A High-Density Hybrid Buck Converter with a Charge Converging Phase Reducing Inductor Current for 12V Power Supply Systems

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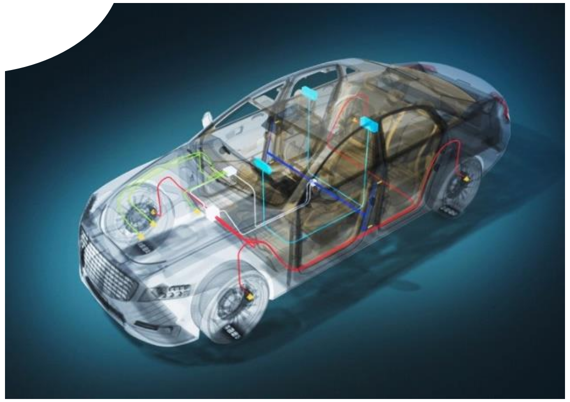
Motivation


Data Center

12V Rail

Portable Devices

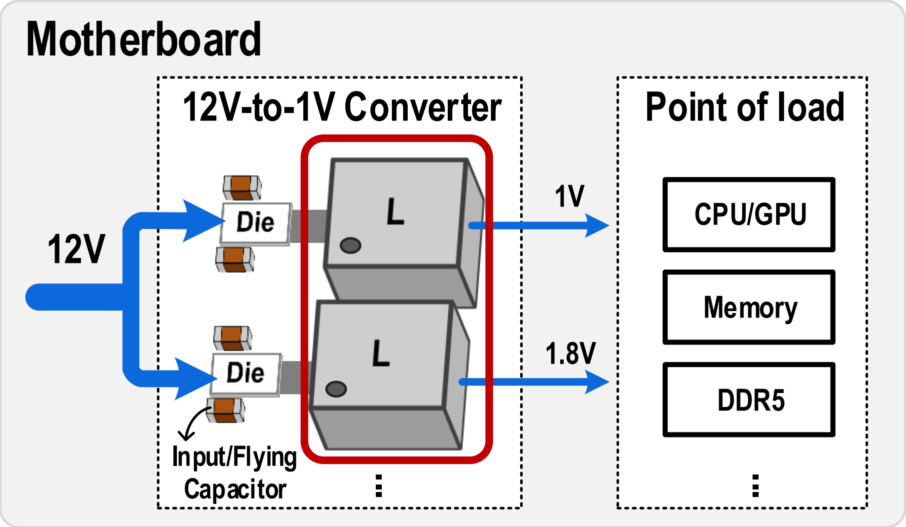
Industrial Automation

Automotive Electronics

[Images from Internet]

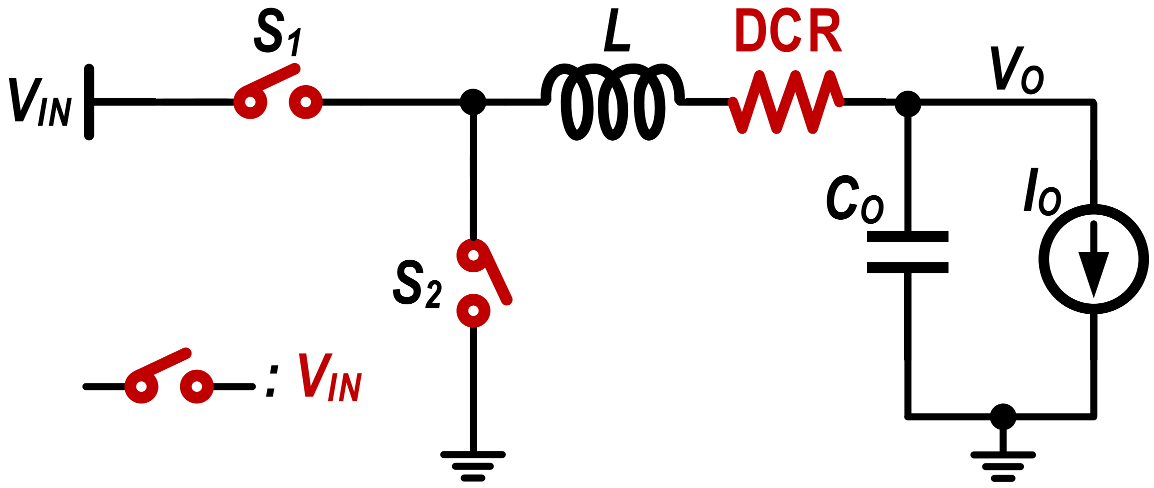
☐ Requirements:

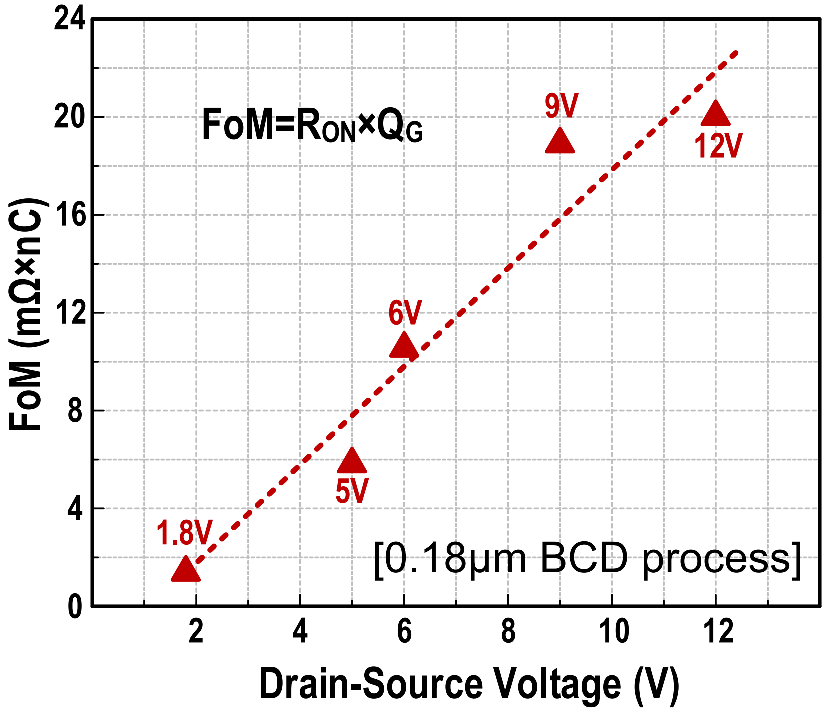
- High voltage conversion ratio
- High efficiency
- High current density



- 12V system is widely used in industrial and automotive applications
- Inductors occupy the most area, leading to **low current density**

Conventional Buck Converter

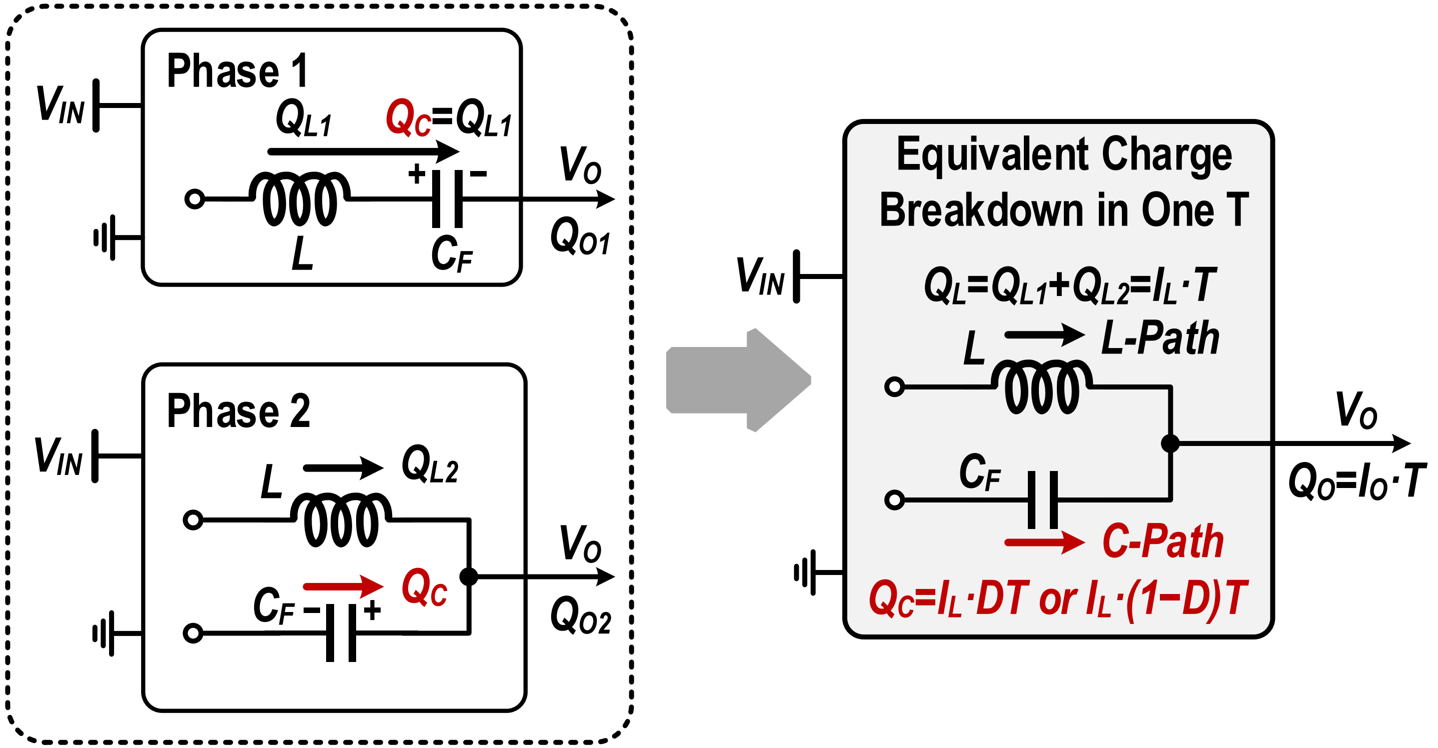


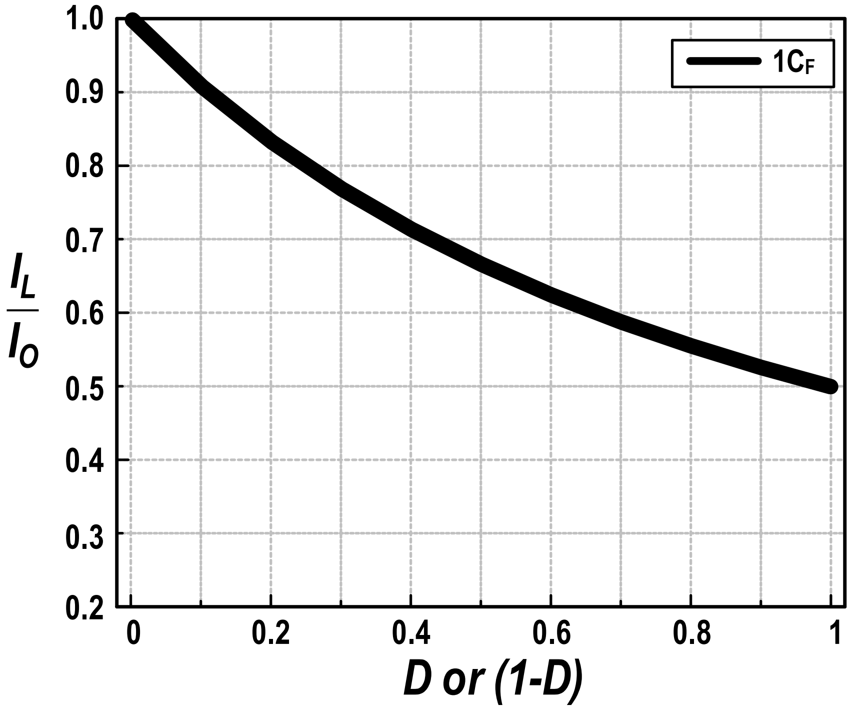


- High-voltage device (high FoM) and high power loss
- High inductor current and large DCR conduction loss

Dual-Path Buck Converters

- **Phase 1**: C_F along with V_O is soft charged by L with a Q_C of **$I_L DT$** or **$I_L(1-D)T$**
- **Phase 2**: Q_C is transferred to the output in parallel with L **realizing I_L reduction**



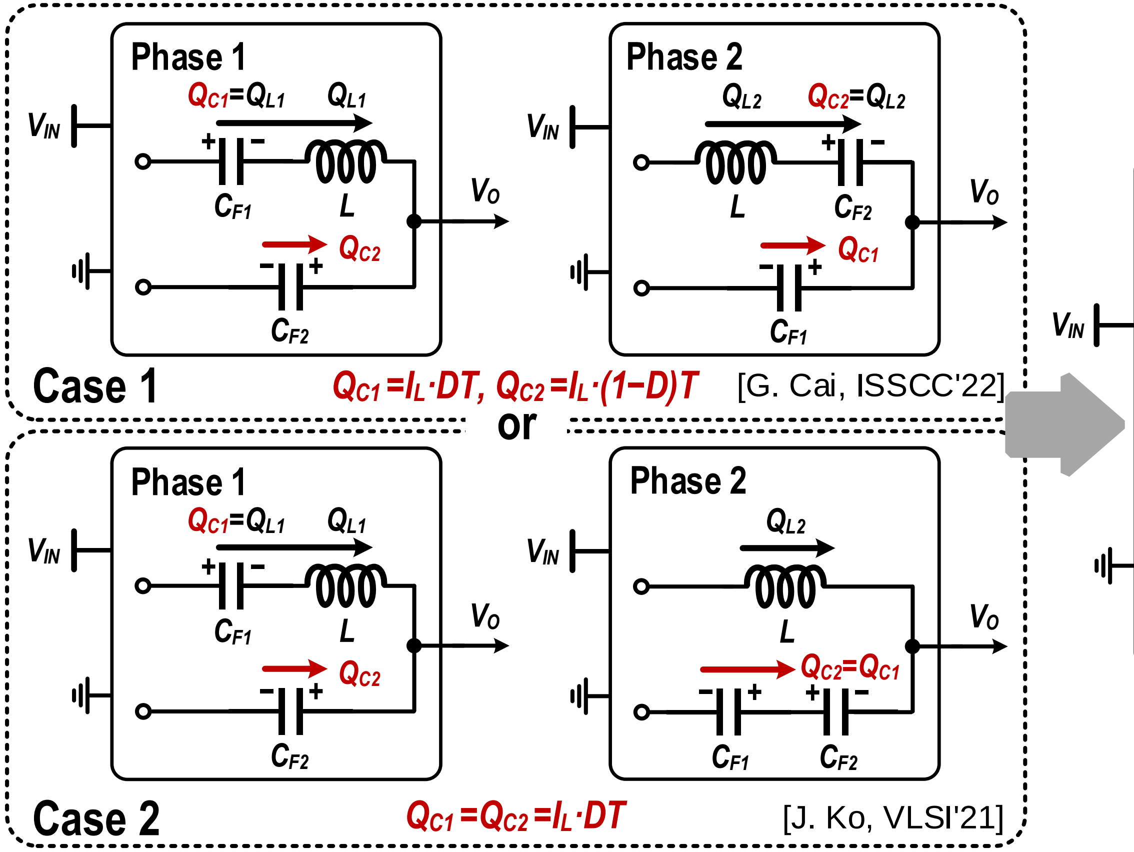


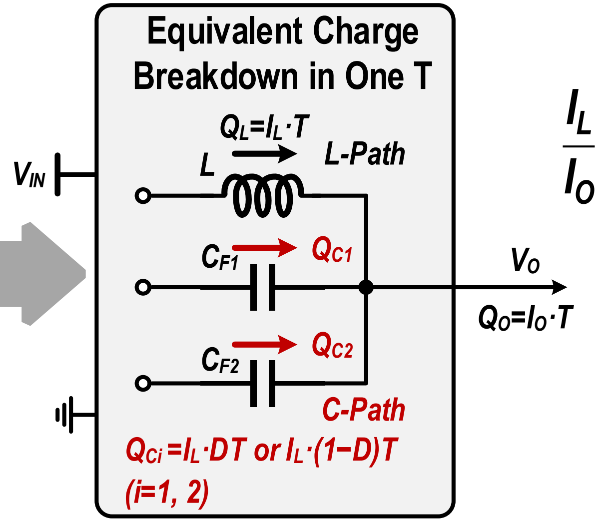
$$\frac{I_L}{I_O}=\frac{Q_L}{Q_O}=\frac{Q_L}{Q_L+Q_C}=\frac{1}{1+D}\ \text{or}\ \frac{1}{2-D}$$

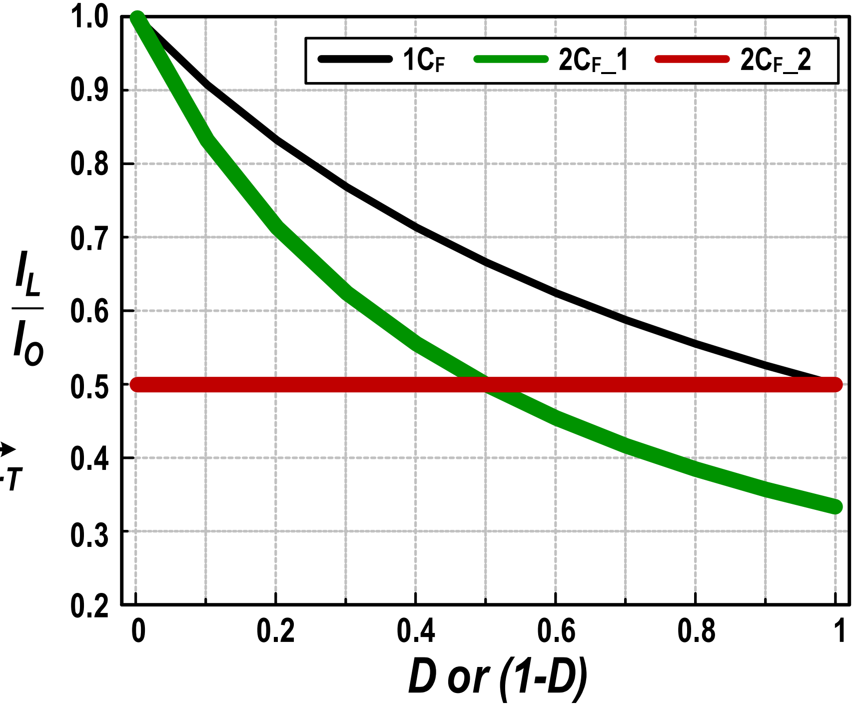
➢ **Q_C dependent on D and modest I_L reduction**

Dual-Path Buck Converters

- By applying 2 C_Fs, I_L is **further reduced**. **Each Q_C is dependent on D** and **still limited to $I_L DT$ or $I_L(1-D)T$**



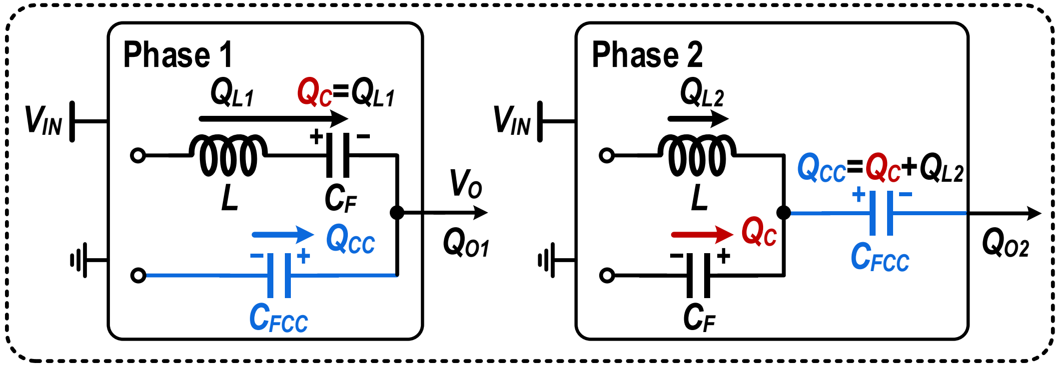


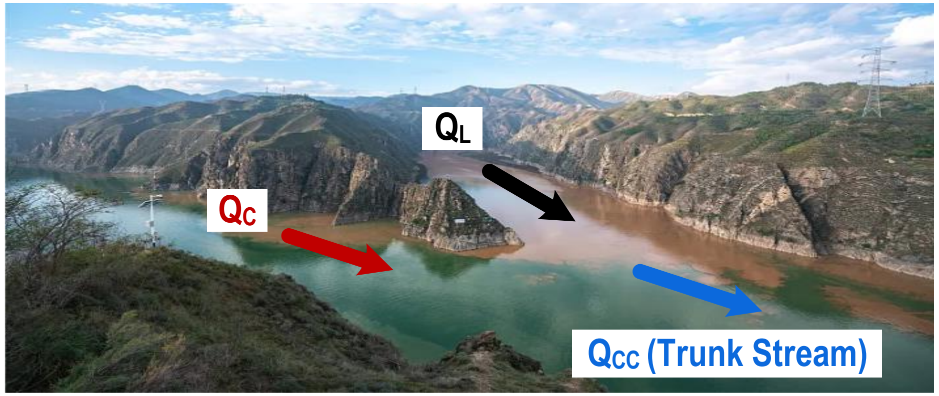


$$\frac{I_L}{I_O}=\frac{Q_L}{Q_L+Q_{C1}+Q_{C2}}=\frac{1}{1+2D}\ \text{or}\ \frac{1}{3-2D}\ \text{or}\ \frac{1}{2}$$

Proposed Charge Converging Phase

- **Phase 1**: C_F and V_O are charged by L while Q_{CC} gets transferred to V_O
- **Phase 2**: **By reusing Q_C, C_{FCC} and V_O are charged simultaneously by L and C_F**





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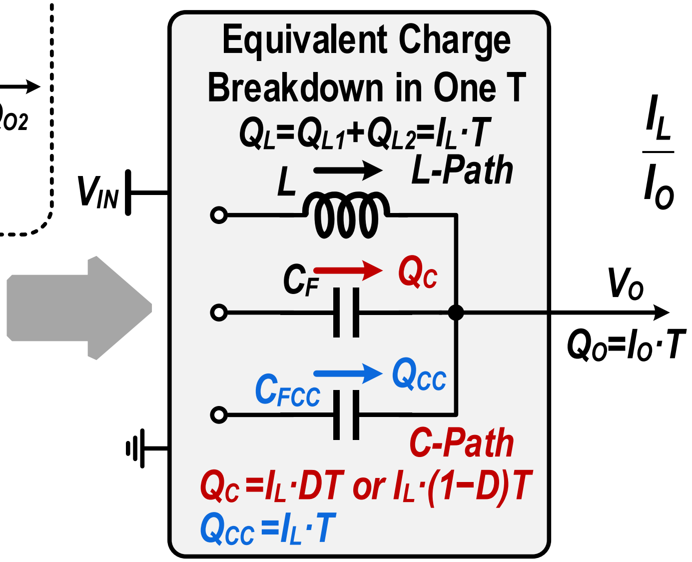
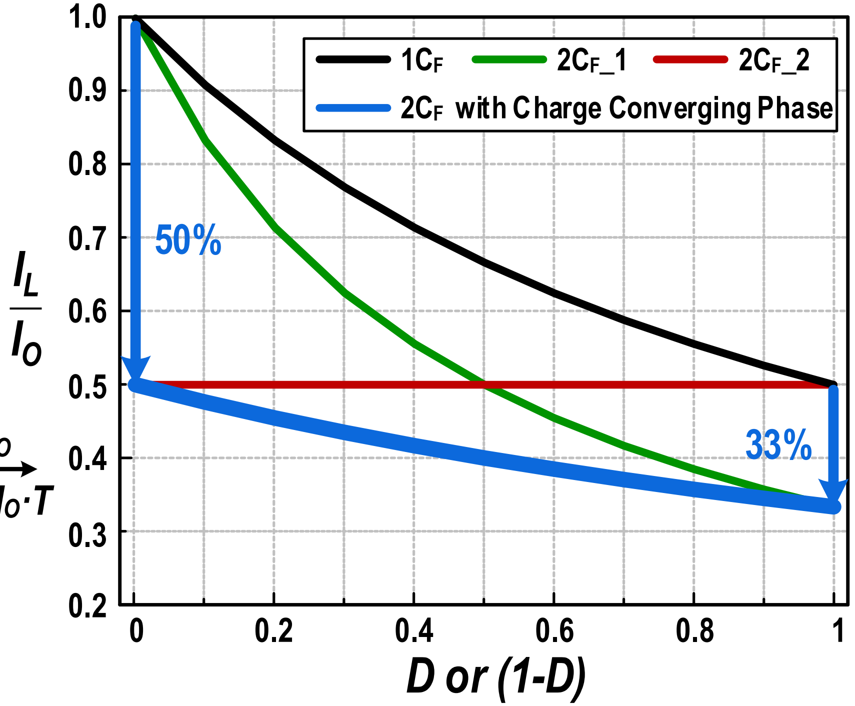
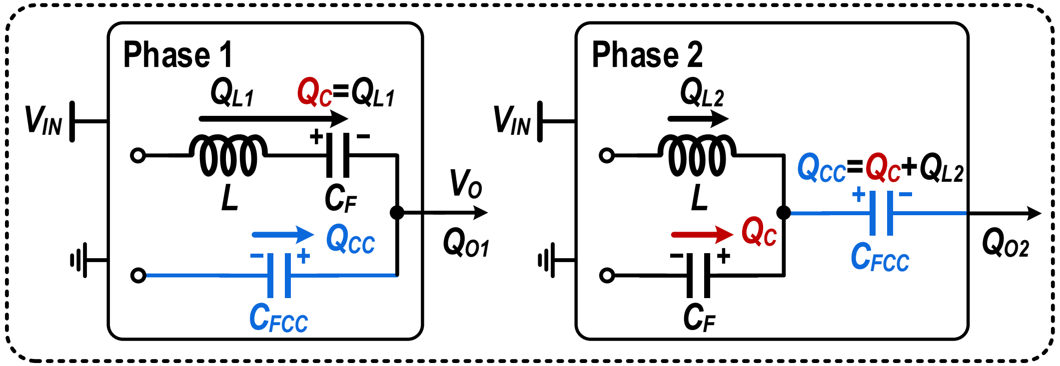


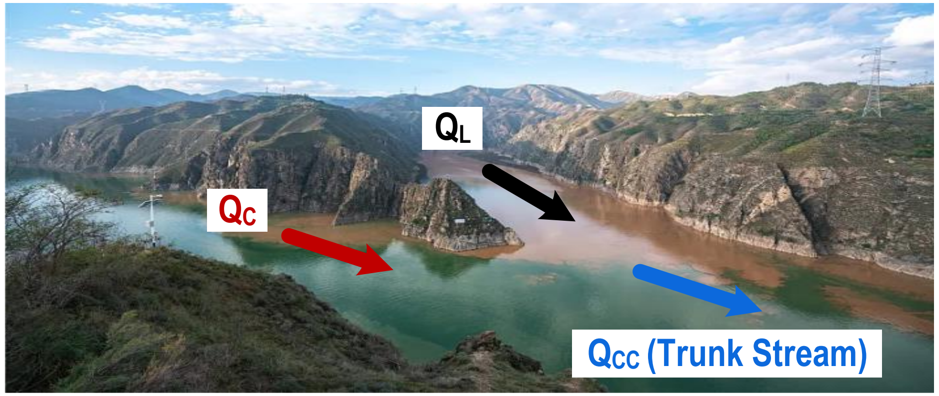


$$\frac{I_L}{I_O} = \frac{Q_L}{Q_L + Q_C + Q_{CC}} = \frac{1}{2+D} \text{ or } \frac{1}{3-D}$$

Proposed Charge Converging Phase

- The charge from C_{FCC} (Q_{CC}) is increased to **I_LT** and **is independent on D**
- **I_L is reduced to always < 0.5×I_O across D range**





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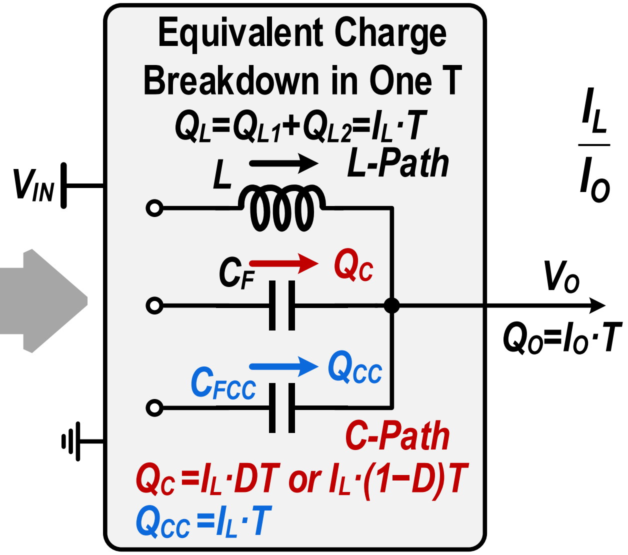
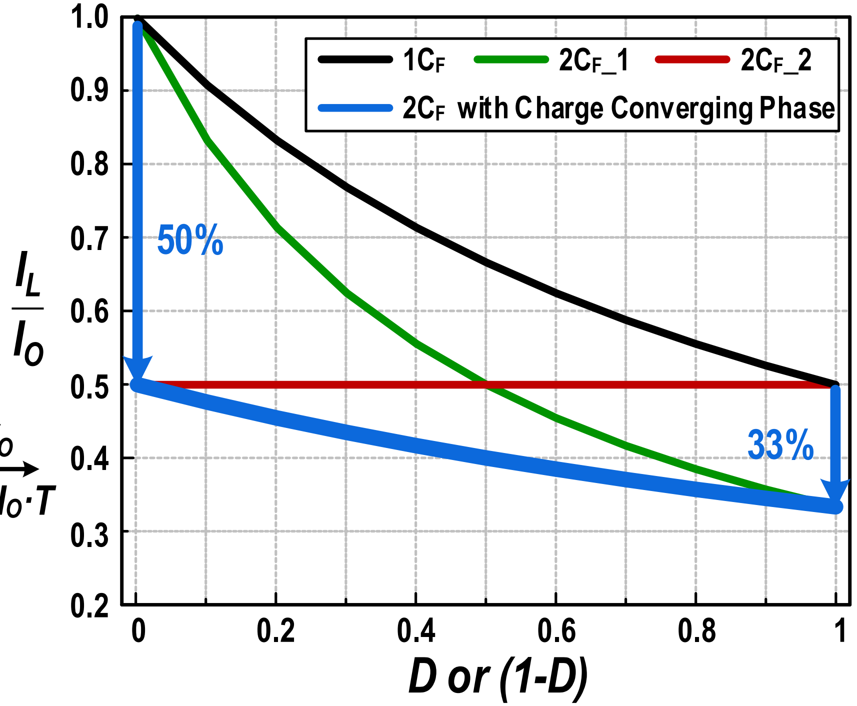
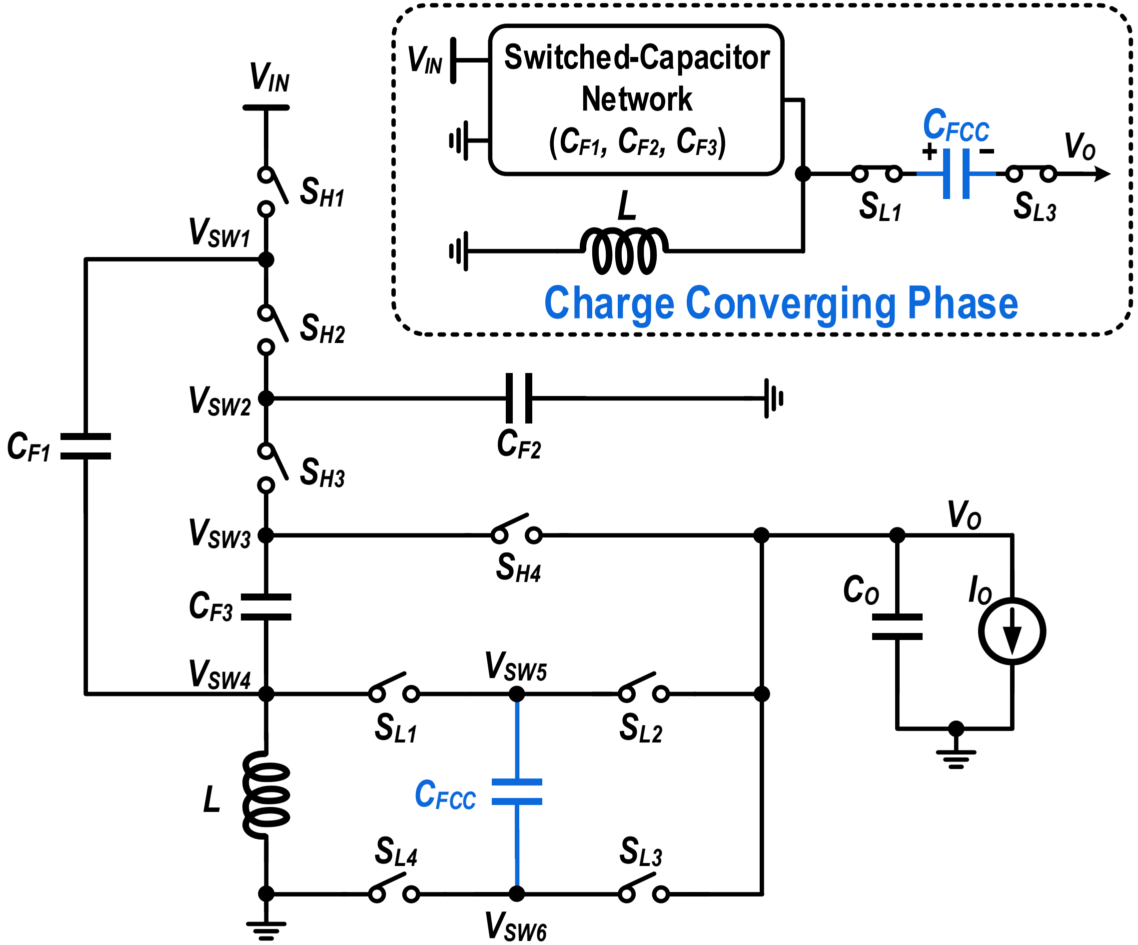




$$\frac{I_L}{I_O} = \frac{Q_L}{Q_L + Q_C + Q_{CC}} = \frac{1}{2+D} \text{ or } \frac{1}{3-D}$$

Proposed Hybrid Buck Converter



- 1 inductor, 4 flying capacitors & 8 switches
- C_{F1}, C_{F2} and C_{F3} are stacked
  - Reducing voltage stress of switches
  - All switches implemented by 5V/1.8V devices
- L, C_{F3}, C_{FCC} form charge converging phase
  - Average inductor current always < $0.5I_O$
  - Reducing DCR Conduction Loss
  - Relieving reliance on a bulky inductor

➔ ☺ **Higher efficiency**

☺ **Higher current density**

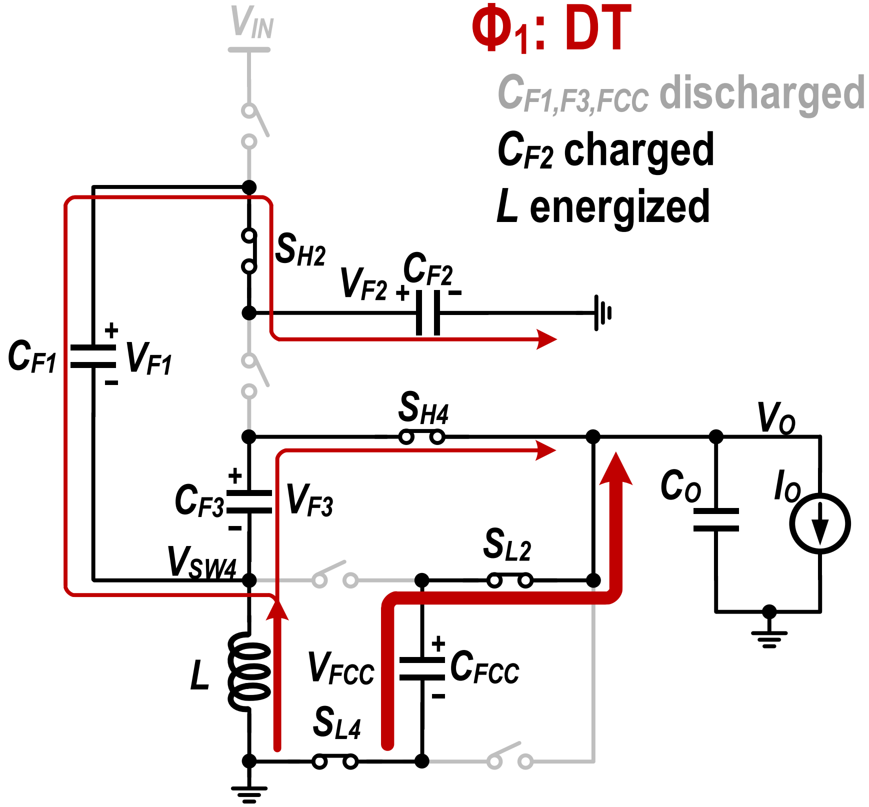
Working Principle

Φ_1: DT

$C_{F1,F3,FCC}$ discharged

C_{F2} charged

L energized



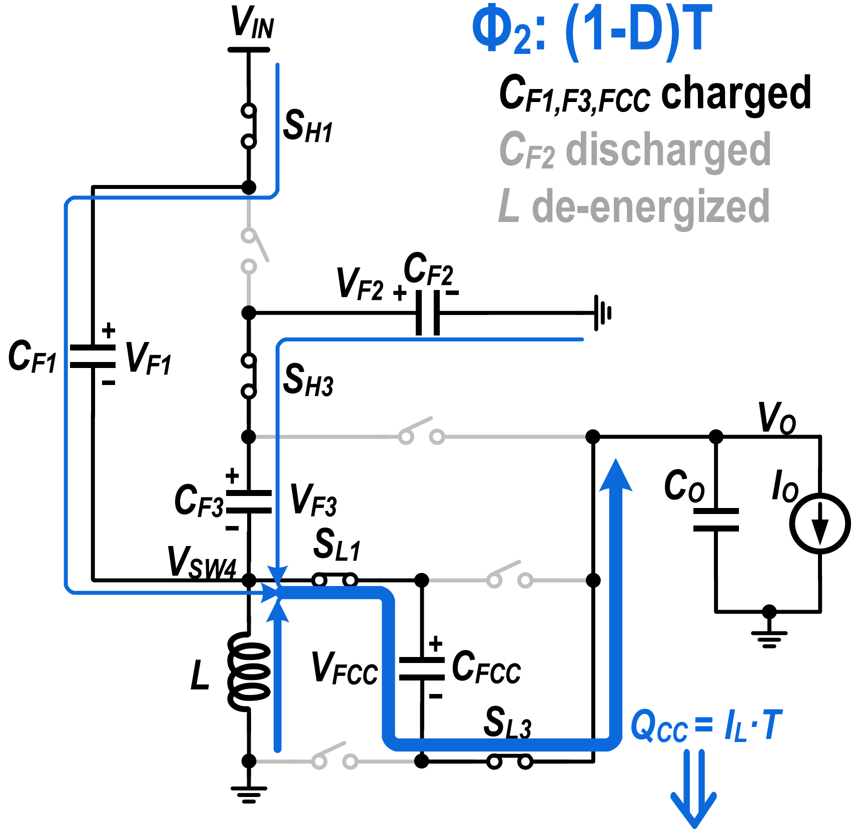
$$\frac{V_O}{V_{IN}} = \frac{D}{4+D} \qquad \frac{I_L}{I_O} = \frac{2}{4+D}$$

Φ_2: (1-D)T

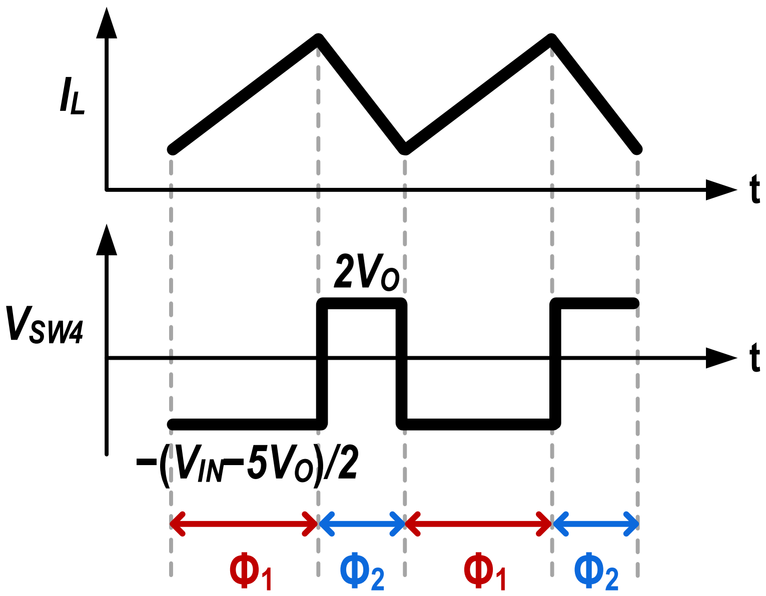
$C_{F1,F3,FCC}$ charged

C_{F2} discharged

L de-energized



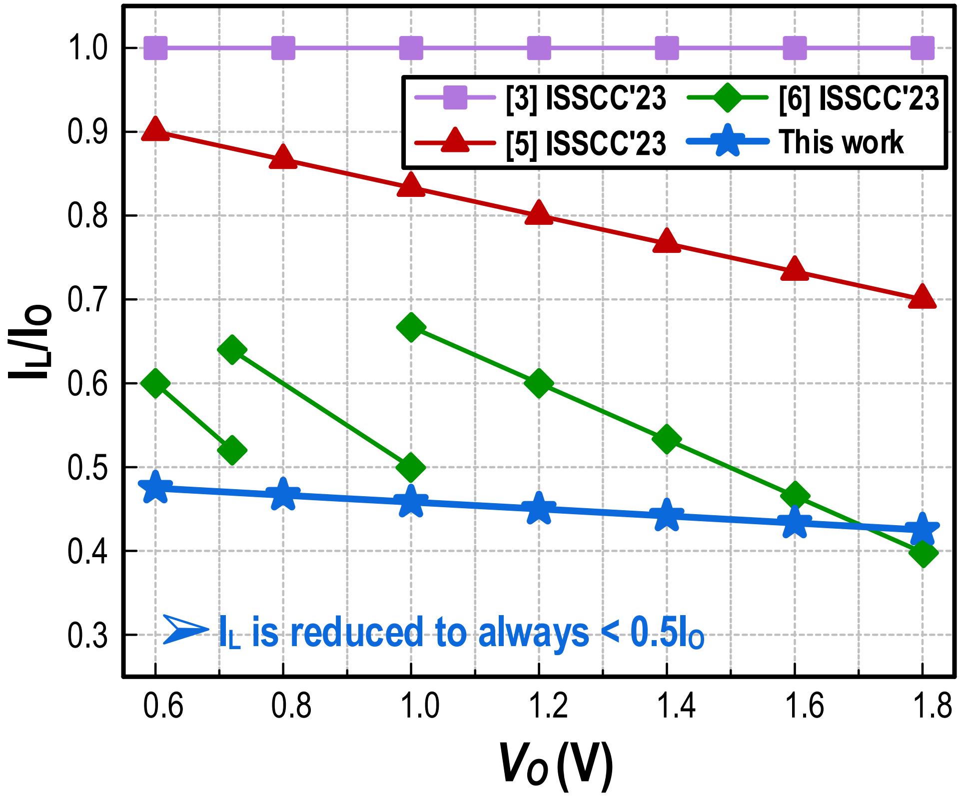
Charge Converging Phase



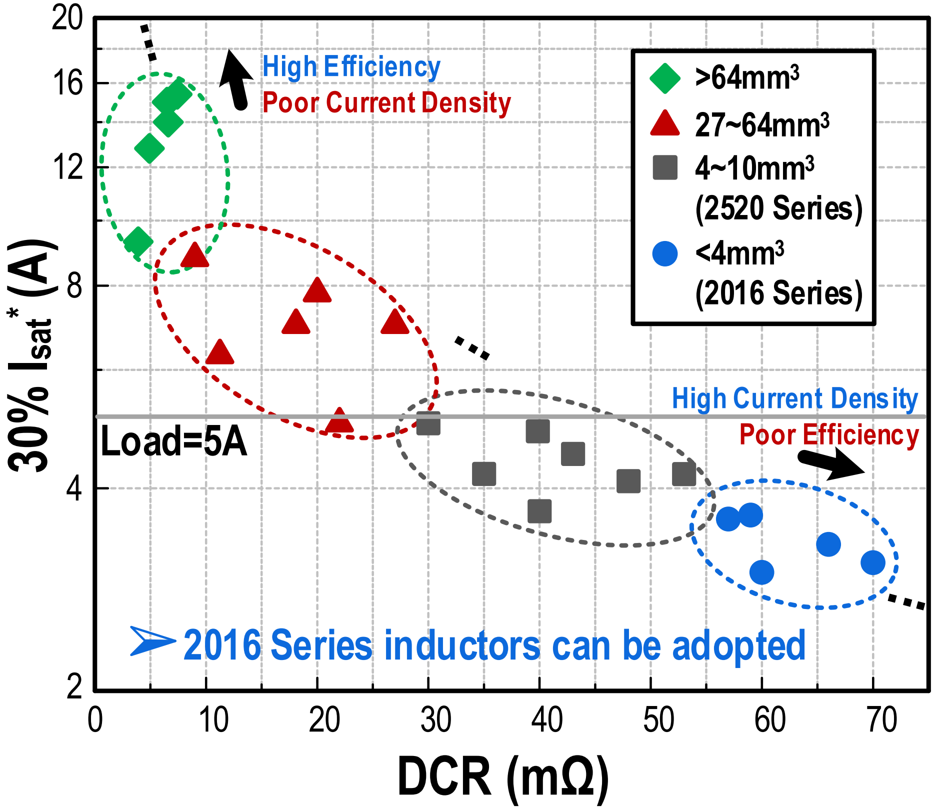
V_{F1}	V_{F2}	V_{F3}	V_{FCC}
$V_{IN}-2V_O$	$\frac{V_{IN}+V_O}{2}$	$\frac{V_{IN}-3V_O}{2}$	V_O

Topology Comparison

Normalized Inductor Current (Single-Inductor Topology)



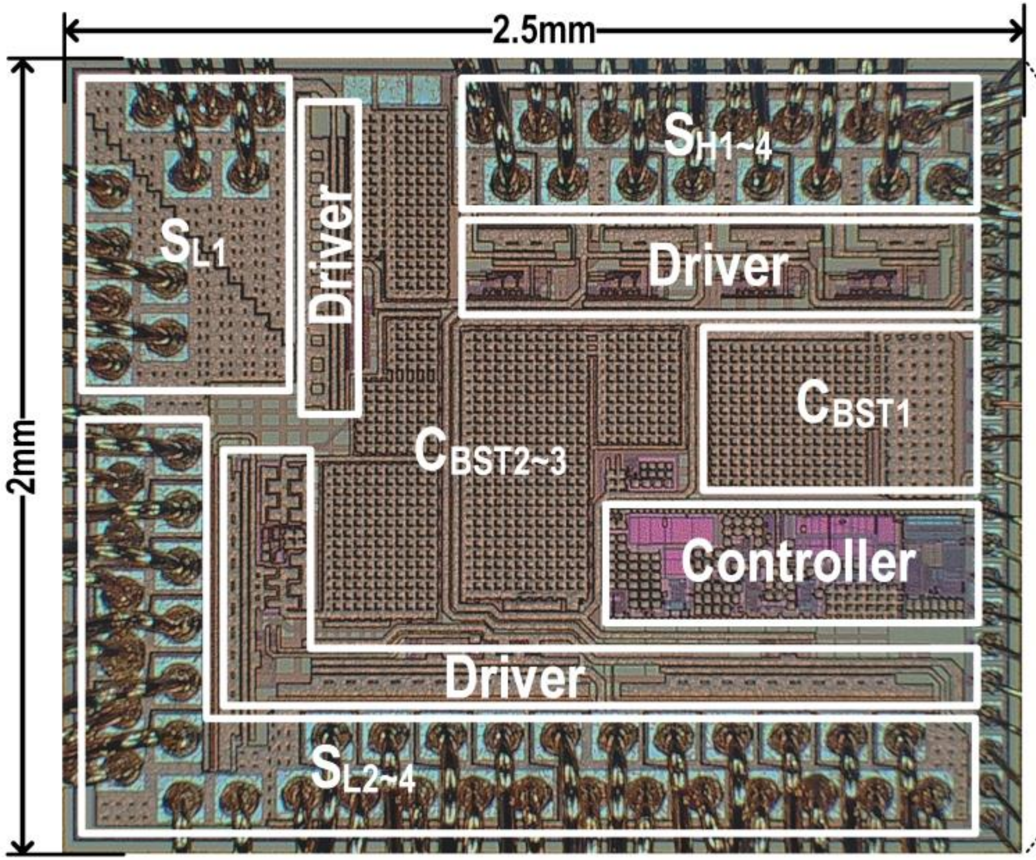
Features of Commercial Surface-Mount Inductors of 1μH

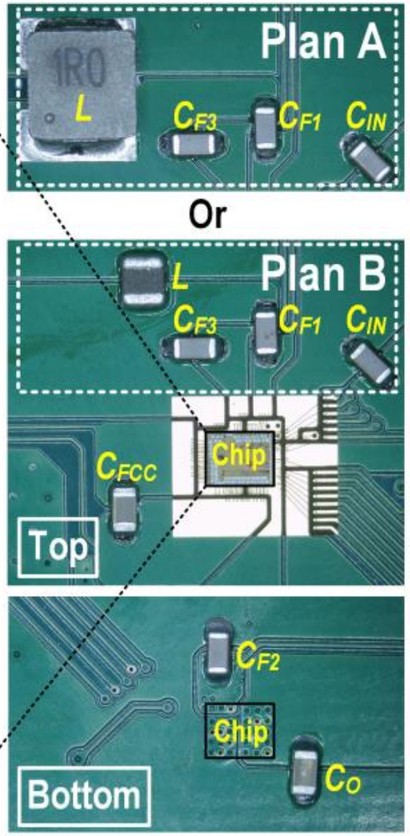


*30% I_{sat}: DC current at which initial inductance drops 30%

- The average inductor current is **consistently reduced to <0.5I_O**
- For 5A load capacity, **2016-series inductors** (30% I_{sat} ~3A) can be adopted

Chip Micrograph and PCB Photo





- 0.18μm BCD process
- Chip area: 2.5mm×2mm
- F_{SW}: 1MHz
- V_{IN}: 12V
- V_O: 1V-1.8V
- Two testing plans
  (Bulky & compact inductors)

Selection of Capacitors

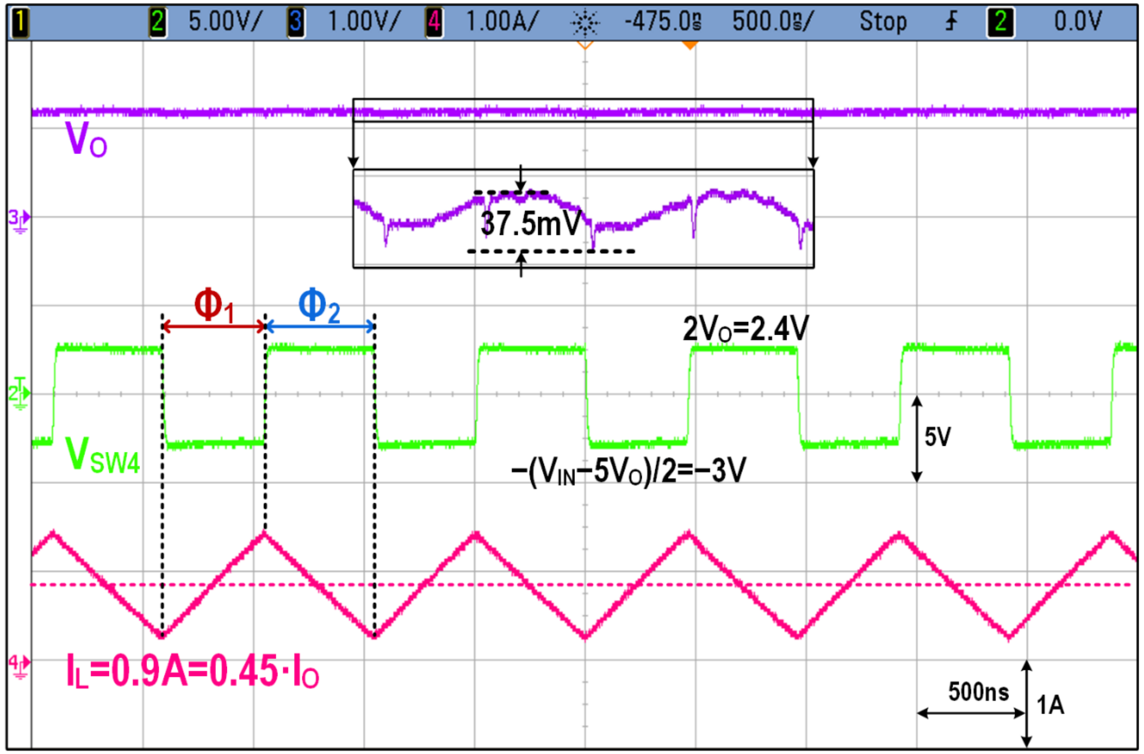
Component	Nominal Value	Footprint (Size)
$C_{IN},C_{F1},C_{F2},C_{F3}$	10μF	0603
C_{FCC},C_O	22μF	(1.6×0.8×0.8mm^3)

Selection of Inductors

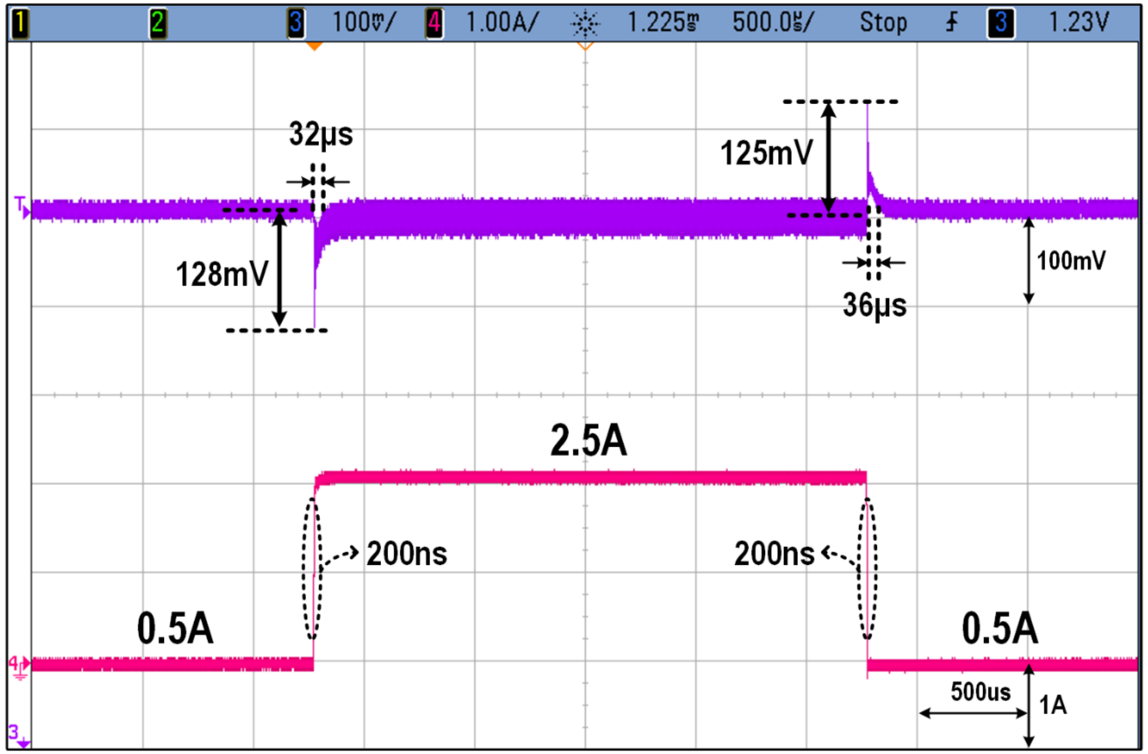
Component	Inductance (DCR)	Isat (30%)	Size
L (Plan A)	1μH (10.5mΩ)	6.7A	4.2×4×2.1mm^3
L (Plan B)	1μH (57mΩ)	3.6A	2×1.6×1mm^3

Measurement Results

Steady State: V_O=1.2V, I_O=2A

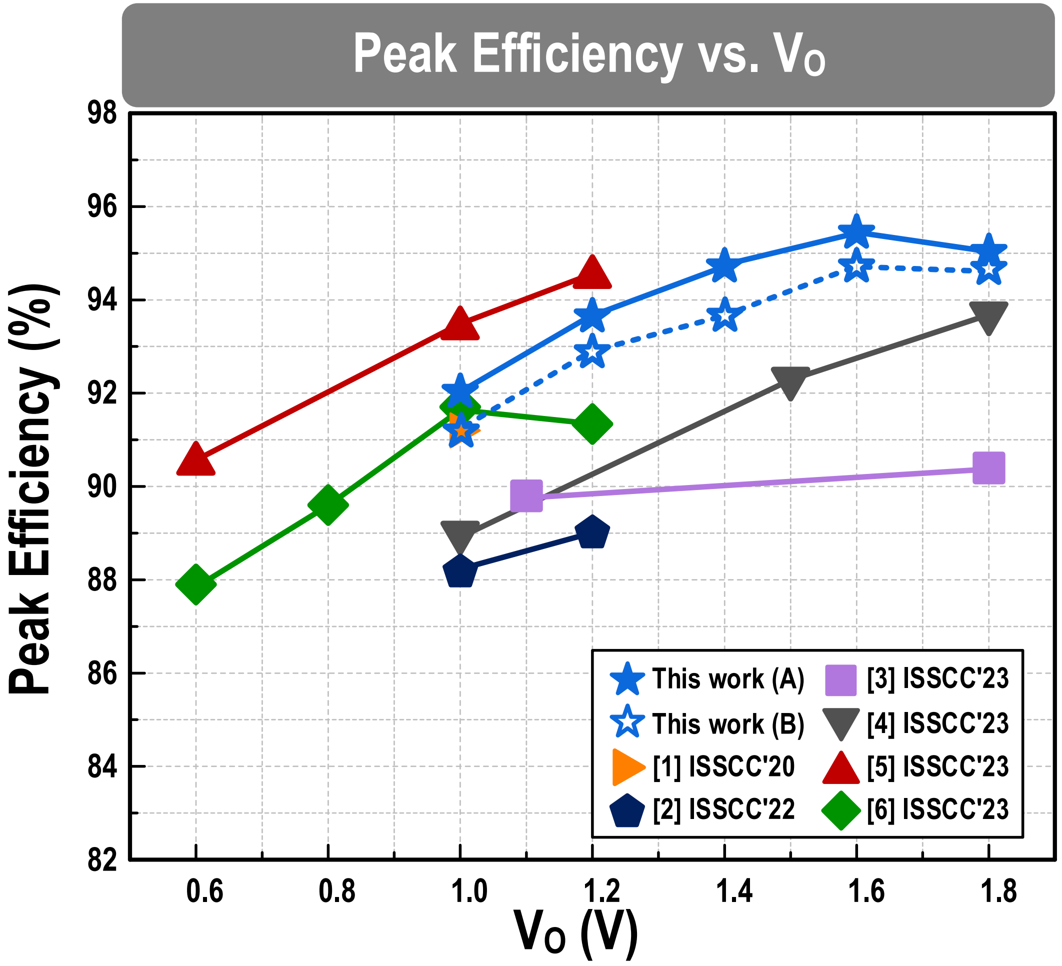


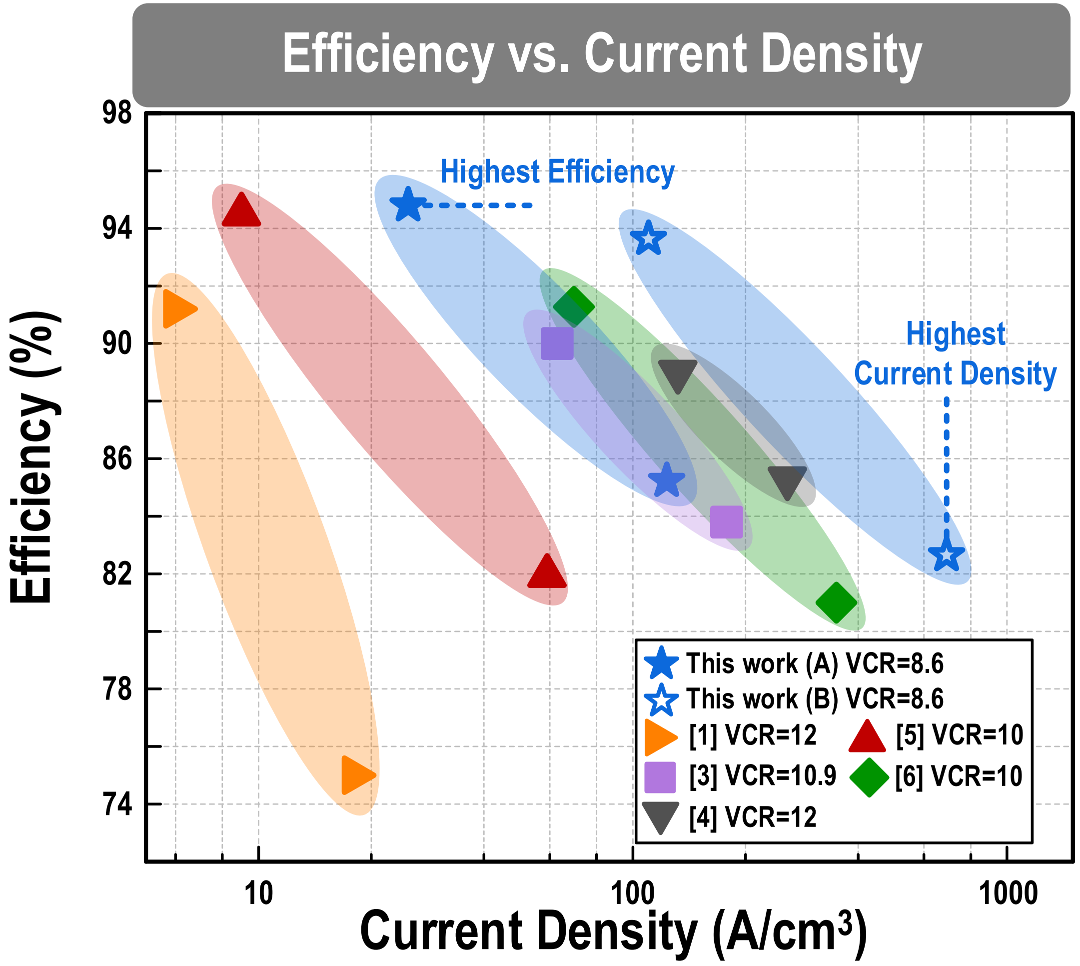
Load Transient: V_O=1.2V, I_O=0.5A-2.5A-0.5A



- Steady state: the average I_L showing **a reduction of 55%**
- Load transient (2A/200ns): verifying the stability of the converter

Measurement Results





- High peak efficiency across a wide V_O range
- **Highest efficiency or highest current density** with an appropriate inductor

Summary and Comparison

	Bulky Inductor Adopted					Compact Inductor Adopted		
Publication	ISSCC 2020[1]	ISSCC 2022[2]	ISSCC 2023[3]	ISSCC2023[5]	This work (A)	ISSCC 2023[4]	ISSCC 2023[6]	This work (B)
Technology	0.18μm BCD	0.18μm BCD	0.18μm BCD	0.18μm BCD	**0.18μm BCD**	0.18μm BCD	0.18μm BCD	**0.18μm BCD**
Topology	Tri-State DSD	DSD	SC Buck	DPSC	**CCP-HB**	2L4PHB	ReSC-PL	**CCP-HB**
Nominal $V_{IN} – V_O$	12V/24V – 1V	12V/24V – 1V	12V – 1.1V	9-16V – 0.6-1.6V	**12V – 1-1.8V**	12V – 1-1.8V	12V – 0.6-1.2V	**12V – 1-1.8V**
Max. Load Current	3A	4A	4A	5A	**5A**	4A	5A	**5A**
Components[a]	2L 2C 7S	2L 1C 4S	1L 4C 6S	1L 4C 8S	**1L 4C 8S**	2L 3C 8S	1L 4C 12S	**1L 4C 8S**
Inductor	2×0.56μH	2×1.8μH	0.22μH	0.68μH	**1μH**	2×1μH	1μH	**1μH**
I_L Reduction[b] @ VCR=10	0%	0%	0%	20%	**55%**	20%	40%	**55%**
Inductor Size (DCR)	6.6×6.4×N.A.[c] mm^3 (N.A.)	N.A.	3.2×2.5×1.2 mm^3 (6mΩ)	6.6×6.4×N.A.[c] mm^3 (N.A.)	**4.2×4×2.1mm^3 (10.5mΩ)**	2.5×2×1mm^3 (48mΩ)	2.5×2×1.2mm^3 (N.A.)	**2×1.6×1mm^3 (57mΩ)**
Peak Efficiency @ V_O (V_{IN}=12V)	91.2%@1V	89%@1.2V[c]	90%@1.1V	94.5%@1.2V	**95.4%@1.6V 93.7%@1.2V**	93.7%@1.8V 89%@1V	91.8%@1V 91.3%@1.2V[c]	**94.7%@1.6V 92.9%@1.2V**
Efficiency @ I_{O_max}	75%@1V,3A[c]	87%@1.2V,4A[c]	83.8%@1.1V,4A	82%@1.2V,5A	**84.8%@1.2V,5A**	85.3%@1V,4A	81%@1.2V,5A[c]	**82.1%@1.2V,5A**
Total Passive Volume[d]	168.96mm^3 [e]	N.A.	22.1mm^3	84.48mm^3 [e]	**39.38mm^3**	15.17mm^3	14.3mm^3	**7.3mm^3**
Current Density	18A/cm^3	N.A.	181A/cm^3	59A/cm^3	**127A/cm^3**	264A/cm^3	350A/cm^3	**685A/cm^3**

(a) Number of inductors (L), flying capacitors (C), switches (S) adopted in the topology. (b) I_L Reduction=$(I_O/N-I_L)/(I_O/N)$, where N is the number of inductors.
(c) Estimated from graph. (d) Counts flying capacitors and inductors. (e) Counts inductors only, and the height is assumed to be 2mm.

Thank you!