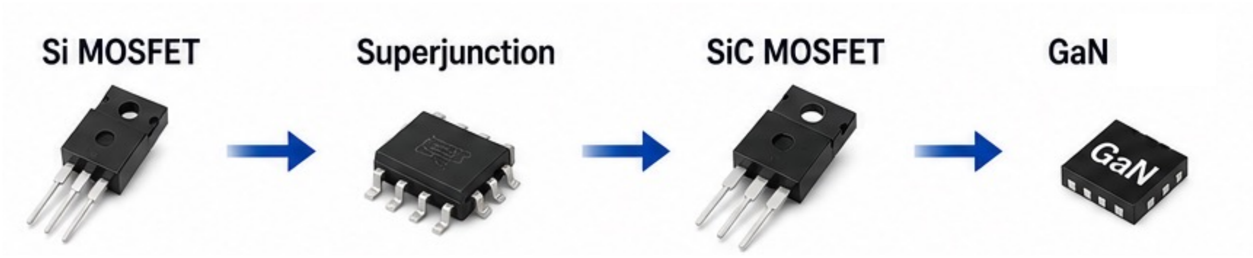


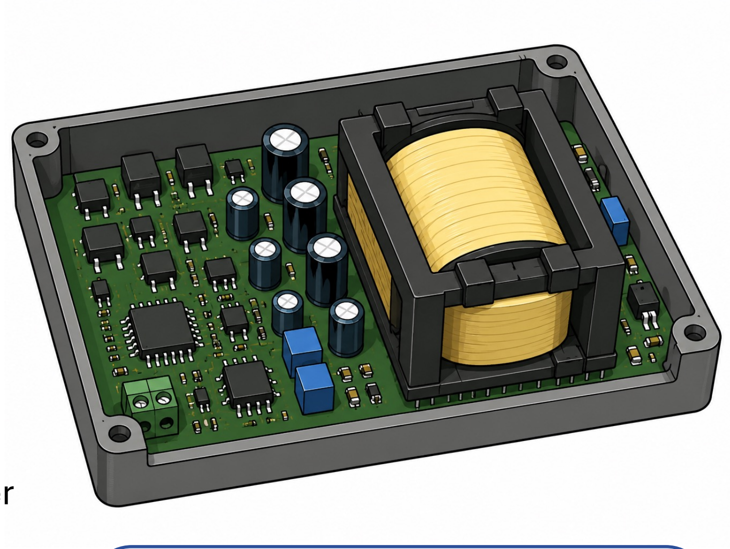
- Enables independent voltage references for different subsystems
- Essential for gate drivers, sensors, communication interfaces, and control systems

Isolation protects people

Electrical isolation is not only about safety! It is essential for reliability, electromagnetic compatibility and system functionality.

The power density challenge





Higher switching frequency

Higher efficiency

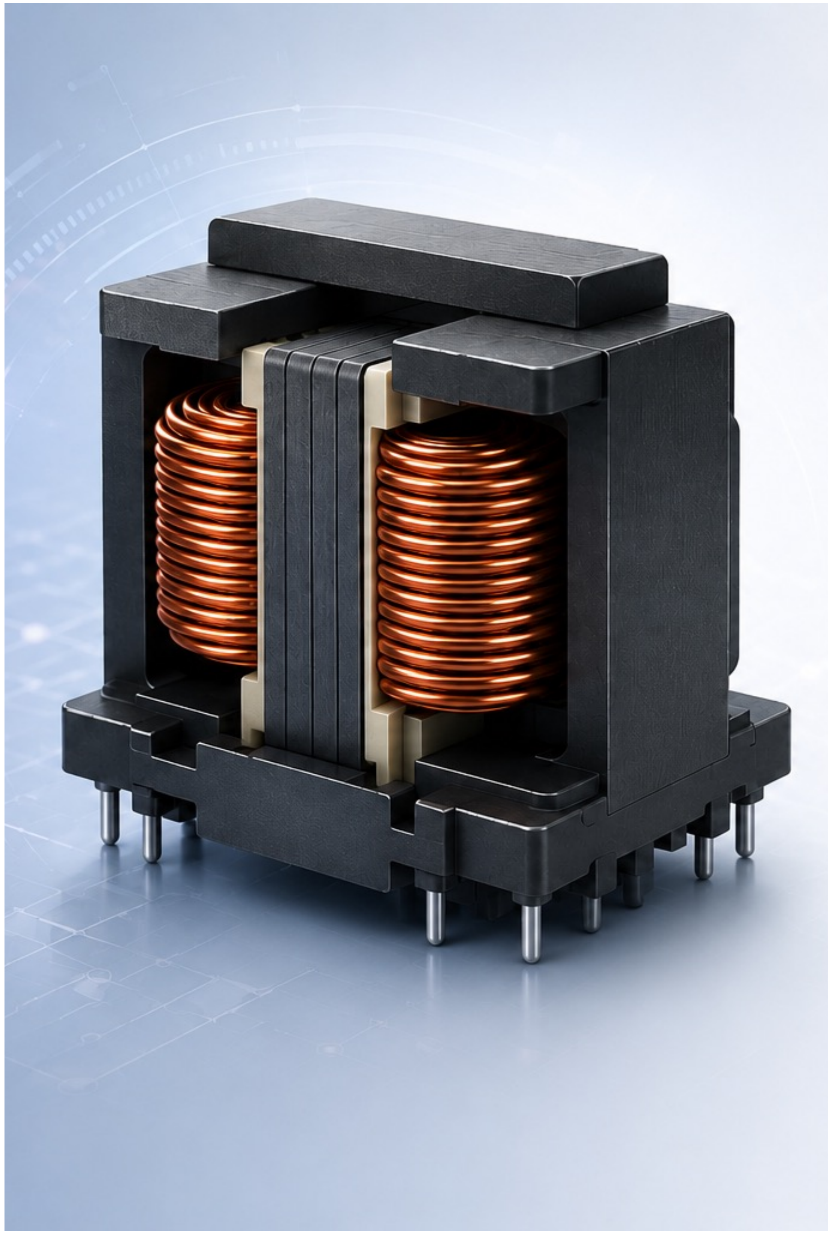
Greater integration

Higher power density

Despite dramatic advances in semiconductor technology, **magnetic components still dominate** converter volume and weight

If semiconductors keep improving,

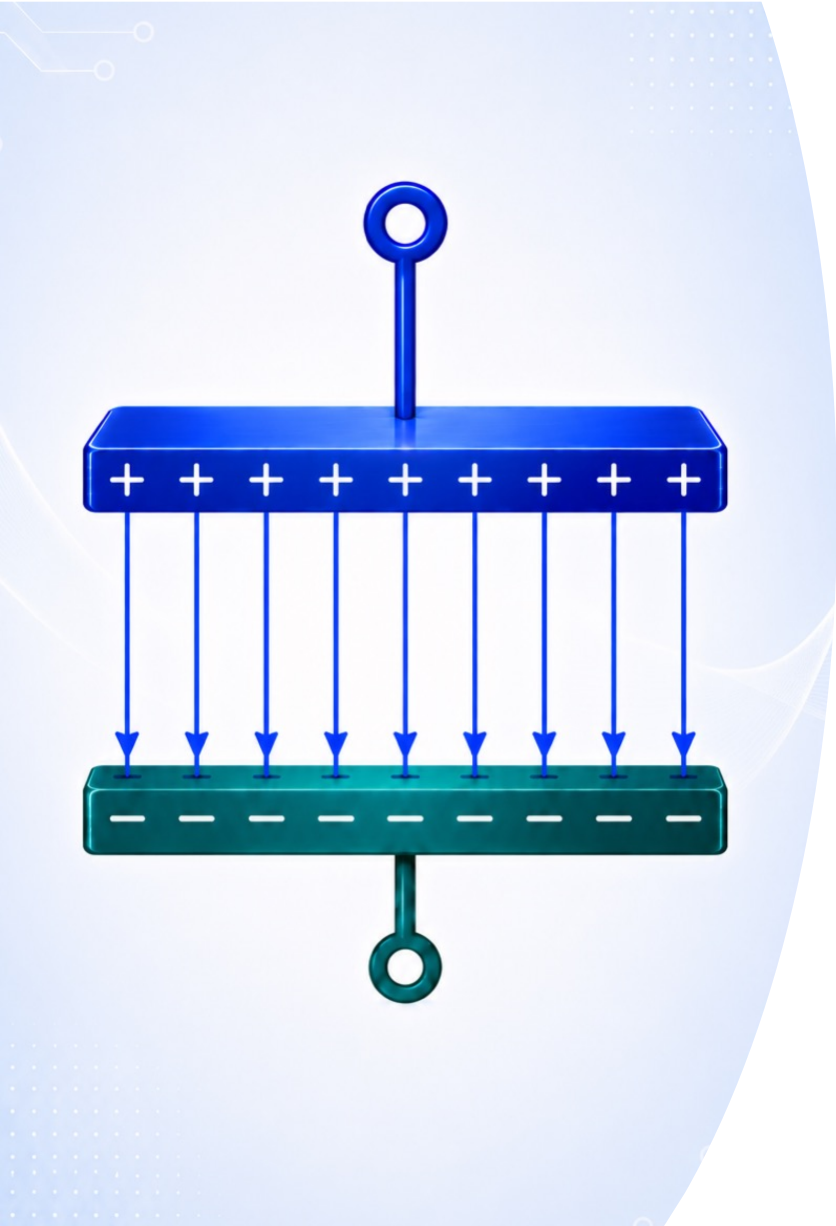
WHY ARE TRANSFORMERS LIMITING POWER DENSITY?



Why Look Beyond Transformers?

- Core losses
- Skin effect
- Proximity effect
- Leakage inductance
- Integration limitations

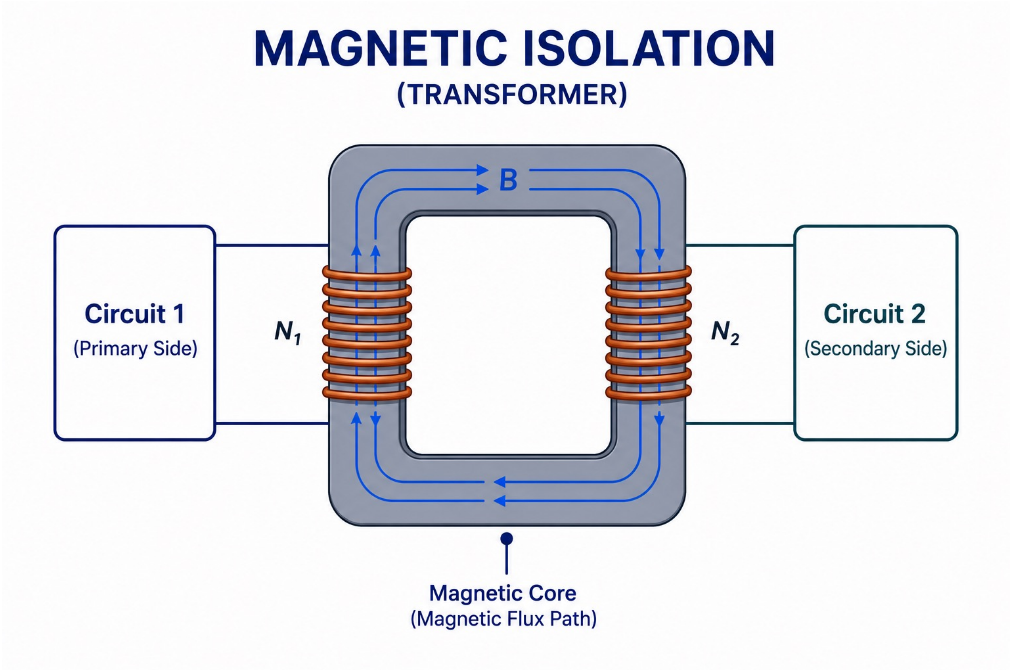
Magnetic components remain the **largest obstacle** to ultra-high power density converters

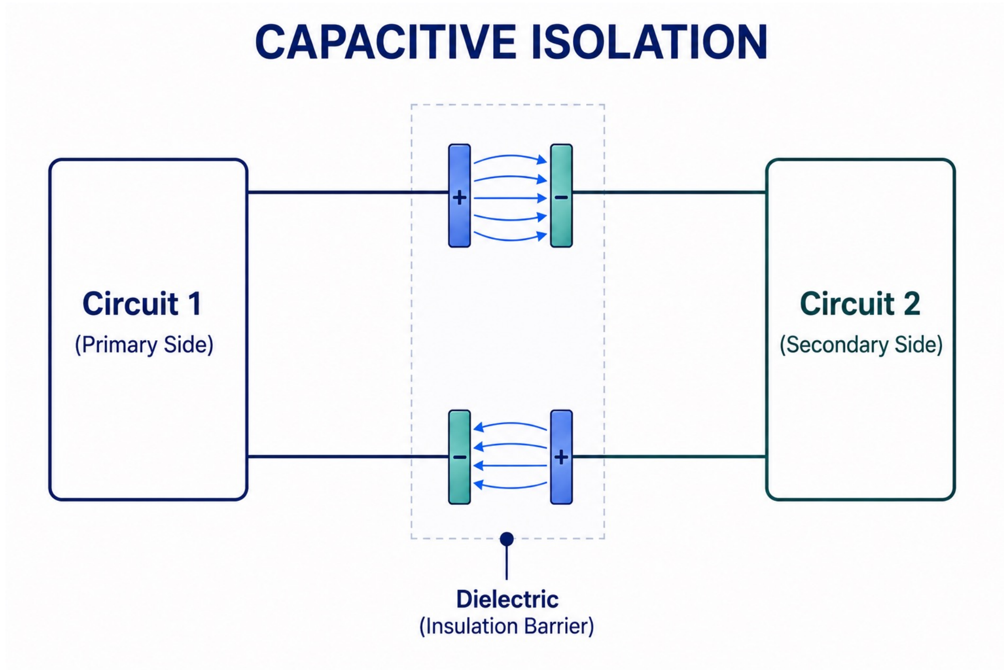


02

Principles of capacitive isolation

Magnetic vs capacitive coupling





Magnetic vs capacitive coupling

Feature	Magnetic	Capacitive
Coupling Mechanism	Magnetic Field	Electric Field
Isolation Element	Transformer	Capacitor
Power Transfer	High	Moderate
Voltage Adaptation	Excellent (Turns Ratio)	Limited
Integration	Difficult	Excellent
Operation at MHz	Challenging	Favorable
Core Losses	Present	None
Power Density	Medium	High

Capacitive isolation favors **integration, MHz operation and power density**, while magnetic isolation provides superior voltage adaptation and power transfer capability.

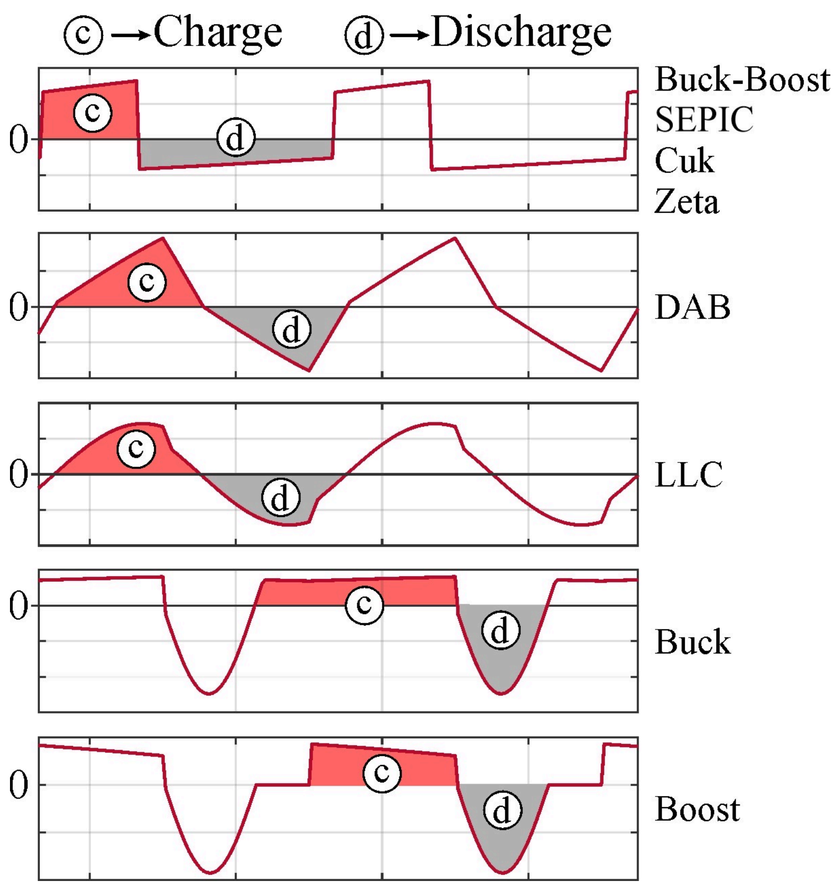
Fundamentals principles

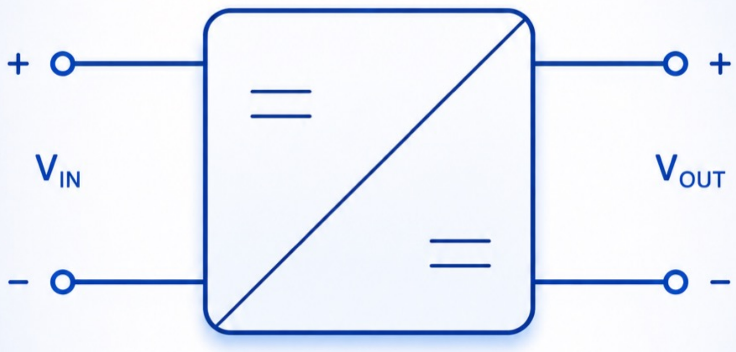
Galvanic isolation
through the dielectric material of capacitors

Power transmission
via the electric field

Average capacitor current
is zero

Charge and discharge stages
- *Linear*
- *Switched-capacitor*
- *Resonant operation*



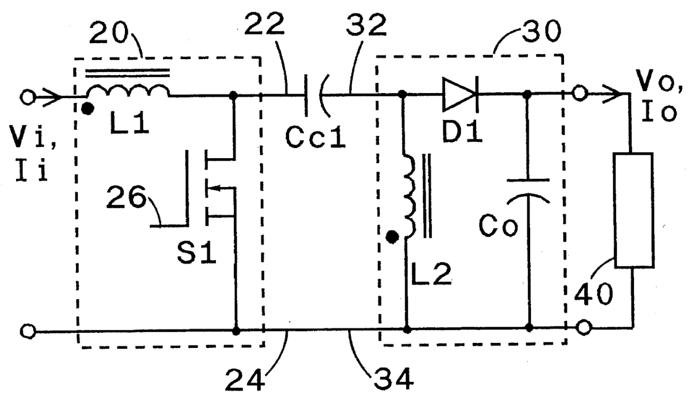


03

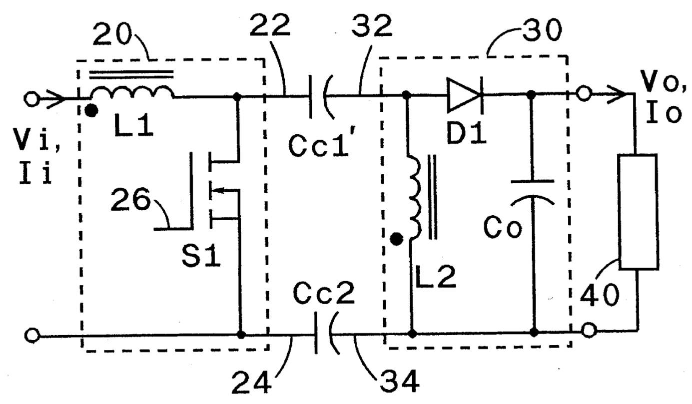
Converter Topologies

Capacitive isolated SEPIC DC-DC converter

Original SEPIC converter



SEPIC with capacitive isolation (transformerless)



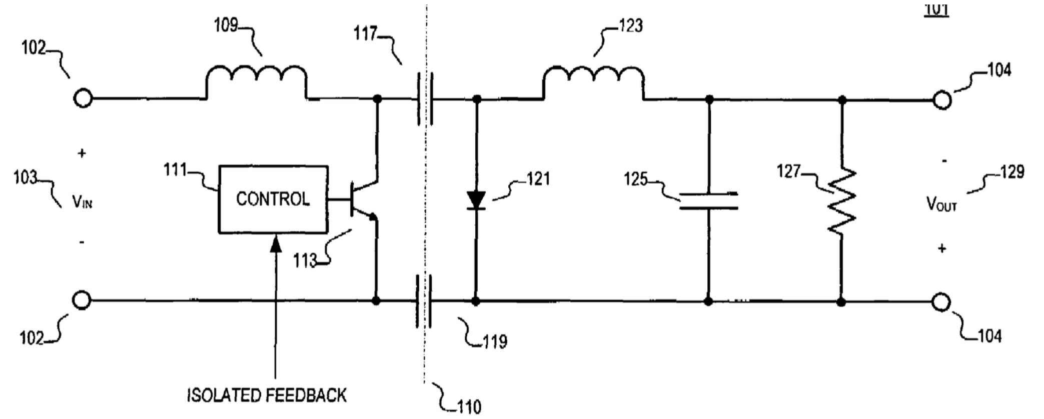
Galvanic isolation is achieved by **splitting the coupling capacitor** into two series capacitors

One of the **earliest applications** of capacitive isolation in DC-DC converters	Additional coupling capacitor provides the **DC isolation** without affecting circuit performance	Preserves the **voltage gain** of the conventional SEPIC converter	Total coupling capacitance may be chosen to **limit the leakage and touch currents** to safe values

Source: G. Barbehenn, S. B. Elgee (Hewlett-Packard Company), *"SEPIC converter with transformerless line isolation"*, US Patent 5,583,421, 1996.

Capacitive isolated Cuk DC-DC converter

Cuk with capacitive isolation (transformerless)



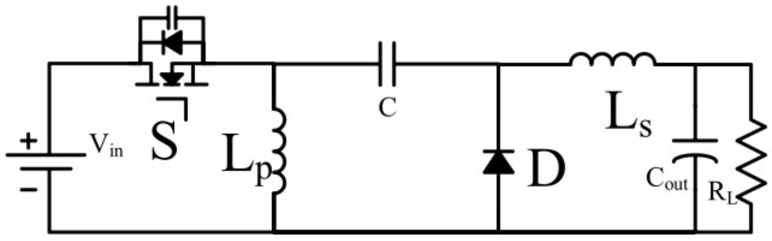
Galvanic isolation is achieved by **splitting the coupling capacitor** into two series capacitors

Direct extension of the concept applied to the SEPIC converter	Additional coupling capacitor provides transformerless **safety isolation** in a power supply	Preserves the **voltage gain** of the conventional Cuk converter	It does not require **additional semiconductor devices**

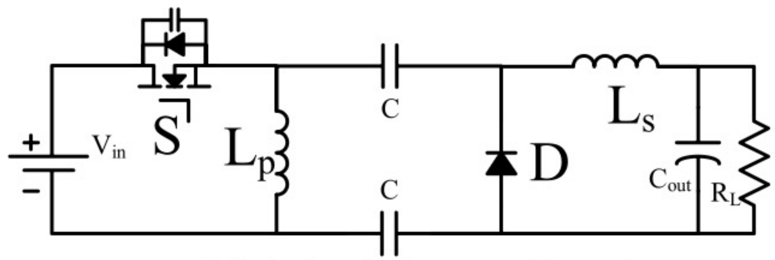
Source: S. Bäurle et al. (Power Integrations, Inc.), *"Transformerless safety isolation in a power supply using safety capacitors for galvanic isolation"*, US Patent 7,453,710 B2, 2008.

Capacitive isolated Zeta DC-DC converter

Original Zeta converter



Zeta with capacitive isolation (transformerless)



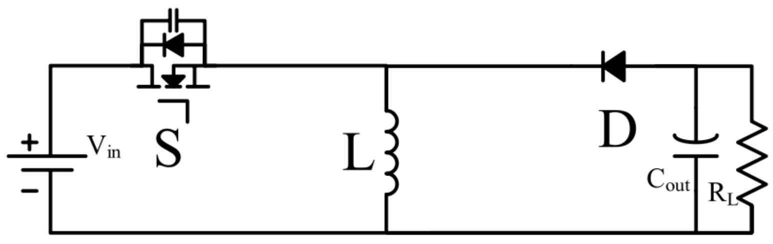
Galvanic isolation is achieved by **splitting the coupling capacitor** into two series capacitors

Direct extension of the concept applied to the SEPIC converter	It does not require **additional semiconductor devices**	Preserves the **voltage gain** of the conventional Zeta converter	**1 kW 200 kHz prototype** with efficiency around 90%

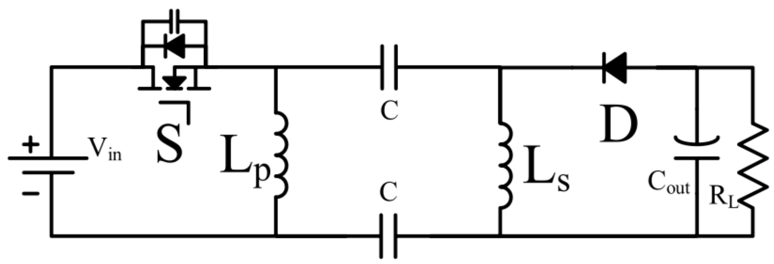
Source: J. Dai, D. C. Ludois, *"Single Active Switch Power Electronics for Kilowatt Scale Capacitive Power Transfer"*, IEEE Trans. on Power Electronics, 2015.

Capacitive isolated buck-boost DC-DC converter

Original buck-boost converter



Buck-boost with capacitive isolation



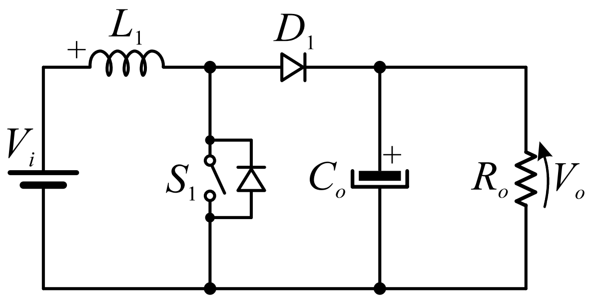
Galvanic isolation is achieved by **splitting the inductor and separating them by two capacitors**

Capacitive isolation is **less straightforward** compared to SEPIC, CuK and Zeta converters	Average voltage on the coupling capacitors is **zero**	Preserves the **voltage gain** of the conventional buck-boost converter	**1 kW 200 kHz prototype** with efficiency around **90%**

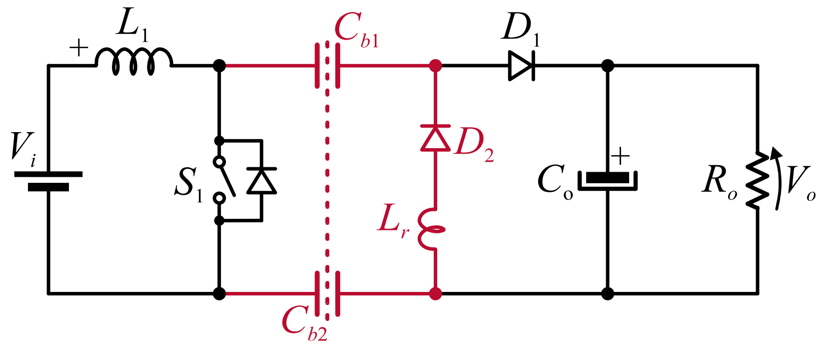
Source: J. Dai, D. C. Ludois, *"Single Active Switch Power Electronics for Kilowatt Scale Capacitive Power Transfer"*, IEEE Trans. on Power Electronics, 2015.

Capacitive isolated boost DC-DC converter

Original boost converter



Boost with capacitive isolation



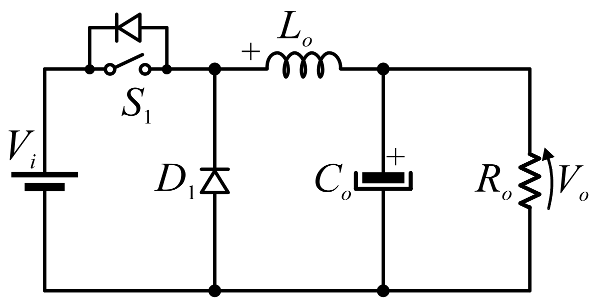
Based on a **switched-capacitor cell**, composed of C_{b1}, C_{b2}, S_1, D_2, and L_r (very small inductor)

Requires **one additional semiconductor device** (diode D_2)	Preserves the **voltage gain** of the conventional boost converter	Originally developed to **enhance safety in PV applications**	**2 kW 200 kHz prototype** with efficiency around **97%**

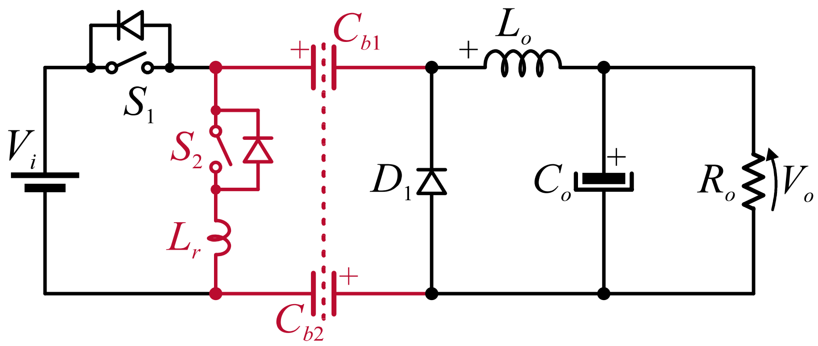
Source: A. Toebe et al., *“A New Capacitive Coupled Step-up DC-DC Converter”*, IEEE Energy Conversion Congress and Exposition (ECCE), 2023.

Capacitive isolated buck DC-DC converter

Original buck converter



Buck with capacitive isolation



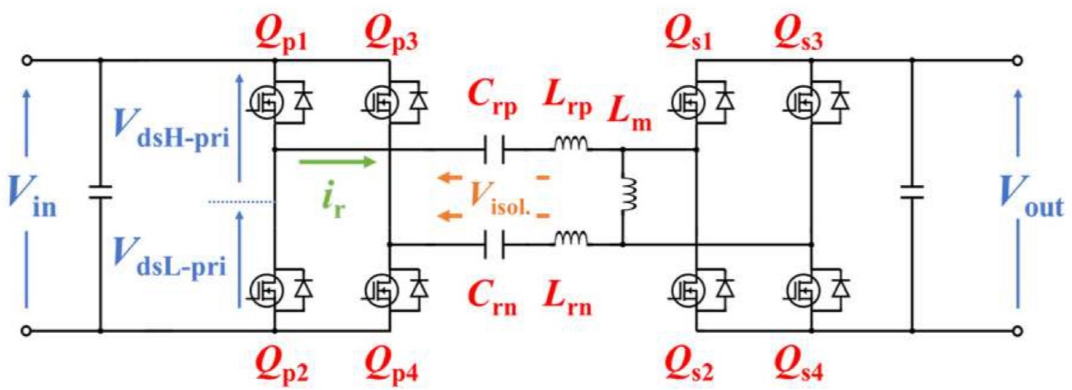
Based on a **switched-capacitor cell**, composed of C_{b1}, C_{b2}, S_2, D_1, and L_r (very small inductor)

Most complex among the six canonical topologies, requiring an **additional active switch (S_2)**	Preserves the **voltage gain** of the conventional buck converter	Originally developed as a candidate for **EV onboard and/or fast dc offboard chargers**	**3 kW 180 kHz prototype** with efficiency around **97%**

Source: A. Toebe et al., *"Capacitive Coupled Step-Down DC–DC Converter With Touch Current Limitation"*, IEEE Trans. on Power Electronics, 2024.

Capacitive isolated LLC resonant DC-DC converter

LLC resonant converter with capacitive isolation (transformerless)



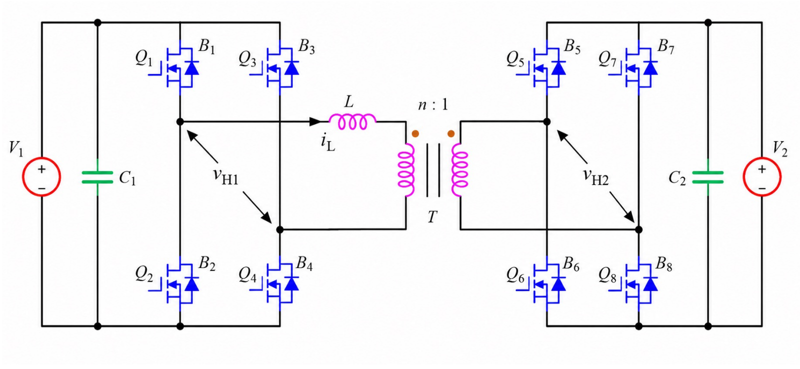
High-frequency transformer replaced by **series-connected coupling capacitors**

Additional magnetizing inductor (L_m) enables LLC operation	Operates as an approximately **1:1 isolated DC transformer**	Designed for 380 Vdc **data-center distribution systems**	**3.6 kW 192 kHz prototype**, with peak efficiency around **99%** (GaN devices)

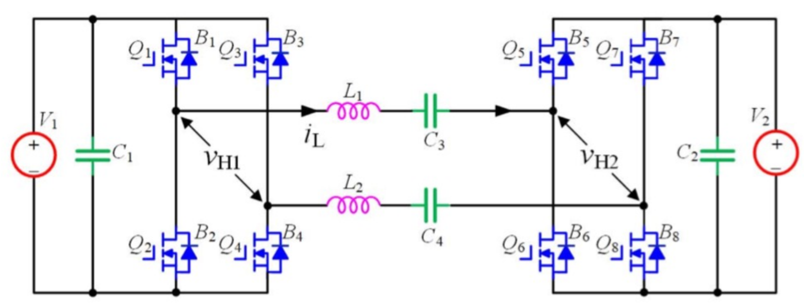
Source: K. Arita et al., *"Highly Efficient (99.2%), Ultra-Compact (32.3 W/cm3) Capacitively Coupled DC/DC Power Electronic Transformer for 380 V DC Power Supply Systems"*, EPE'23 ECCE Europe, 2023.

Capacitive isolated DAB converter

Original DAB converter



DAB converter with capacitive isolation



High-frequency transformer replaced by **two low-ESR film capacitors**

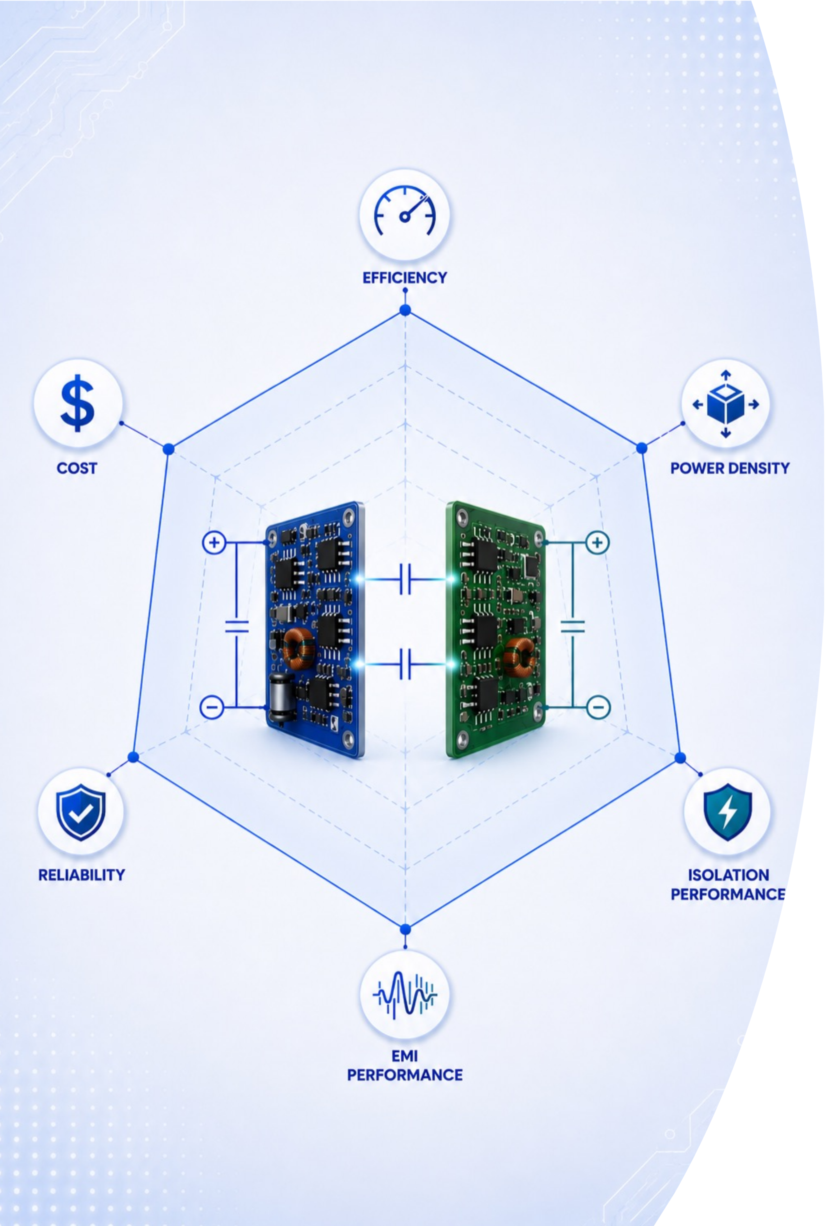
Preserves **bidirectional power transfer and galvanic isolation**

Equivalent **power-transfer characteristics** to a conventional DAB

Targeted for **EV on-board charger (OBC)** applications

1 kW 100 kHz prototype with efficiency around **98%**

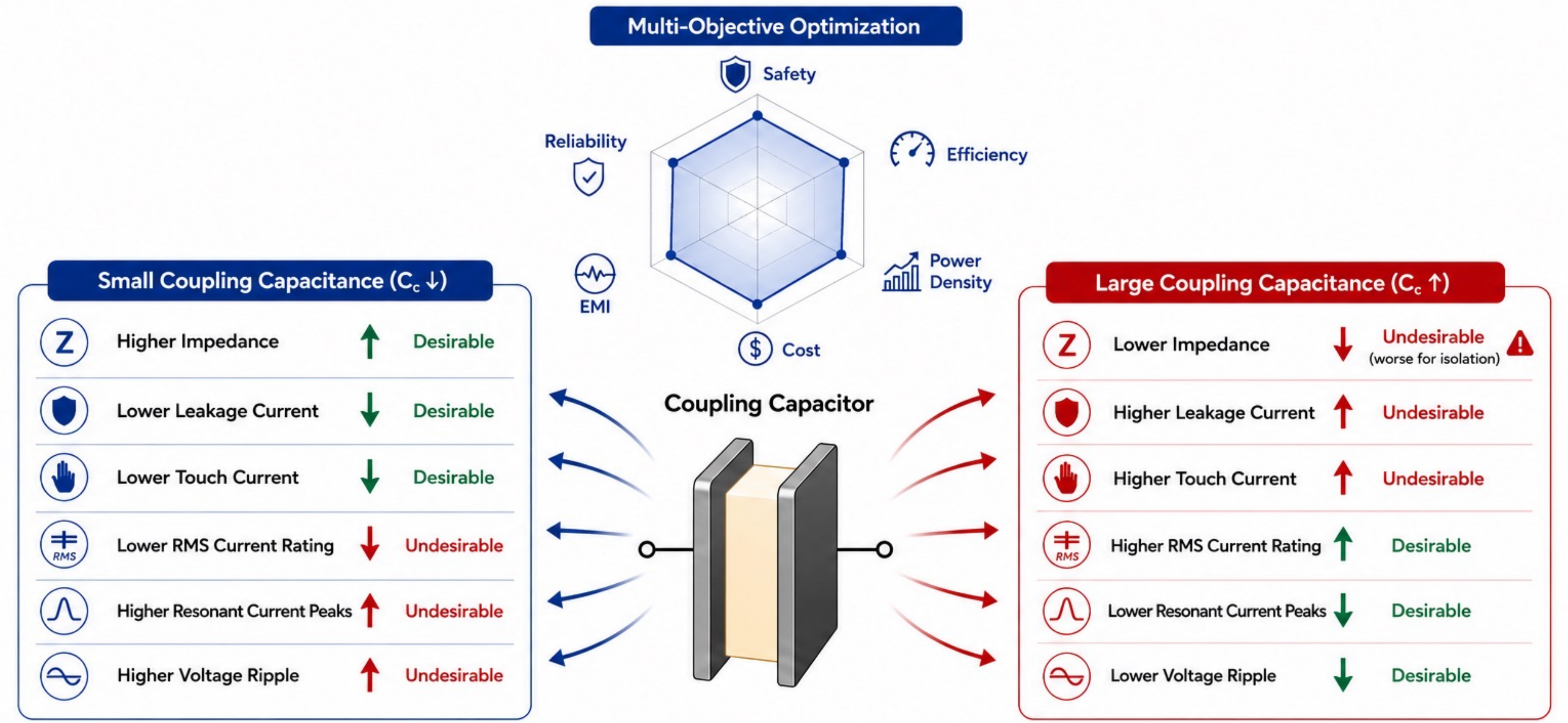
Source: G. Qiu et al., *“Capacitively Isolated Dual Active Bridge Converter for On-Board Charger Applications”*, IEEE Trans. on Industrial Electronics, 2025.



04

Design Considerations and Challenges

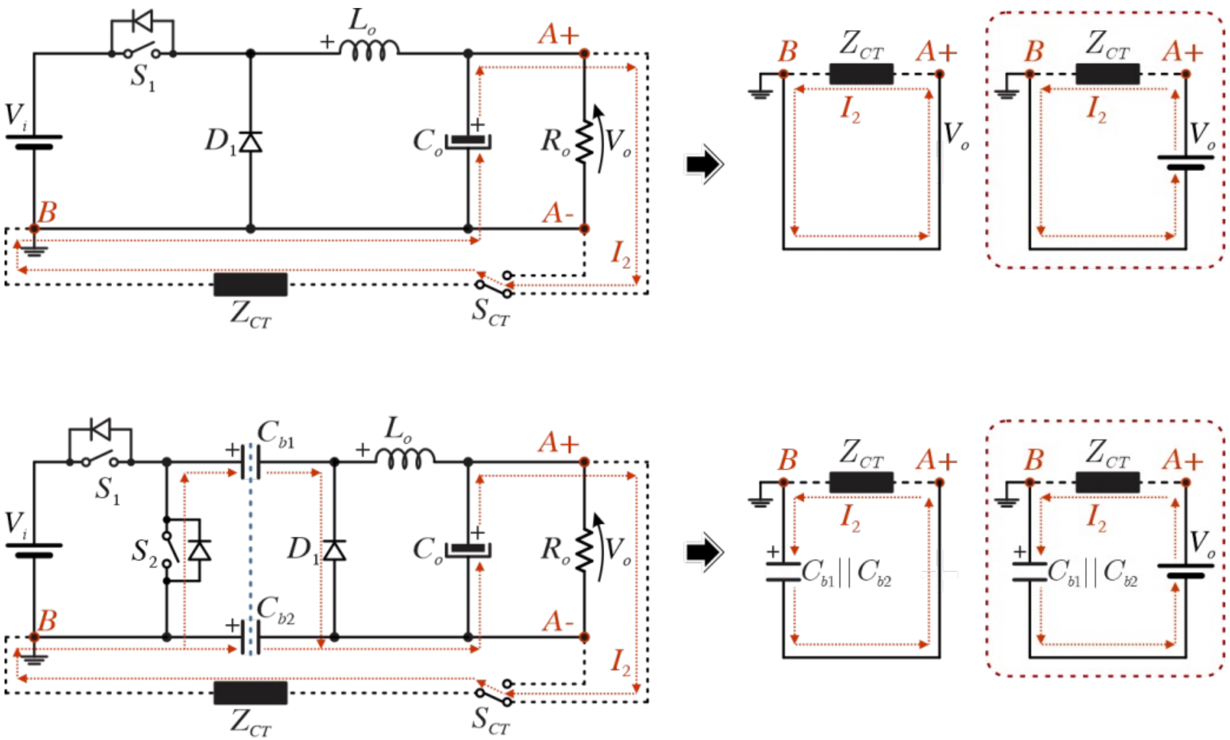
Coupling capacitance design

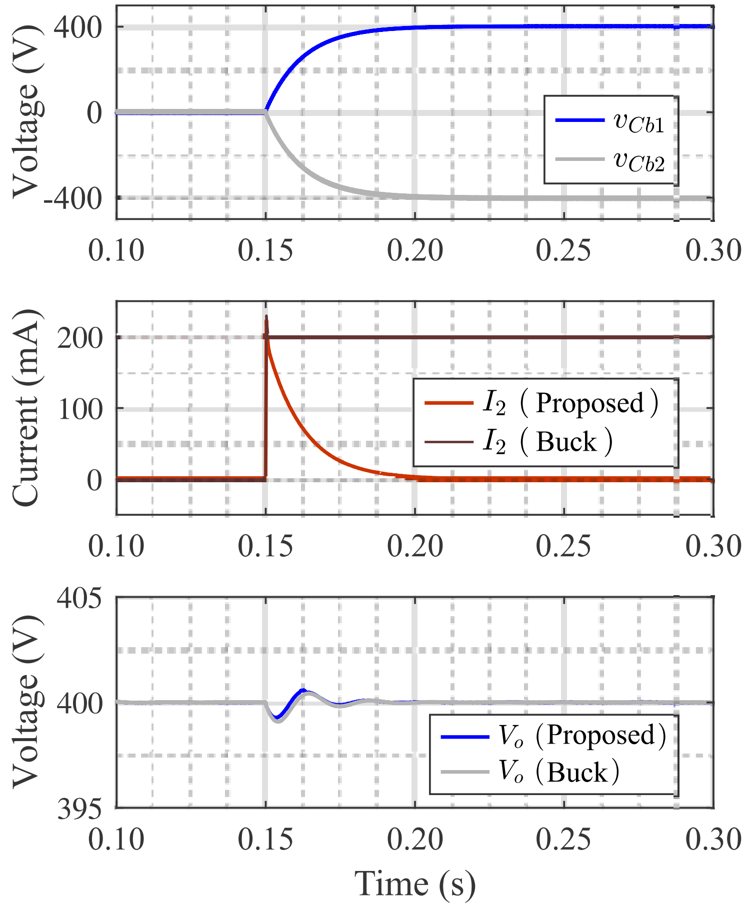


No single capacitance value simultaneously optimizes all performance metrics

Coupling capacitance selection requires balancing safety, power transfer capability, converter performance, and practical implementation constraints.

Touch current limitation

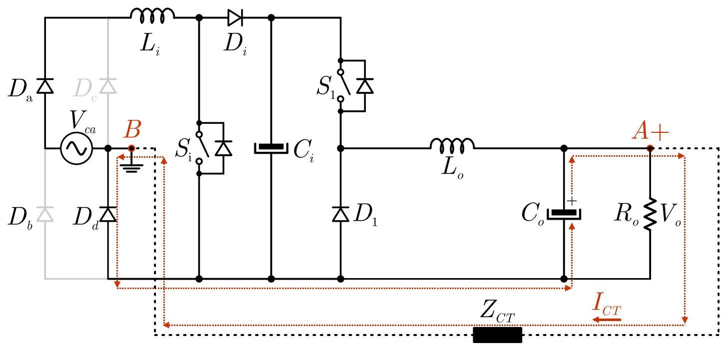


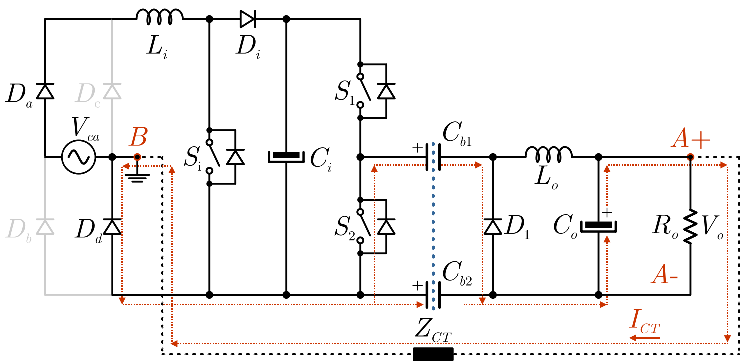


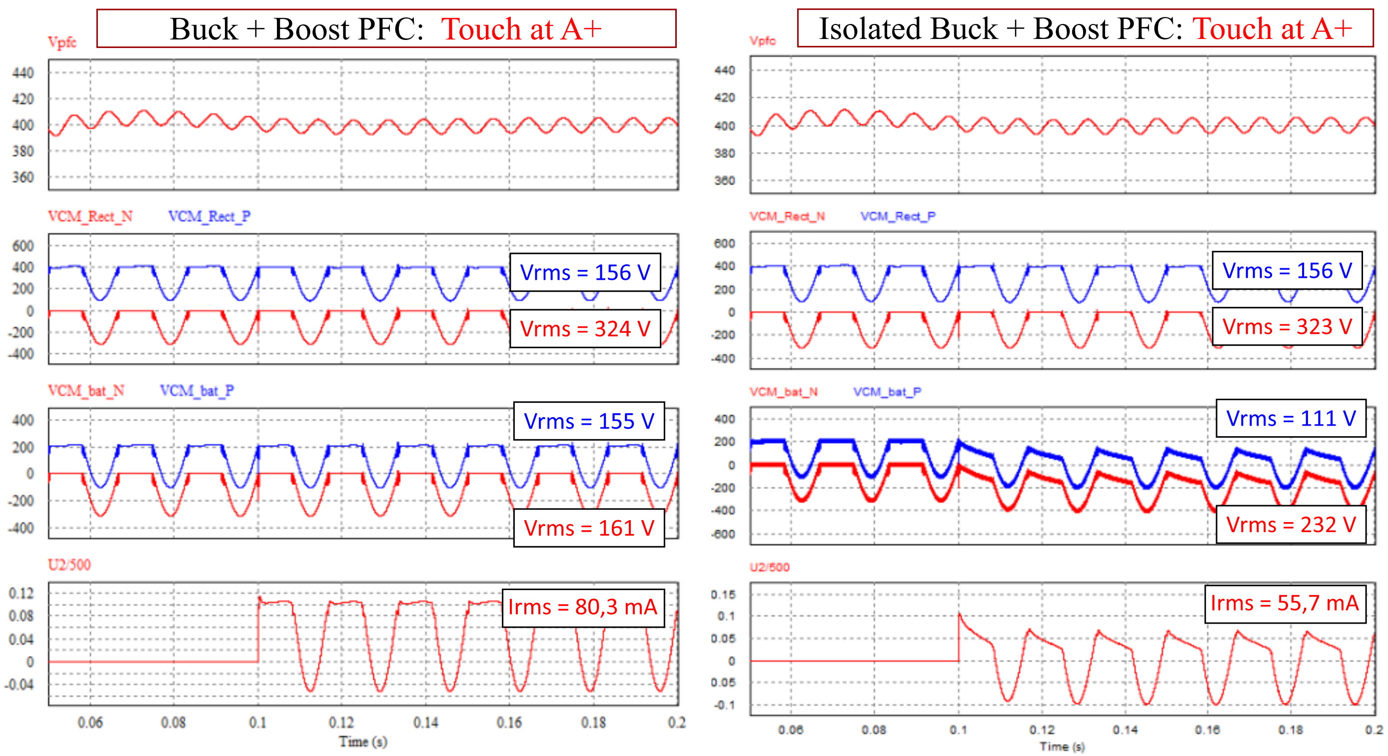
(b)

Touch current limitation

Impact of low-frequency common-mode voltage



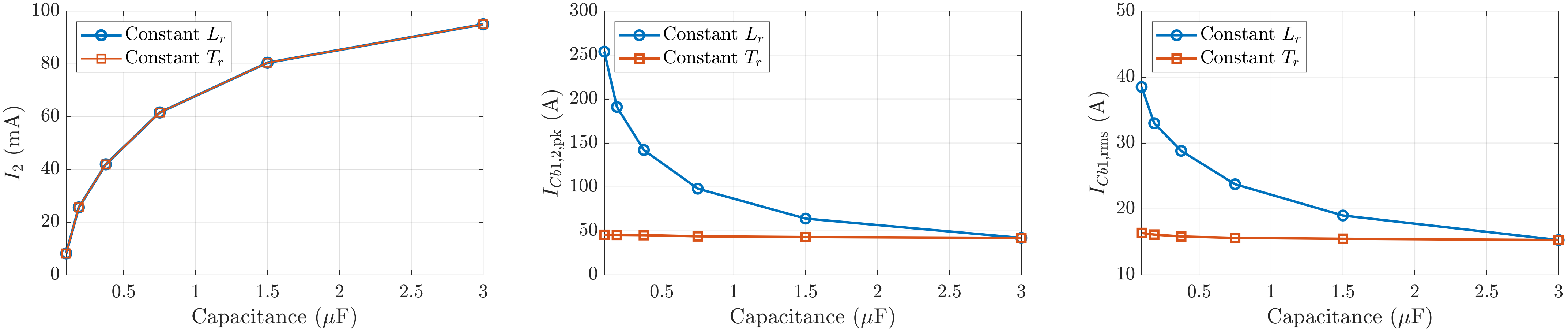


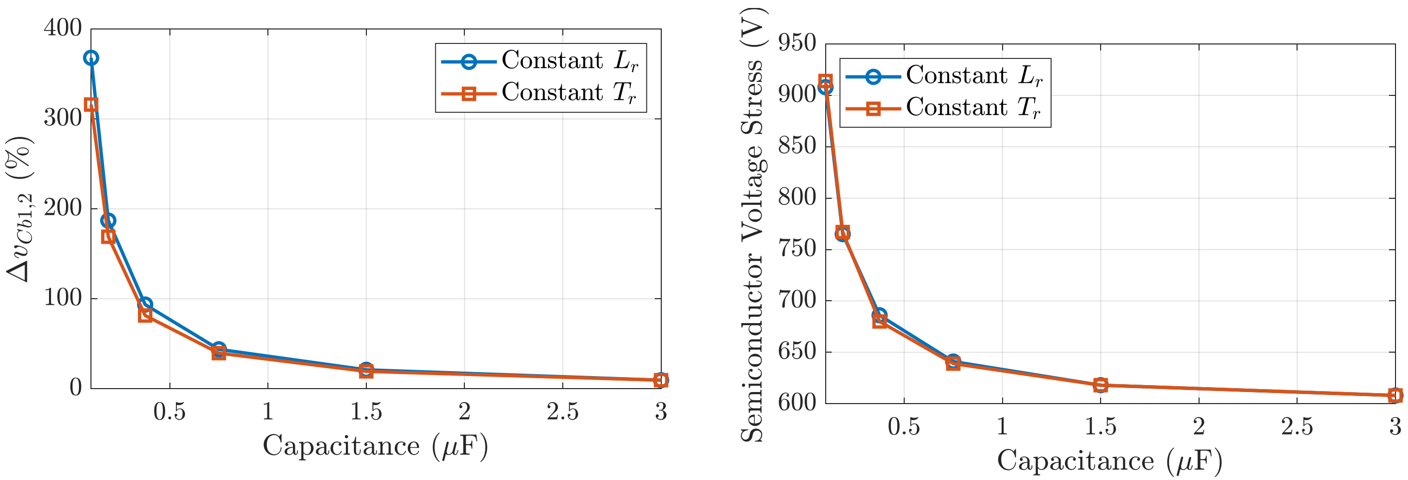


Coupling capacitors reduce touch current by approximately 30%

Touch current limitation

Variation of coupling capacitance

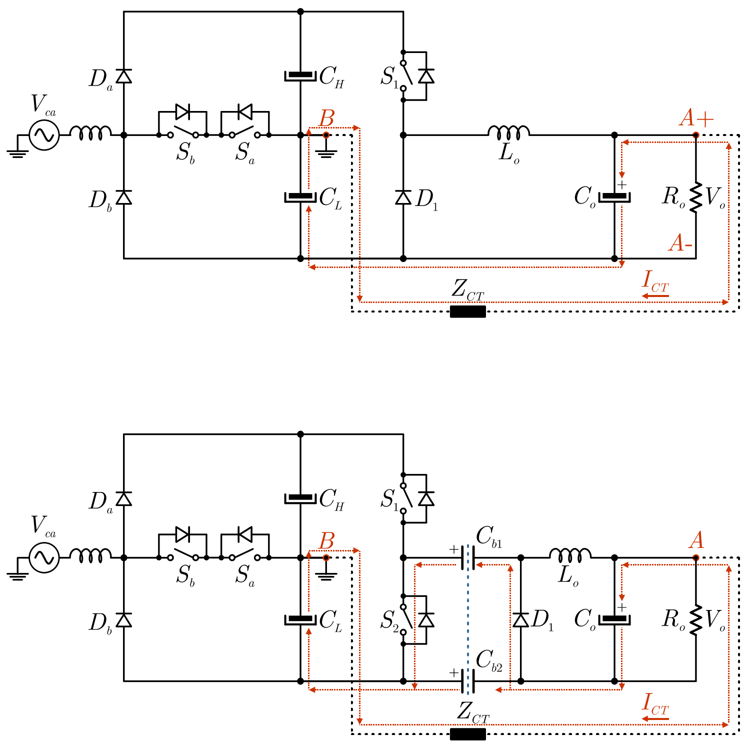


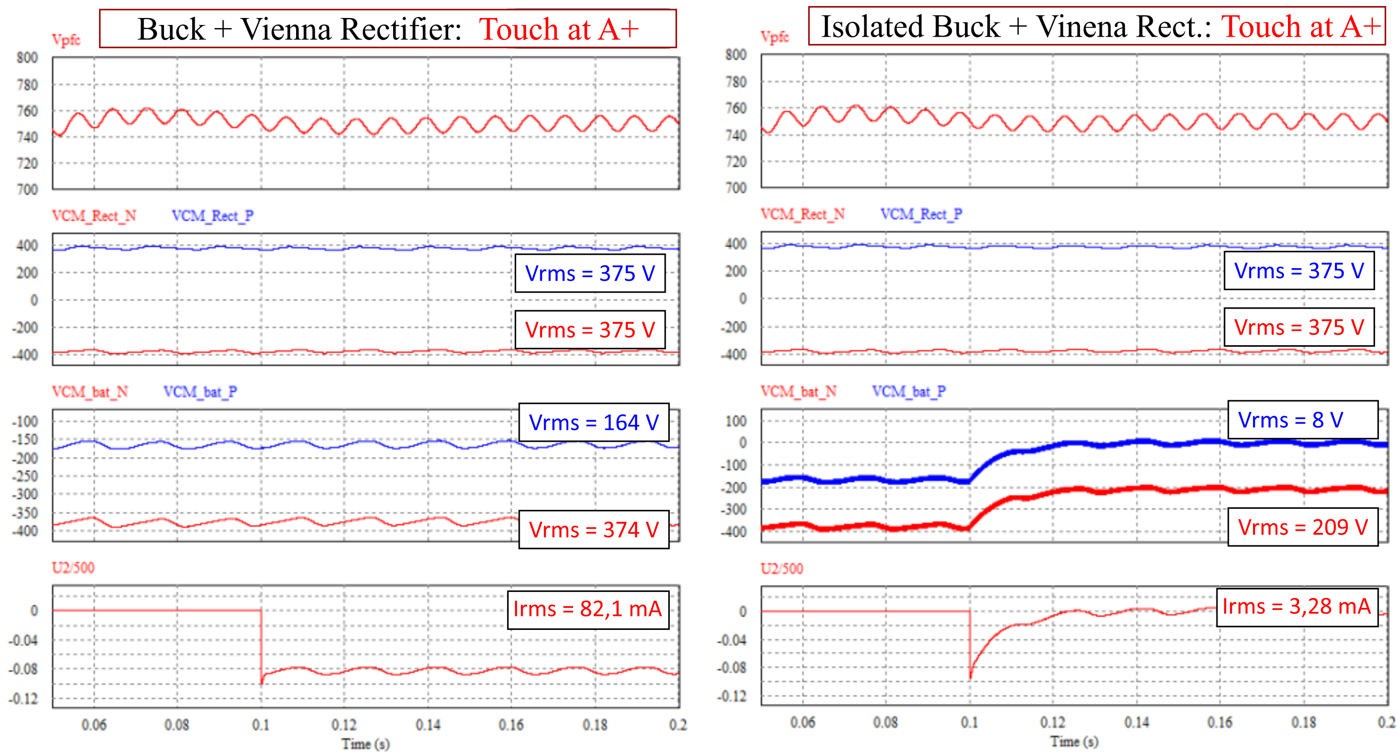


- Constant L_r (75 nH)
- Constant resonance period T_r (2.1 μs)
- f_s = 180 kHz

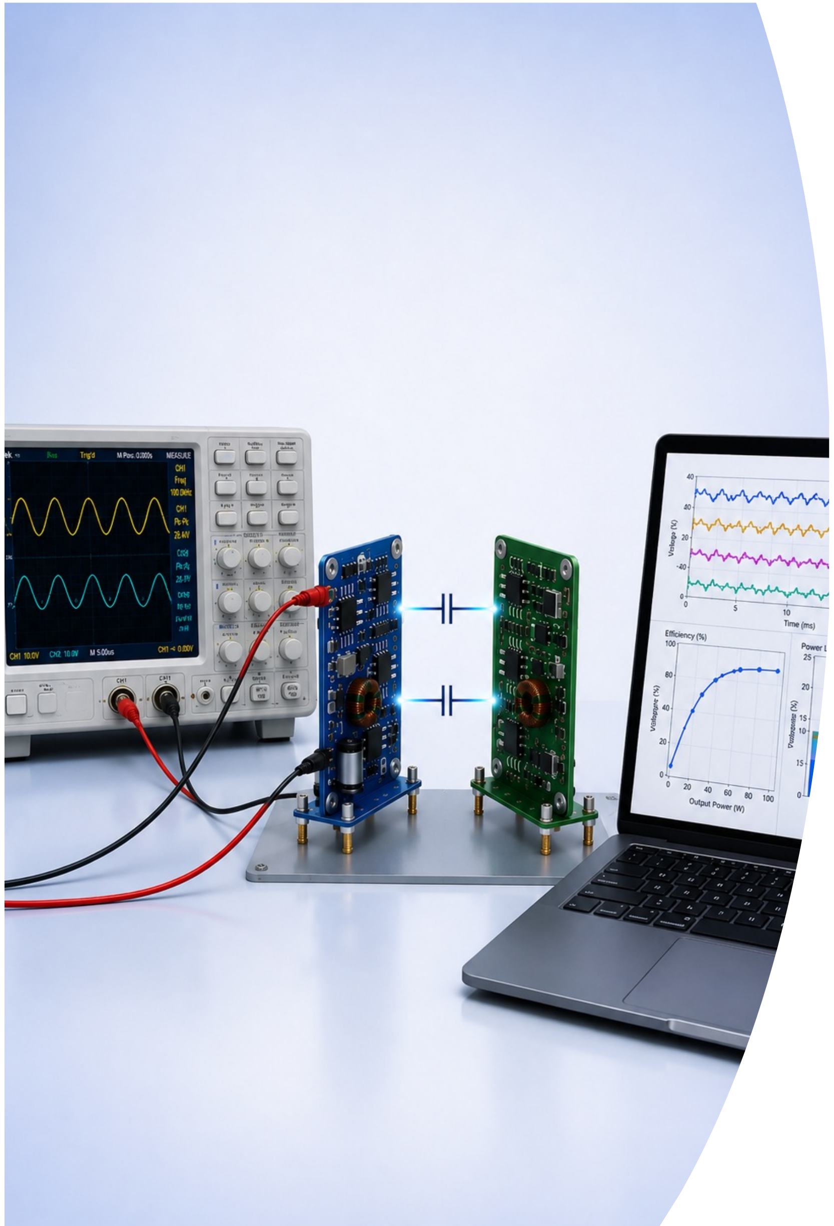
Touch current limitation

Impact of low-frequency common-mode voltage





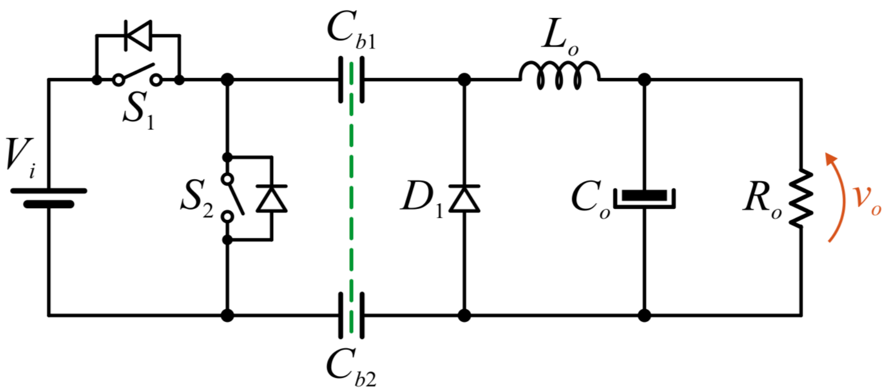
Coupling capacitors reduce significantly the touch current



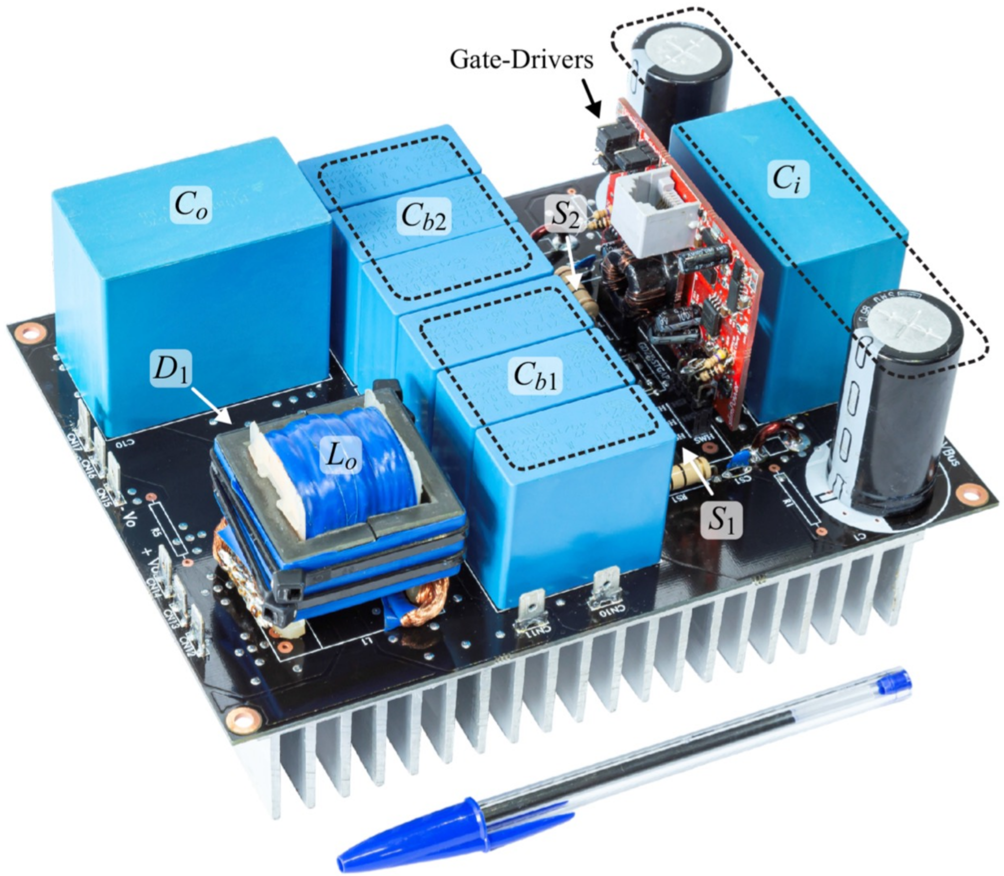
05

Experimental Validation

Capacitive coupled step-down DC–DC converter

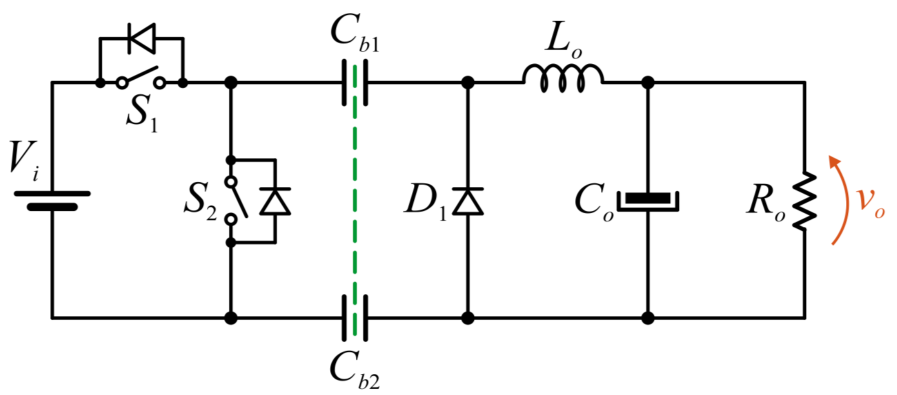


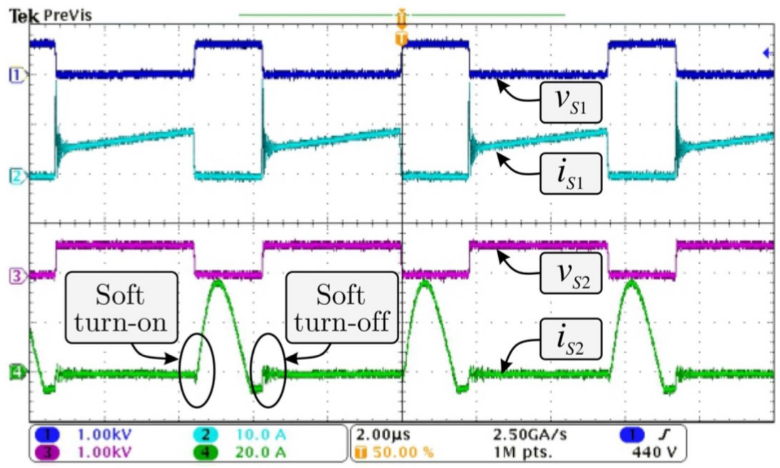
Parameter	Value
Input voltage	$V_i = 600$ V
Output voltage	$V_o = 400$ V
Output power	$P_o = 3$ kW
Switching frequency	$f_s = 180$ kHz
Output inductance	$L_o = 250$ μH
Output capacitance	$C_o = 25$ μF
Coupling capacitors	$C_{b1}, C_{b2} = 3$ μF
Loop inductance	$L_p = 40 - 180$ nH

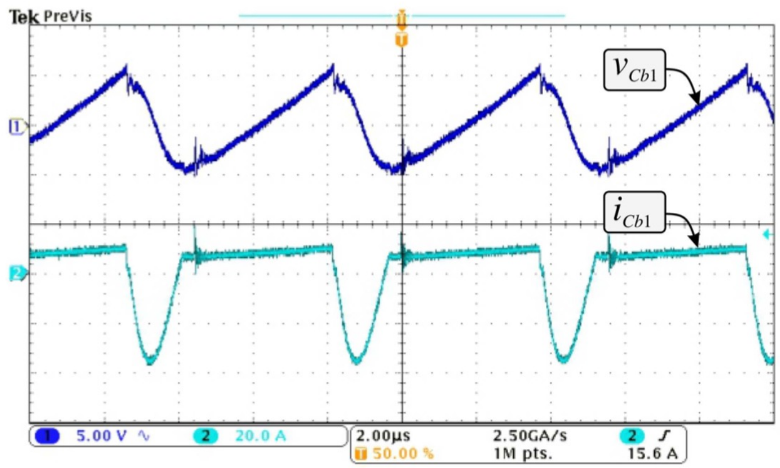


Source: A. Toebe et al., *“Capacitive Coupled Step-Down DC–DC Converter With Touch Current Limitation”*, IEEE Trans. on Power Electronics, 2024.

Capacitive coupled step-down DC–DC converter







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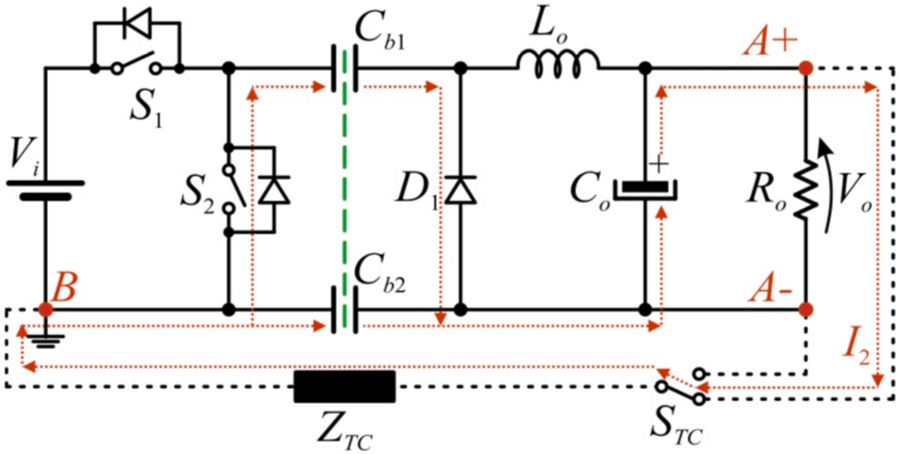
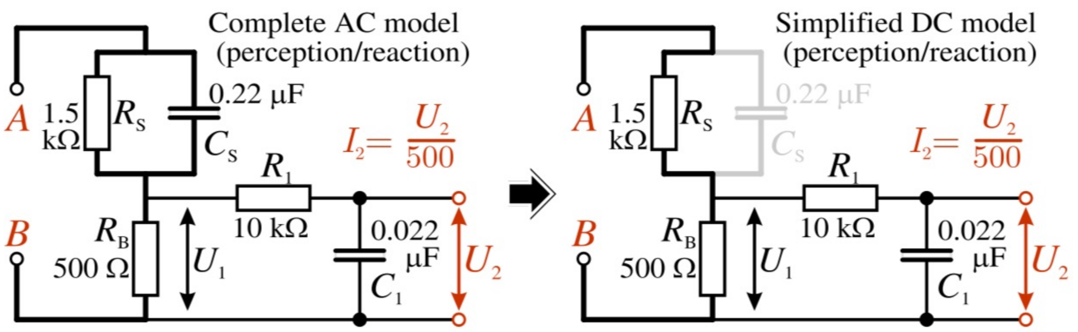
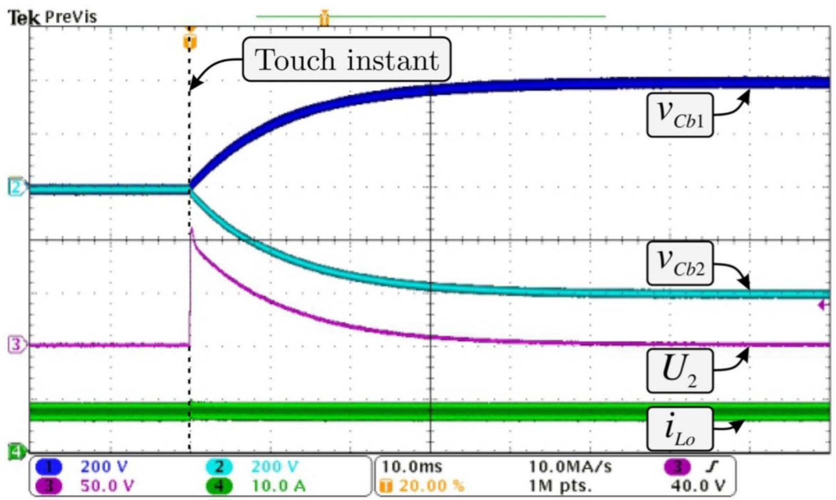
Capacitive coupled step-down DC–DC converter

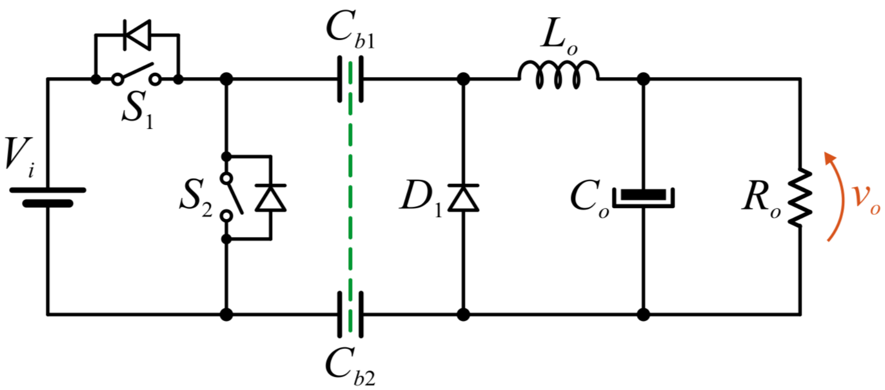


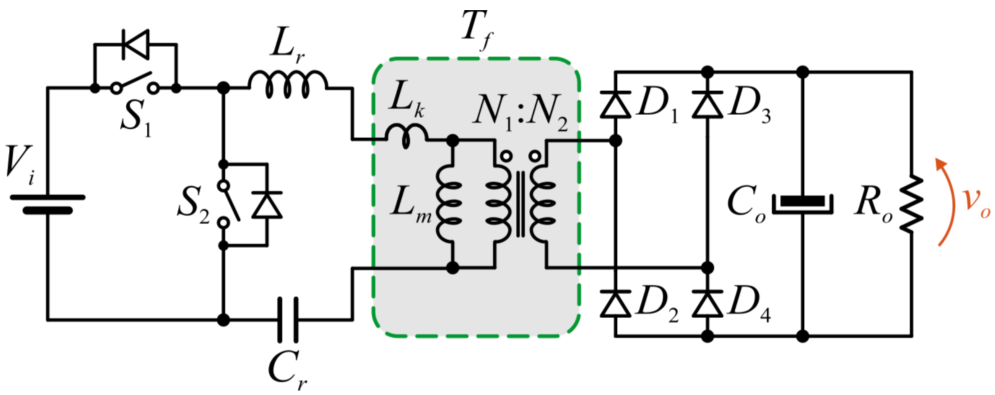


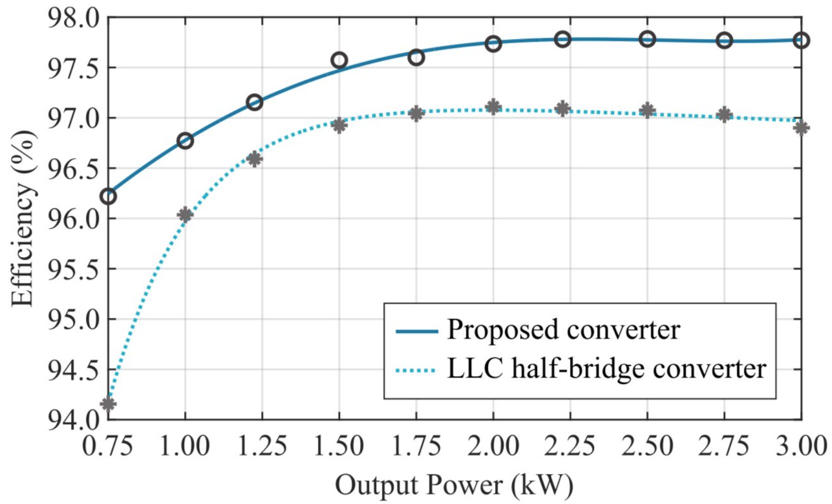


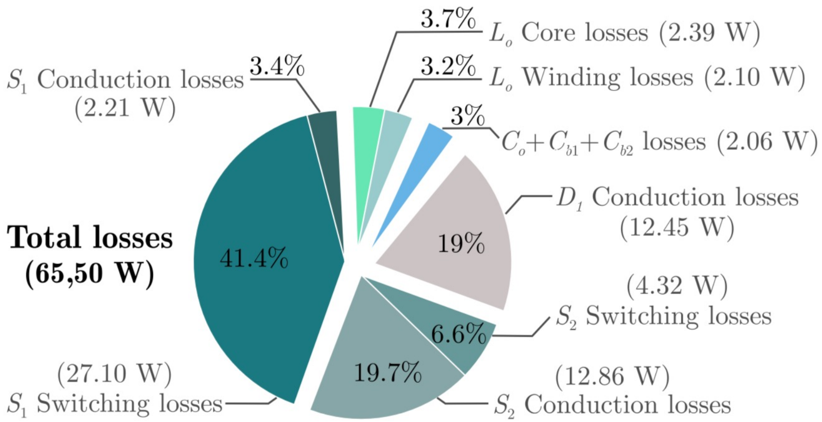
Source: A. Toebe et al., *“Capacitive Coupled Step-Down DC–DC Converter With Touch Current Limitation”*, IEEE Trans. on Power Electronics, 2024.

Capacitive coupled step-down DC–DC converter



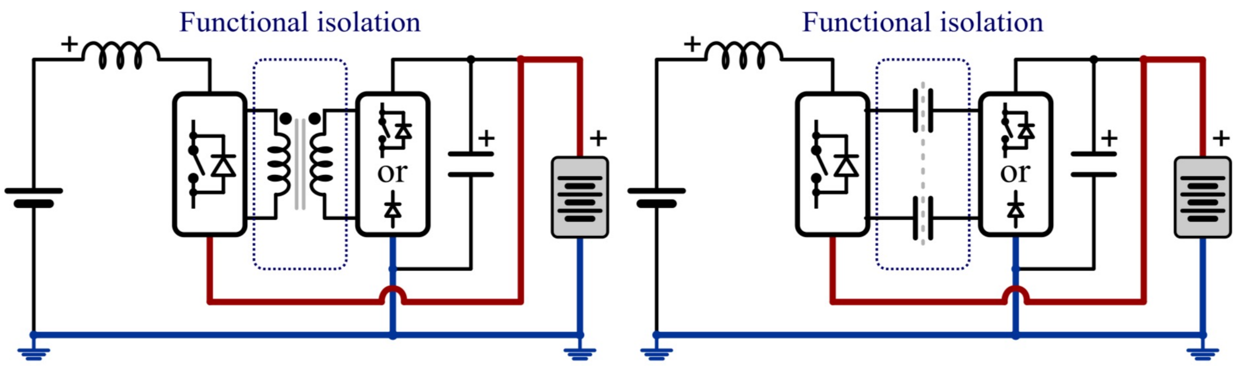




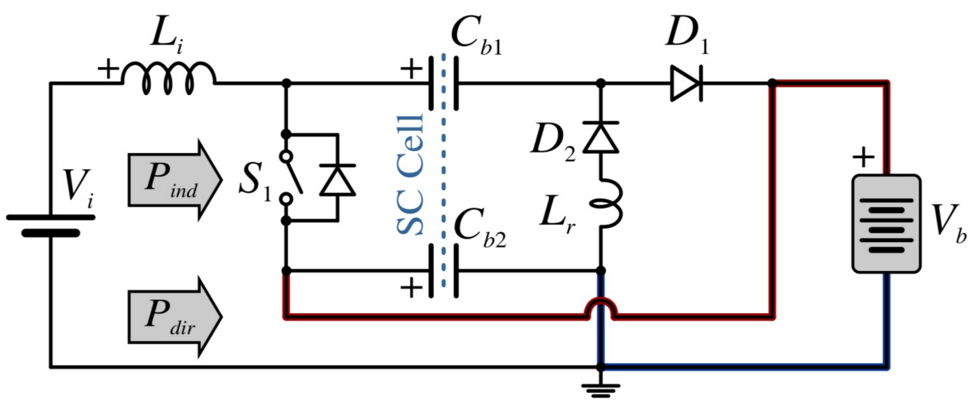


Source: A. Toebe et al., *"Capacitive Coupled Step-Down DC–DC Converter With Touch Current Limitation"*, IEEE Trans. on Power Electronics, 2024.

Step-down partial-power DC–DC converter

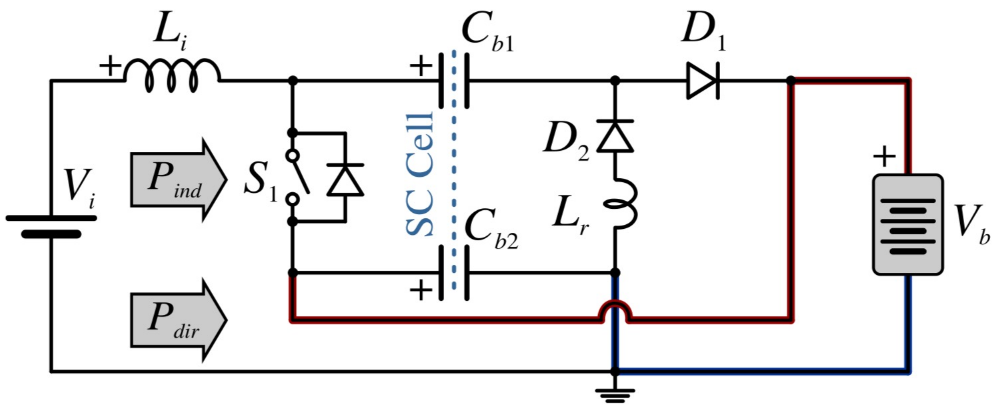


Step-down partial-power converter with capacitive isolation

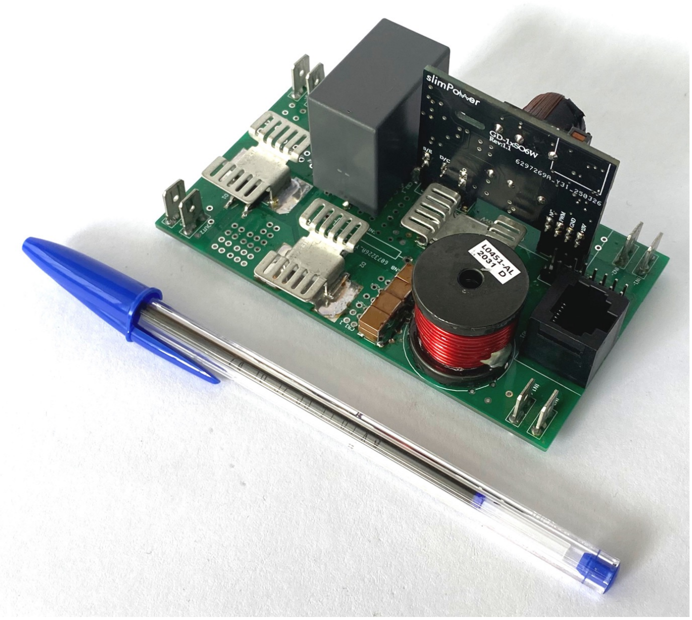


Source: N. G. F. dos Santos et al., *"A High-Efficient Single-Switch Switched-Capacitor Partial Power Converter for On-Board Chargers"*, IEEE Trans. on Power Electronics, 2024.

Step-down partial-power DC–DC converter



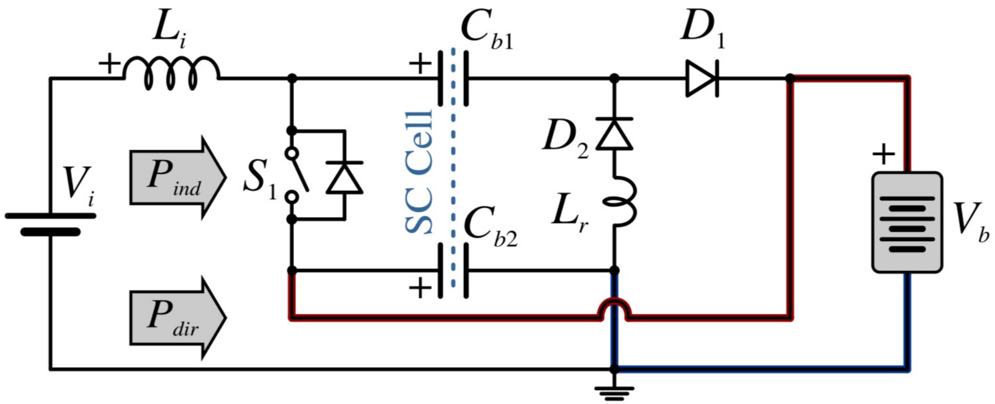
Parameter	Part	Parameter	Part
Controller	TMS320F280037	P_b	up to 3 kW
V_i	450 V	V_b	250–400 V
f_S	250 kHz	L_i	220 μH
L_i turns	27 (250×37 AWG)	L_i core	NEE-42/21/20
C_{b1}	1 μF (1000 V) B32656A0105	C_{b2}	36 μF (500 V) C4AQLLW5360A36K
S_1	UJ4C075023K4S 23 mΩ (750 V)	Diodes	FFSH2065A 1.5 V (650 V)
C_{eq}	973 nF	L_r*	95 nH$^\diamond$
d_{min}	$\approx 0.23^\diamond$	d	0.2–0.875

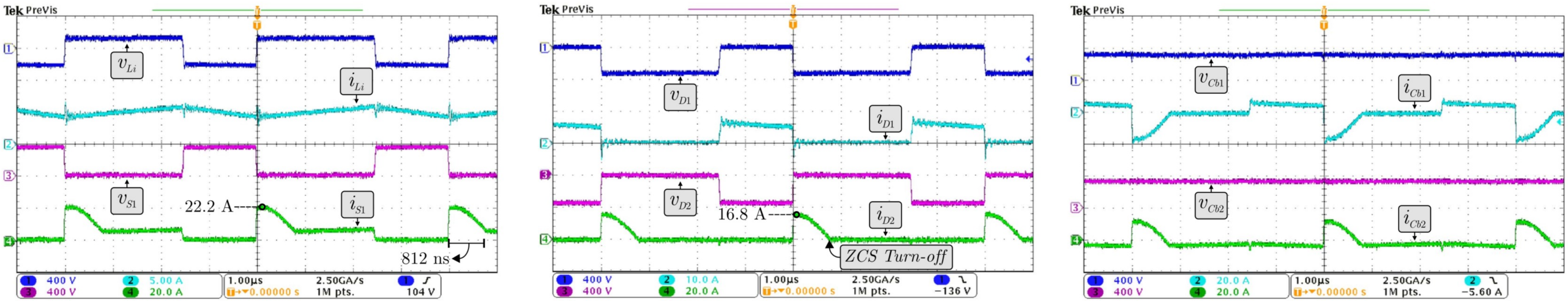


3 kW prototype
Dimensions: 106mm x 60mm x 40mm
Power density ≈ 11,8 kW/l

Source: N. G. F. dos Santos et al., *"A High-Efficient Single-Switch Switched-Capacitor Partial Power Converter for On-Board Chargers"*, IEEE Trans. on Power Electronics, 2024.

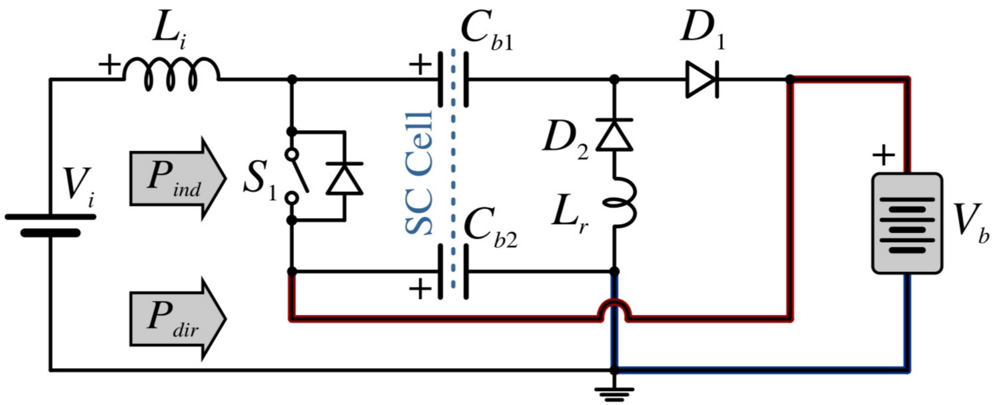
Step-down partial-power DC–DC converter

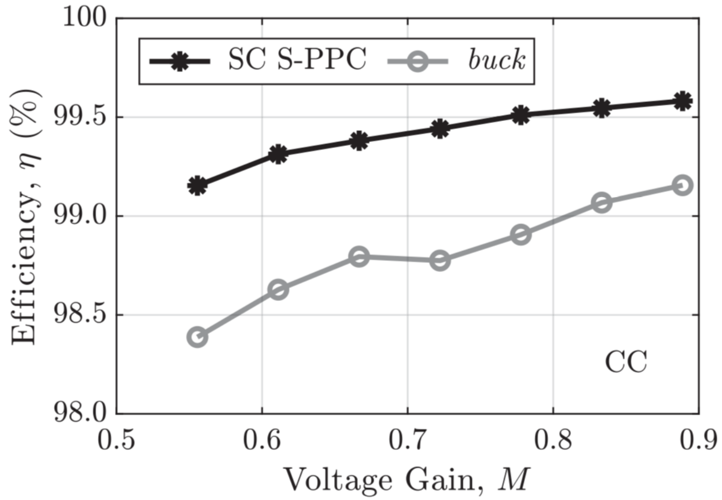


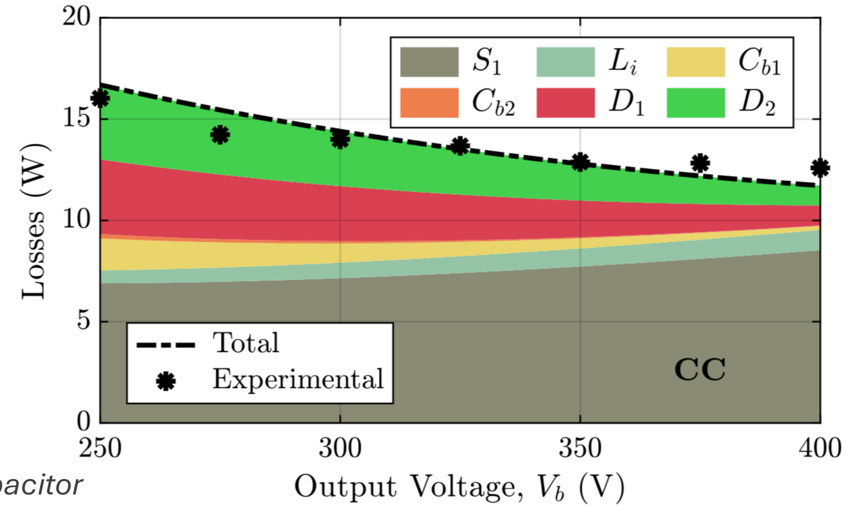


Source: N. G. F. dos Santos et al., *“A High-Efficient Single-Switch Switched-Capacitor Partial Power Converter for On-Board Chargers”*, IEEE Trans. on Power Electronics, 2024.

Step-down partial-power DC–DC converter







Source: N. G. F. dos Santos et al., *"A High-Efficient Single-Switch Switched-Capacitor Partial Power Converter for On-Board Chargers"*, IEEE Trans. on Power Electronics, 2024.

06

Outlook and Research Opportunities

Outlook and research opportunities

Key takeaways about capacitive isolation

- ✓ Galvanic isolation can be achieved without transformers
- ✓ Capacitive isolation enables higher integration and power density
- ✓ Multiple converter families have already been demonstrated
- ✓ Experimental results show efficiencies above 97–99%
- ! Coupling capacitor design is a multi-objective optimization problem
- ! Limited voltage adaptation capability
- ! Lower power-transfer capability in some applications

Capacitive isolation is not a universal replacement for transformers, but it is emerging as *a compelling solution for ultra-high-power-density converters.*

Outlook and research opportunities

Towards ultra-high power density transformerless isolation

Ultra-high power density transformerless isolated converters

Thank you!!!

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