



浙江大學  
ZHEJIANG UNIVERSITY

PWR  
SOC 23

# Hybrid DC-DC Converters and the Applications for Processor Power Delivery

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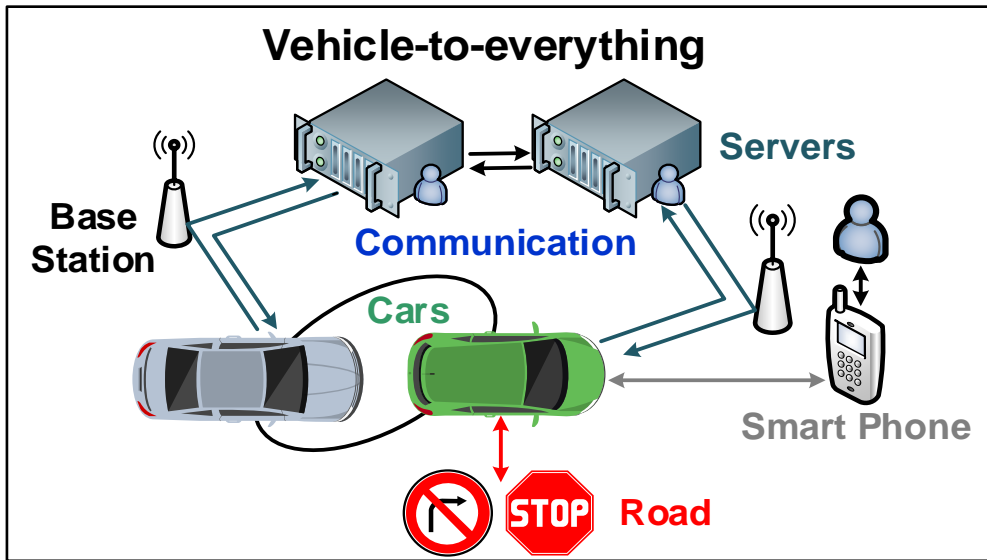
# Motivation



Artificial Intelligence

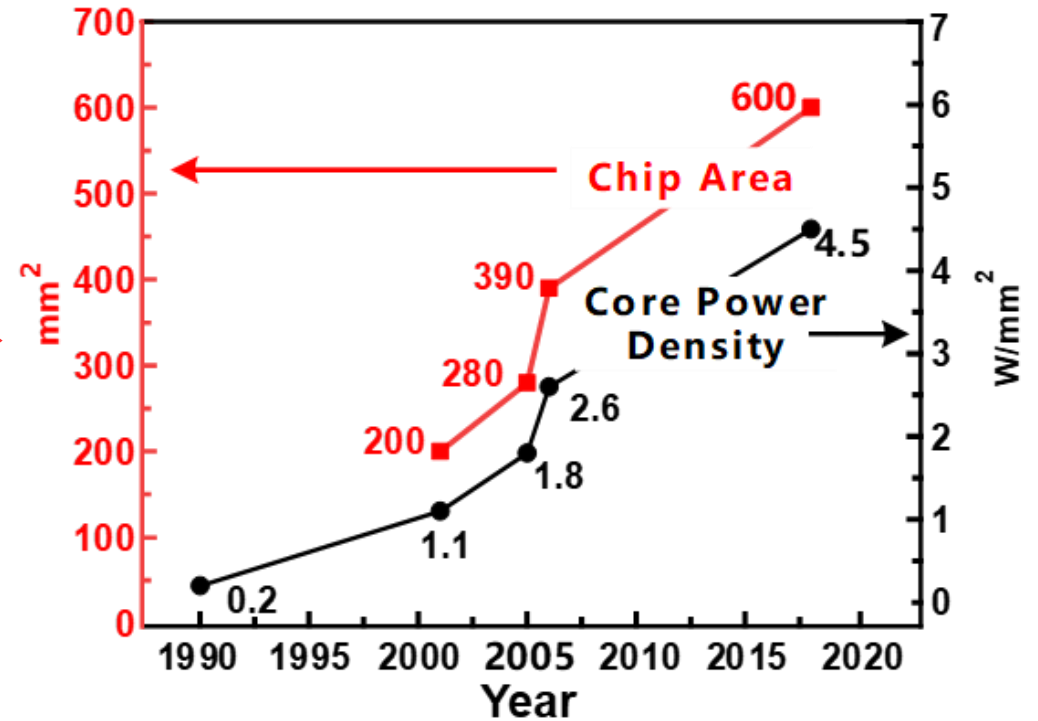


Cloud Computing

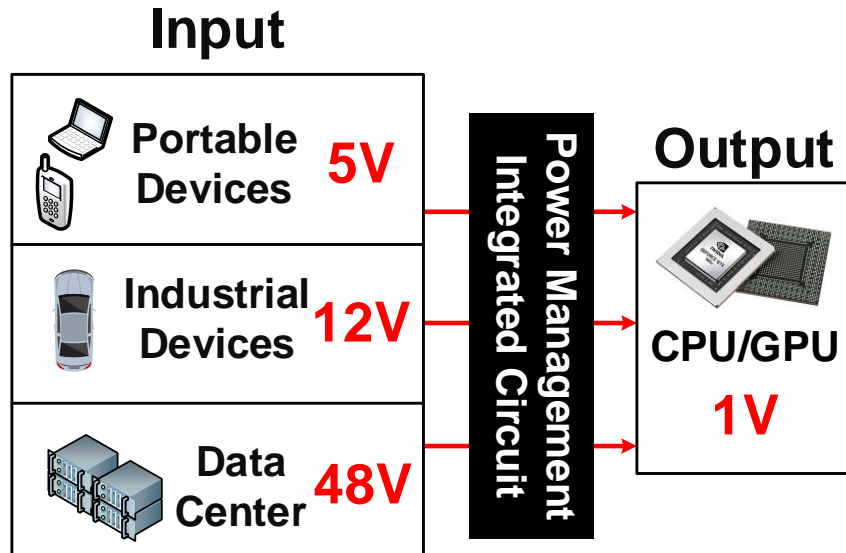


Internet of Vehicles System

## More Computing Force



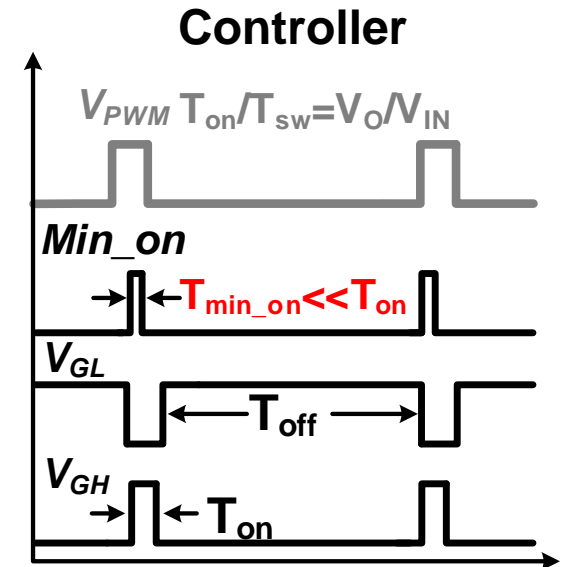
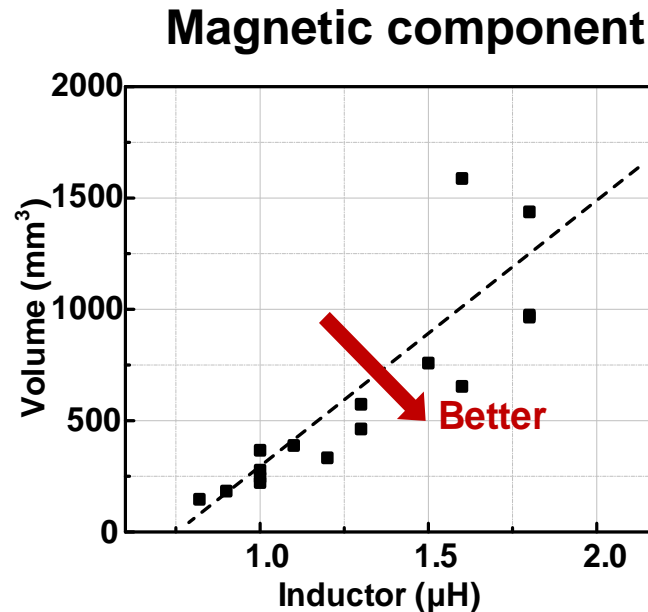
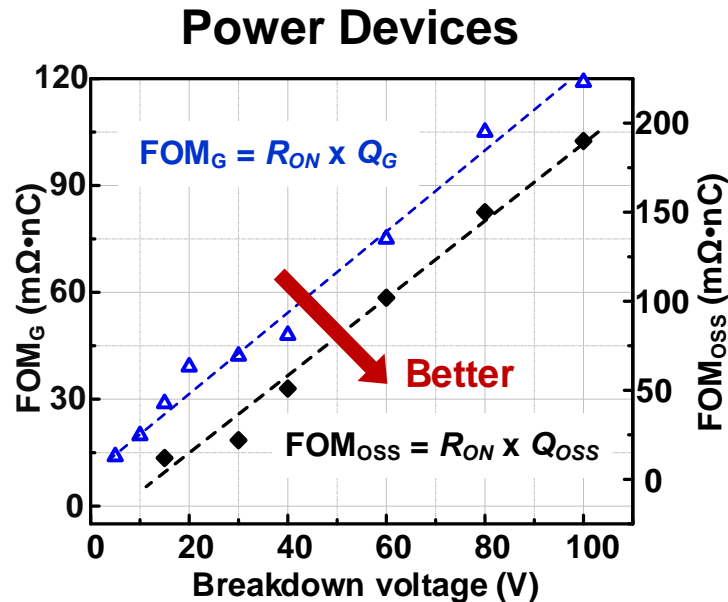
**Massive energy consumption**



- Large Conversion Ratios, e.g. 5V/1V, 12V/1V, 48V/1V
- High Efficiency
- High Current Density,  $>1 \text{ A/mm}^2$
- Wide Regulation Range (0.4V~1.2V)
- Reliability and Low Cost

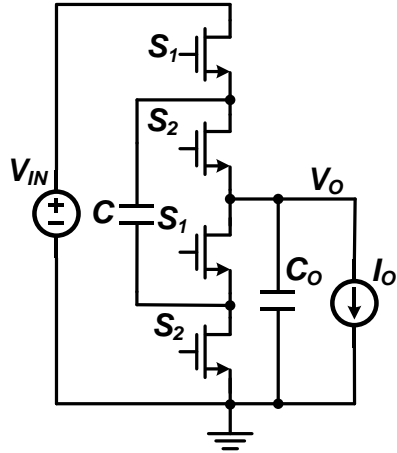
# Challenges

- Power Devices → Limited Efficiency
- Magnetics → Limited Power Density
- Controller → Limited Switching Speed



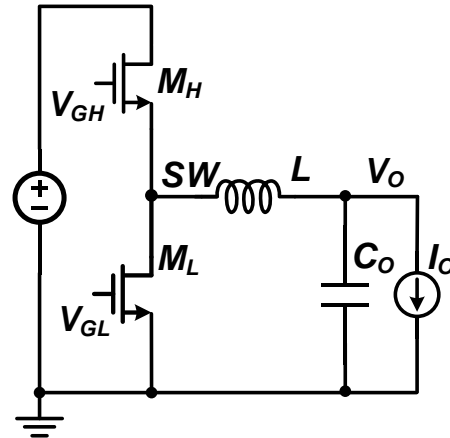
**Need for advanced DC-DC converters**

## Switching-Cap(SC) Converter

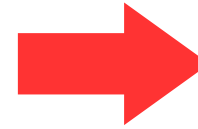


- High Efficiency
- High Power Density
- Fixed Output
- Low Load Capability

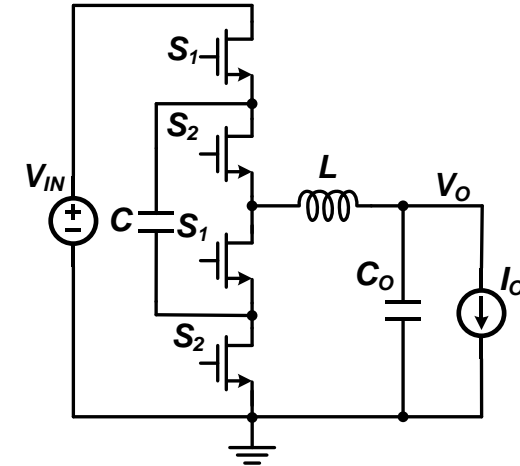
## Switching-Inductor Converter



- Decent Efficiency
- Decent Power Density
- Continuous Output
- High Load Capability



## Hybrid Converter



- High Efficiency
- High Power Density
- Continuous Output
- High Load Capability

# Prior Hybrid Converters

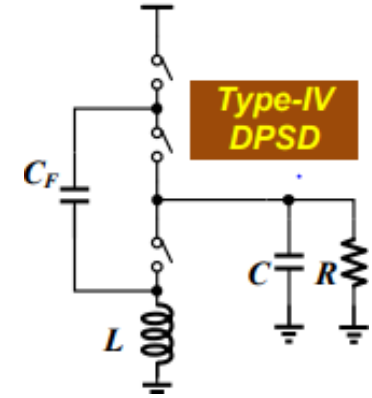
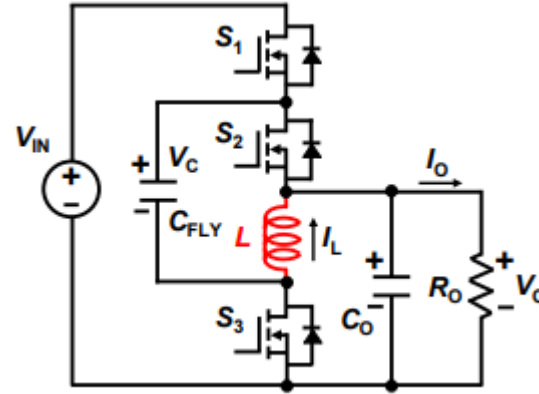
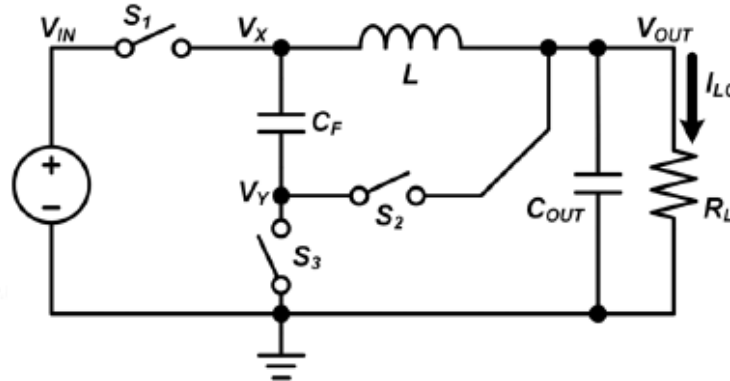
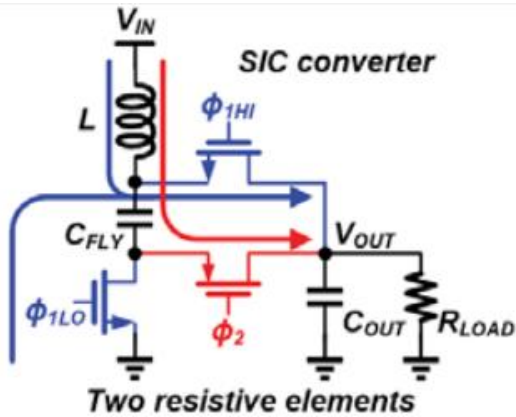
## Buck Type

\* N Tang et al., ISSCC, 2019

\* Y Huh et al., JSSC, 2019

\* K Hata et al., APEC, 2020

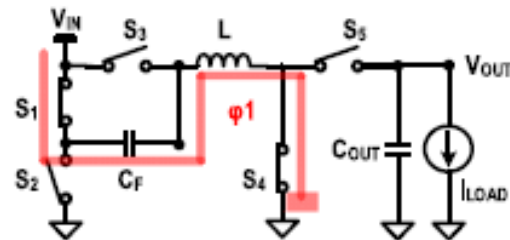
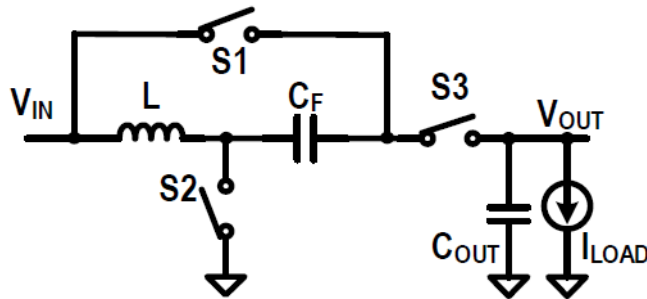
\* S Zhen et al., ISCAS, 2021



## Boost Type

\* Y Lin et al., ISSCC, 2021

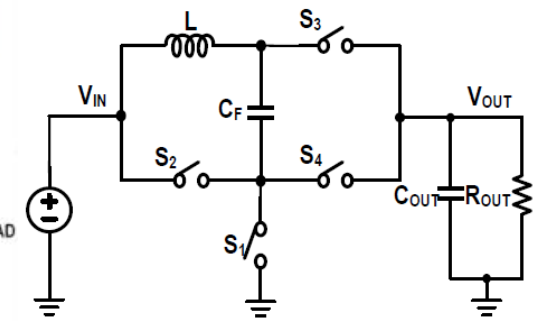
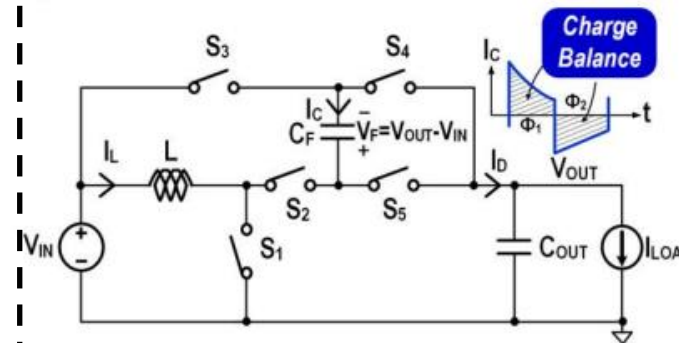
\* Si Li et al., JSSC, 2023



## Buck-Boost Type

\* S Shin et al., ISSCC, 2018

\* J Jin et al., ISSCC, 2023



\* N Tang et al., ISSCC, 2019

\* Y Huh et al., JSSC, 2019

\* K Hata et al., APEC, 2020

\* S Zhen et al., ISCAS, 2021



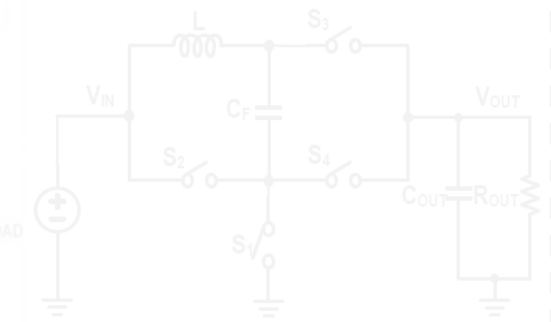
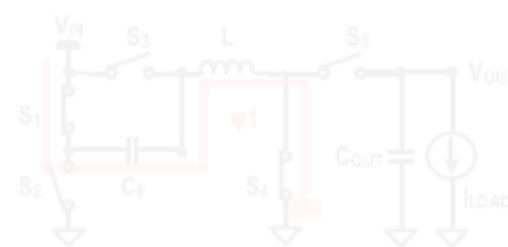
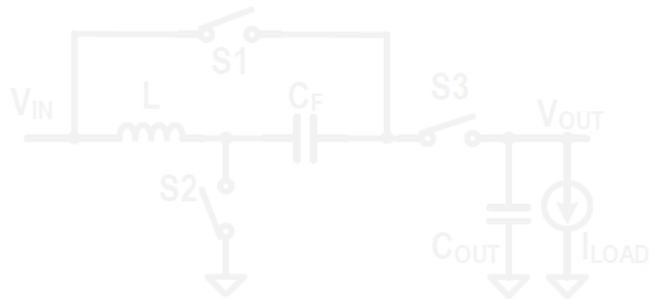
## Ways to make Hybrid Converters?

\* Y Lin et al., ISSCC, 2021

\* Si Li et al., JSSC, 2023

\* S Shin et al., ISSCC, 2018

\* J Jin et al., ISSCC, 2023



## ■ Summary of Hybrid Converter Constructions

- $L$  Replacement in SC Converters
- $L$  Insertion in SC Converters
- $L + C$  Combinations
- Other Extensions

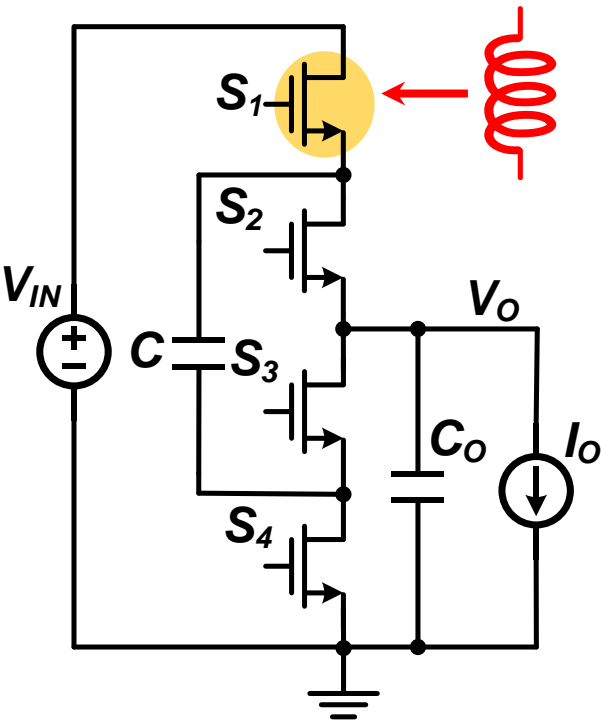
## ■ 12V/1V Hybrid DC-DC Converter

- Prior 12V/1V Hybrid Converters
- Proposed 12V/1V DPSC Converter



# Construction Summary 1

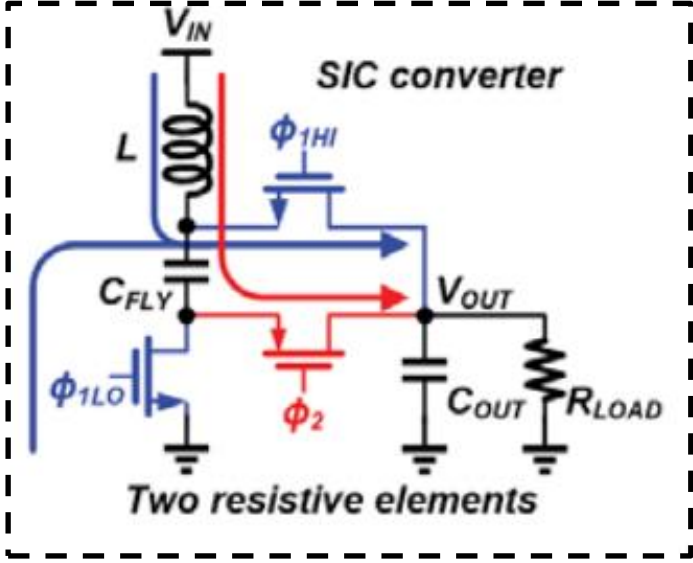
## L Replacement in SC Converters



2:1 SC Converter

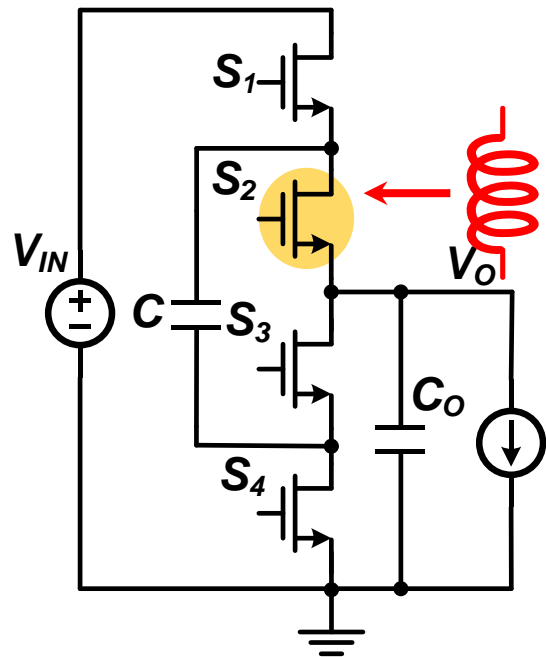


\* N Tang et al., ISSCC, 2019

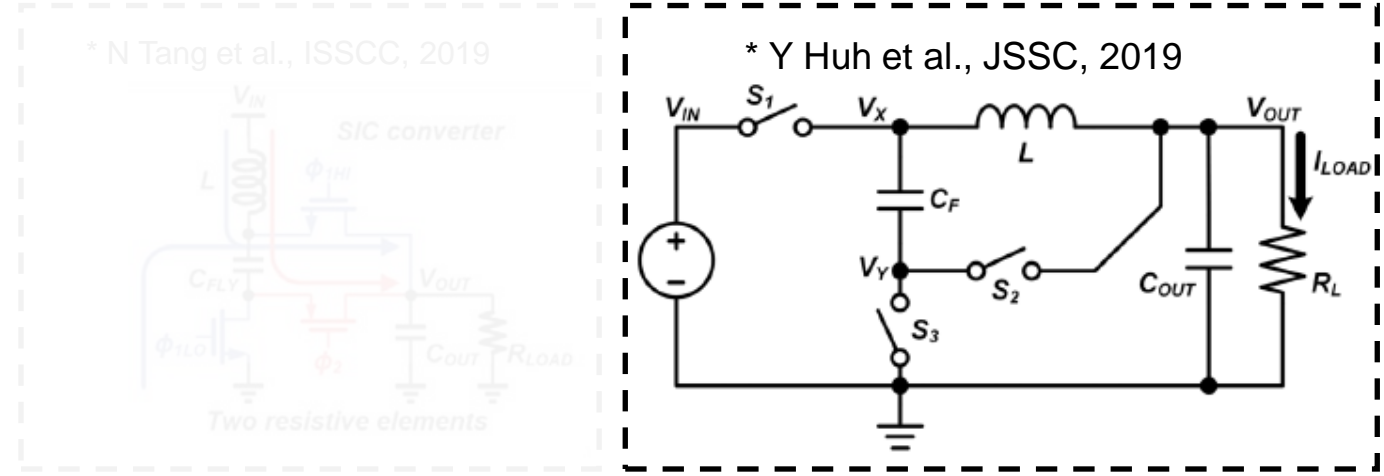


# Construction Summary 1

## L Replacement in SC Converters



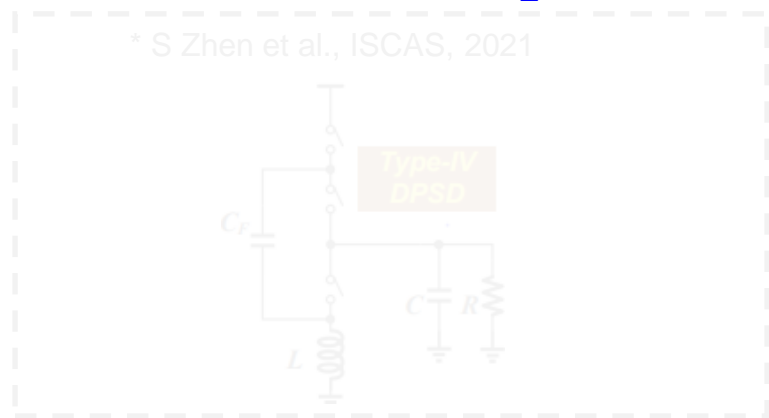
2:1 SC Converter



L replaces S<sub>2</sub>



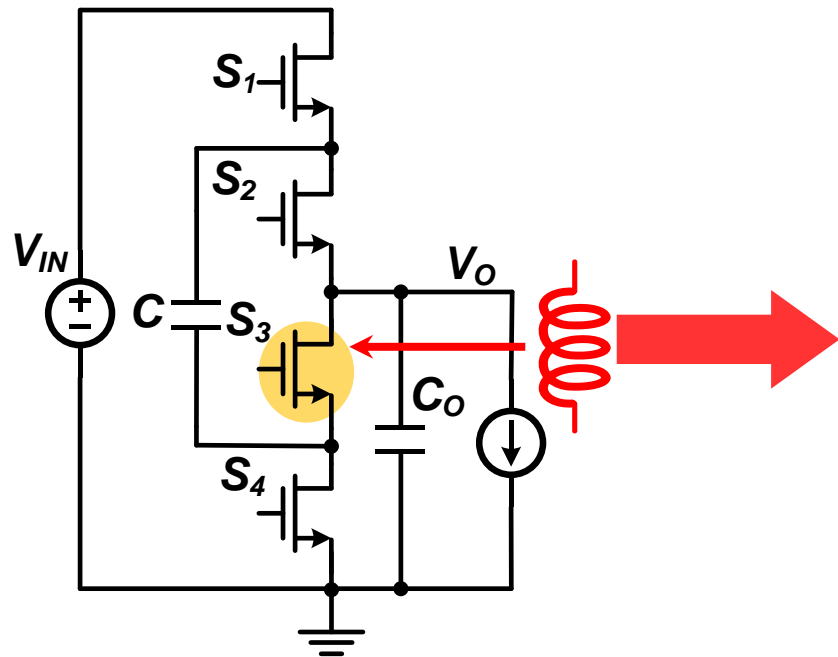
L replaces S<sub>3</sub>



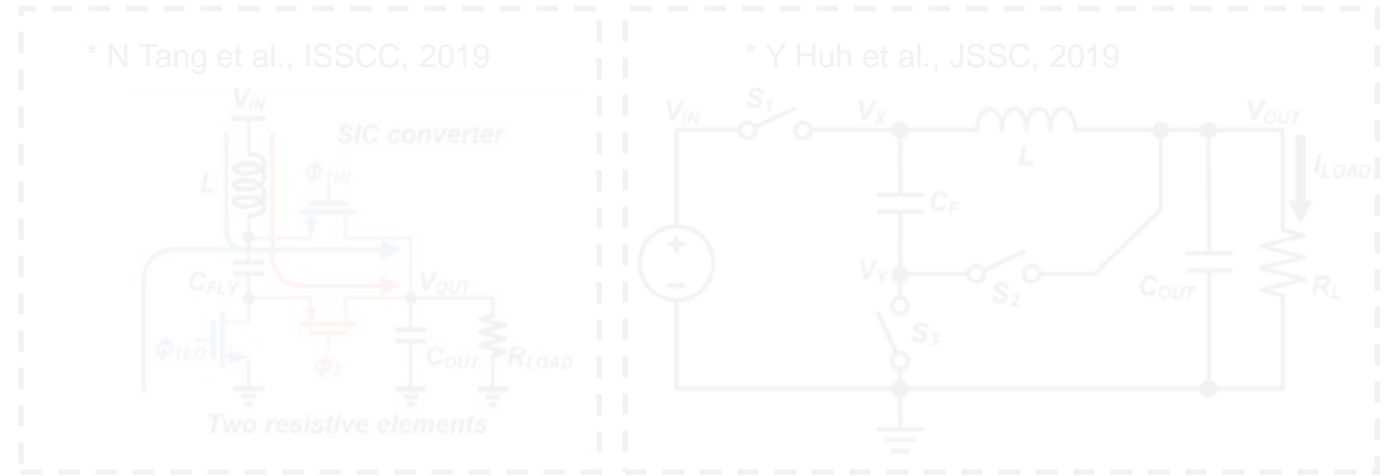
L replaces S<sub>4</sub>

# Construction Summary 1

## L Replacement in SC Converters



2:1 SC Converter

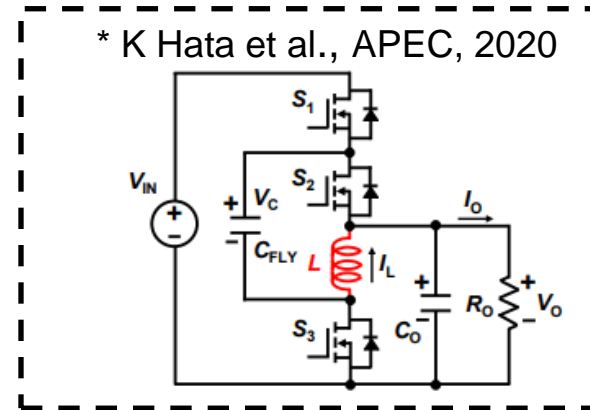


\* N Tang et al., ISSCC, 2019

\* Y Huh et al., JSSC, 2019

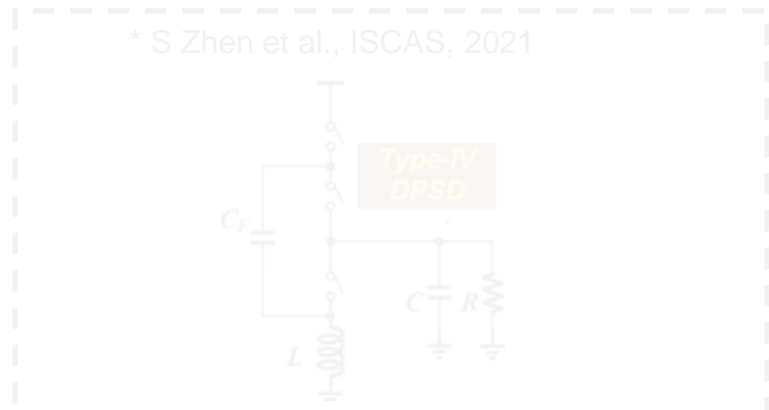
SIC converter  
Two resistive elements

L replaces  $S_2$



\* K Hata et al., APEC, 2020

L replaces  $S_3$

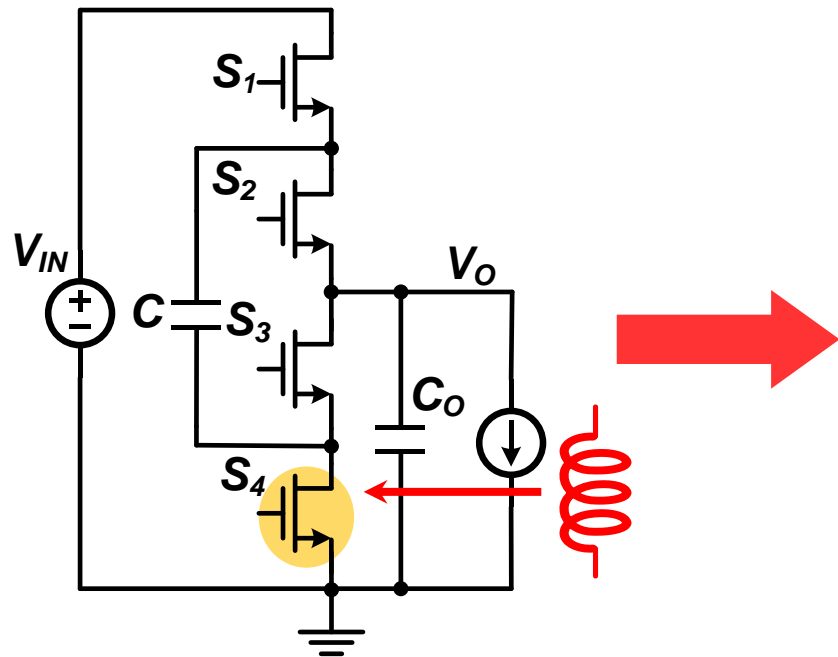


\* S Zhen et al., ISCAS, 2021

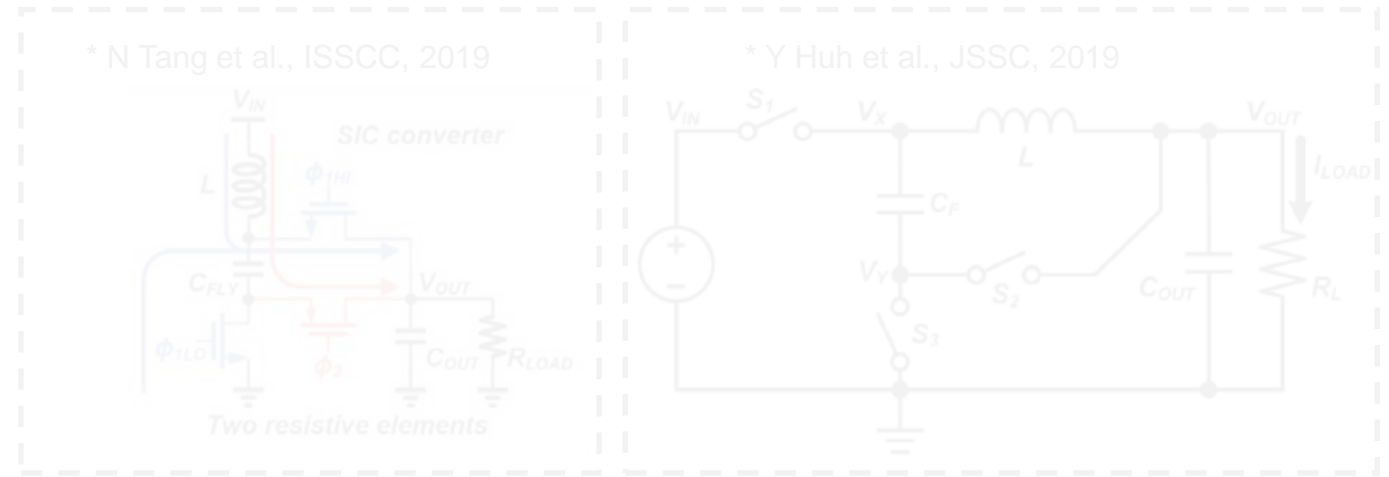
L replaces  $S_4$

# Construction Summary 1

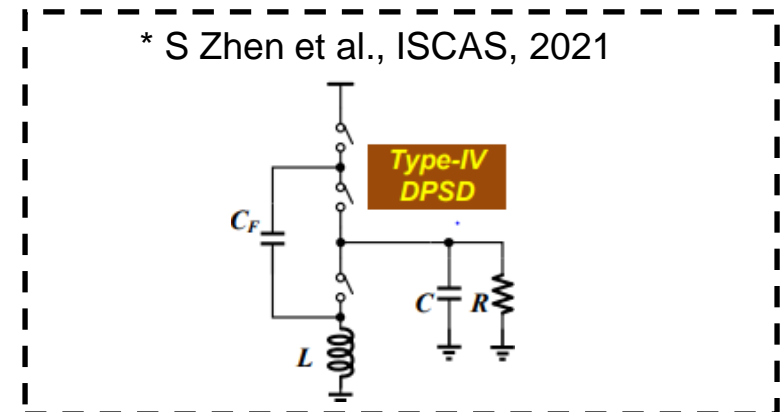
## L Replacement in SC Converters



2:1 SC Converter



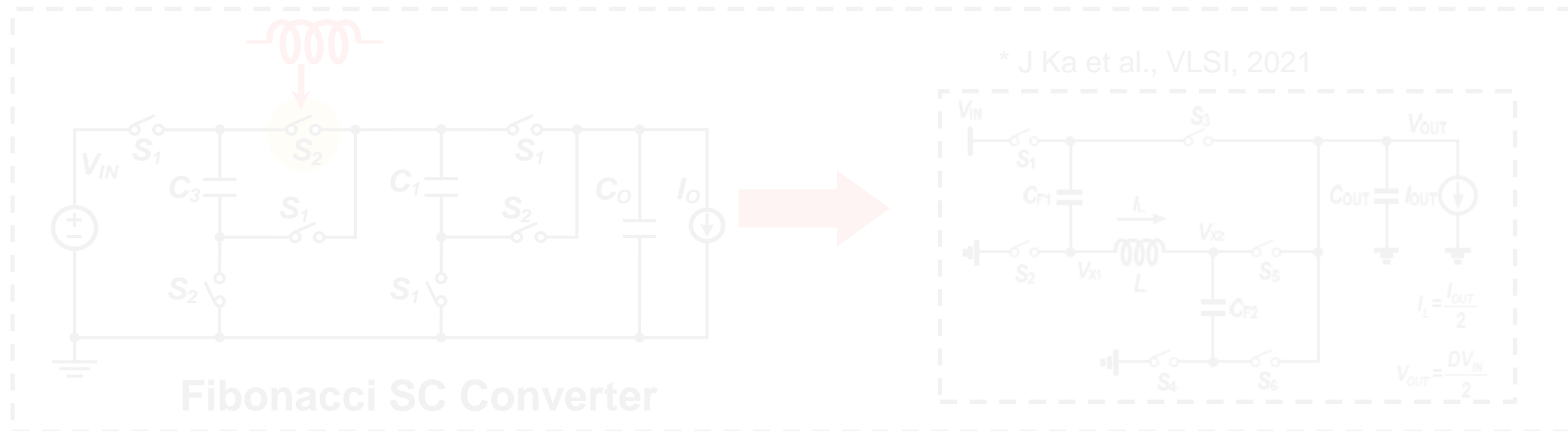
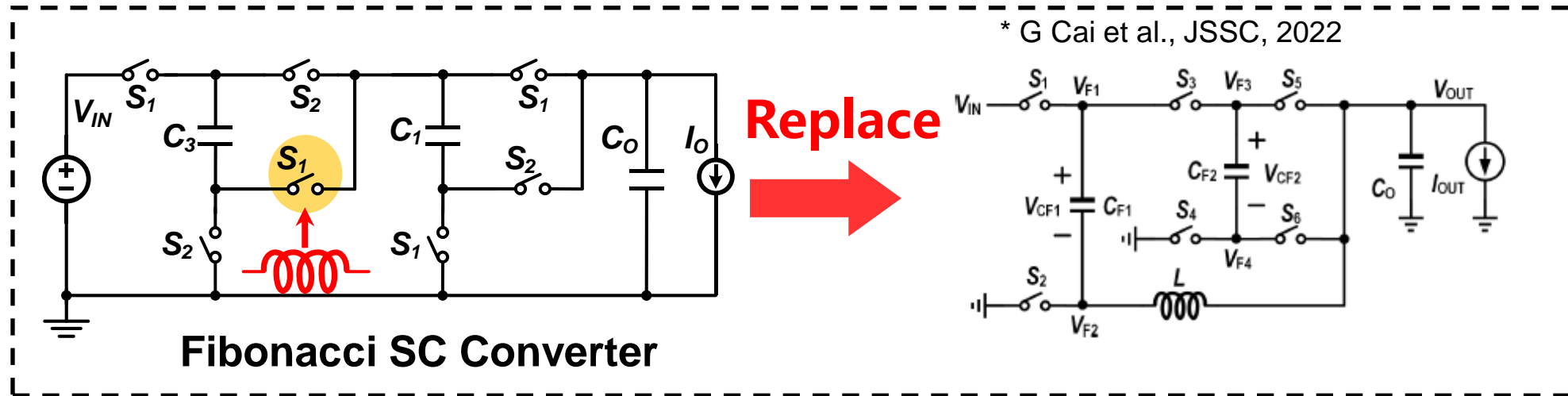
L replaces S<sub>3</sub>



L replaces S<sub>4</sub>

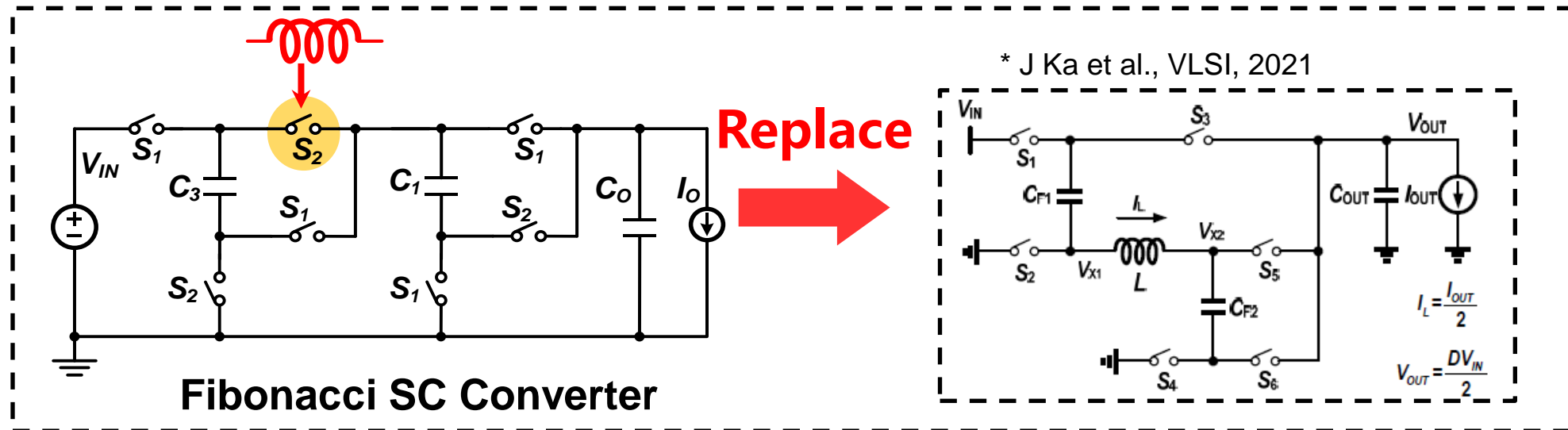
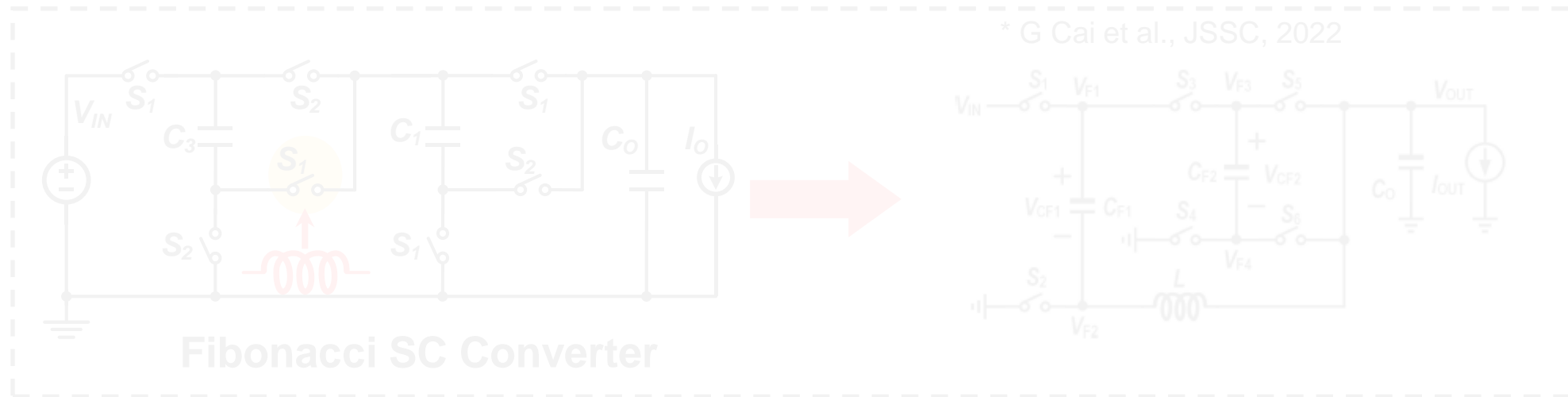
# Construction Summary 1

## L Replacement in SC Converters



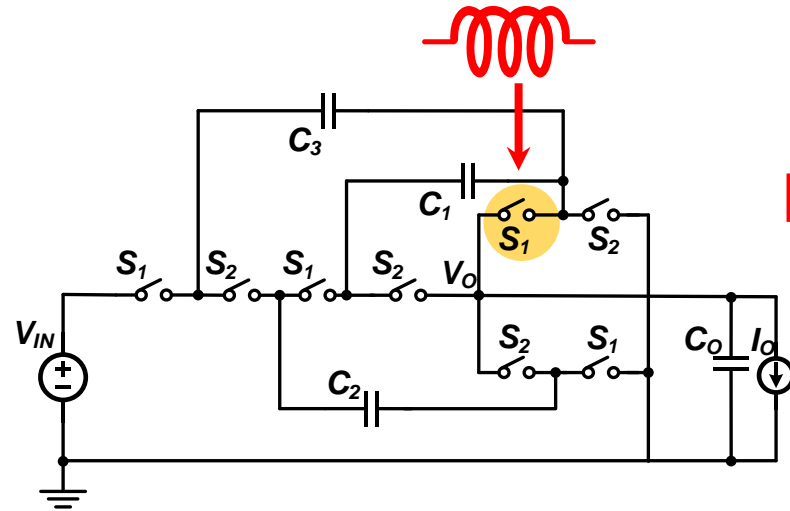
# Construction Summary 1

## L Replacement in SC Converters



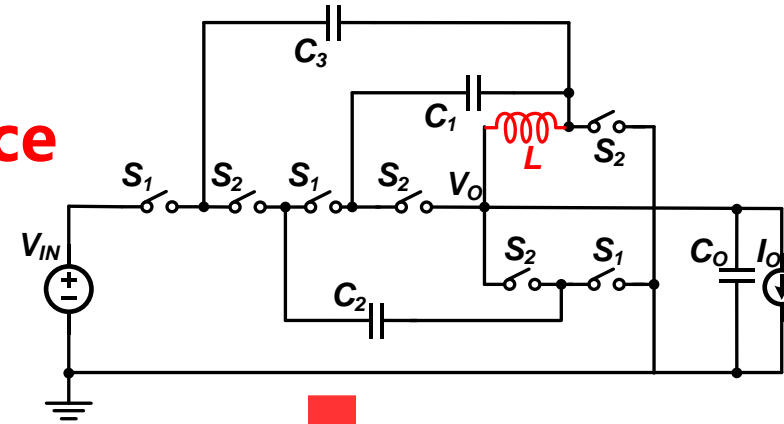
# Construction Summary 1

## L Replacement in SC Converters

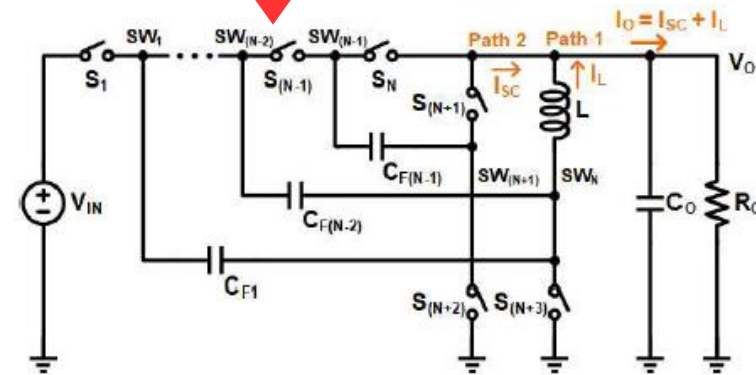


Dickson SC Converter

Replace



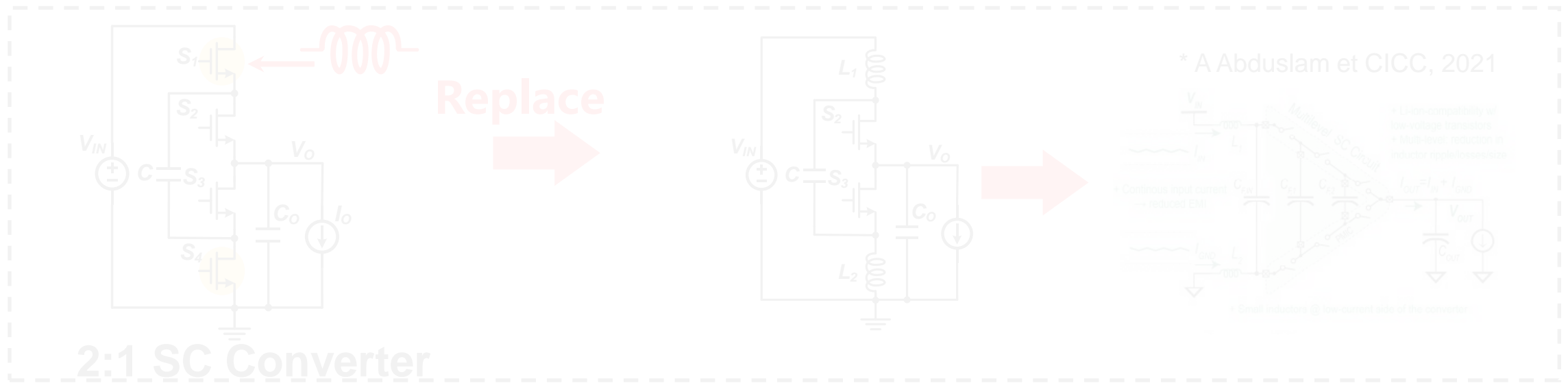
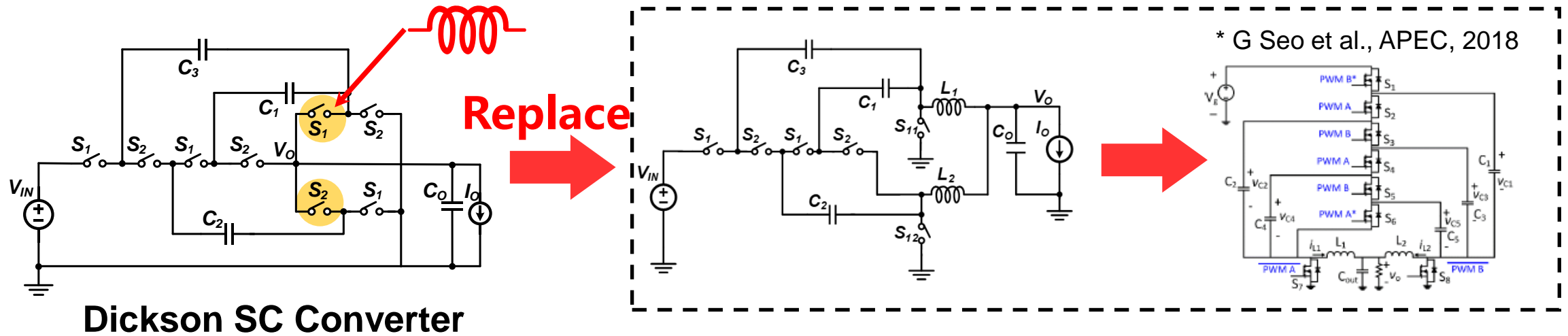
\* C Chen et al., ECCE, 2021



Dual-Path Hybrid Dickson Converter

# Construction Summary 1

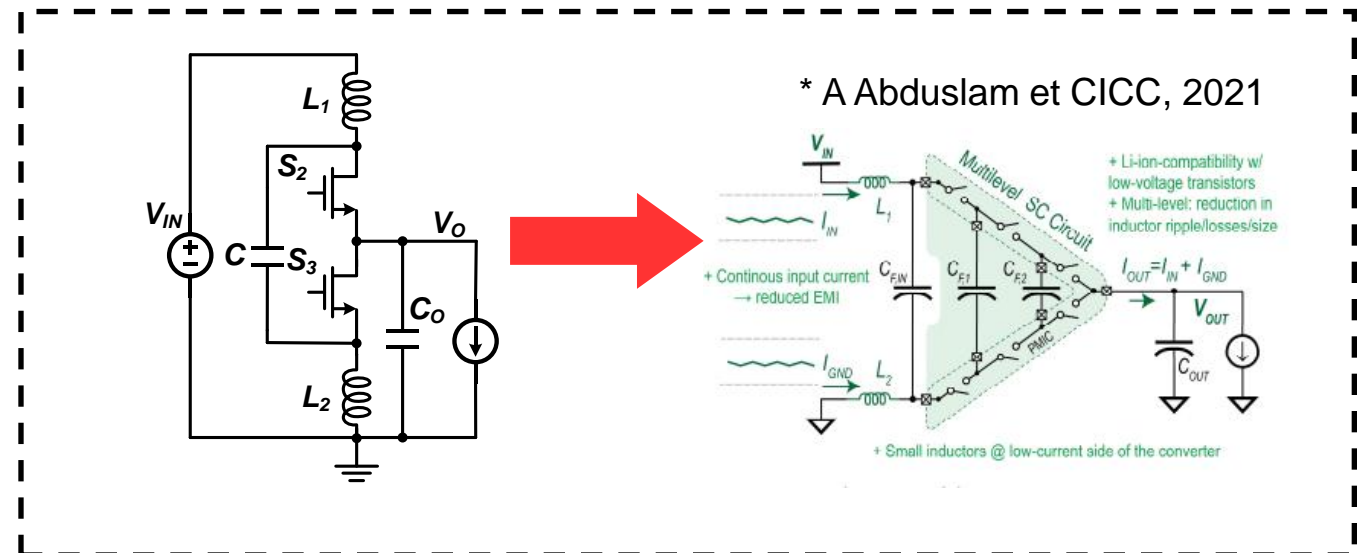
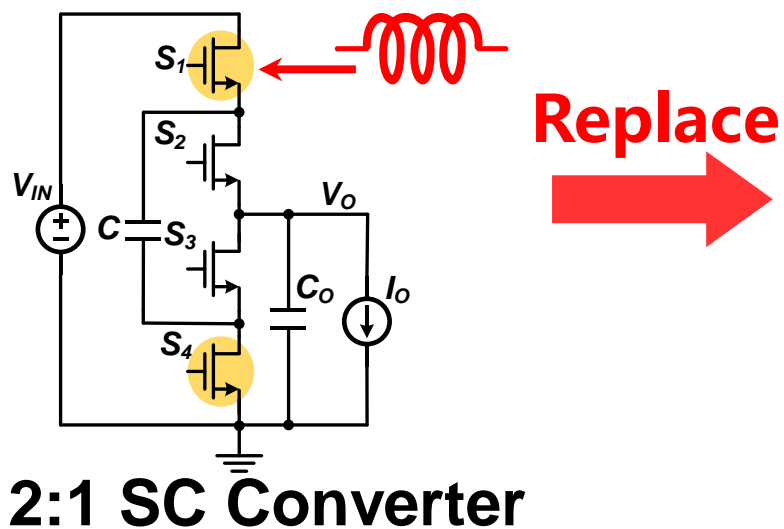
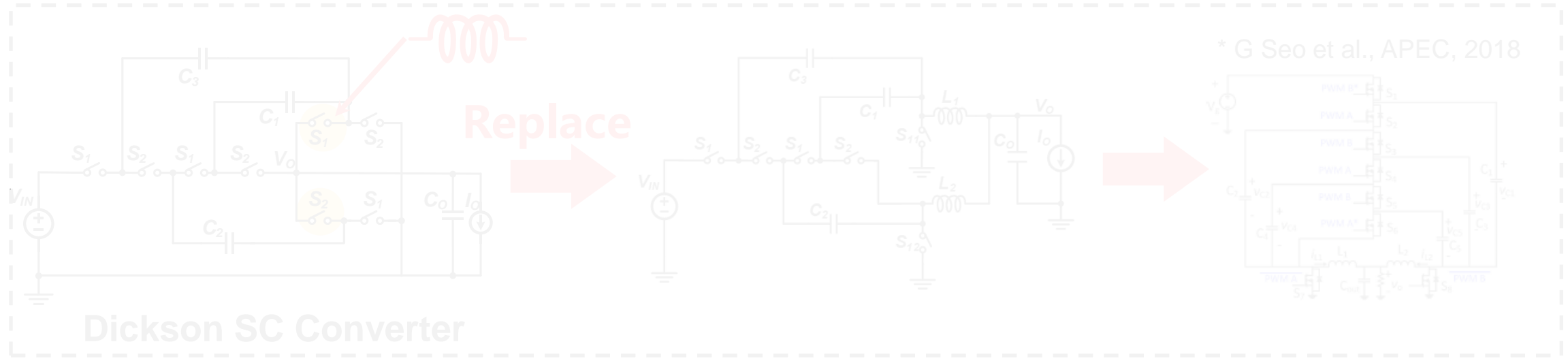
## L Replacement in SC Converters





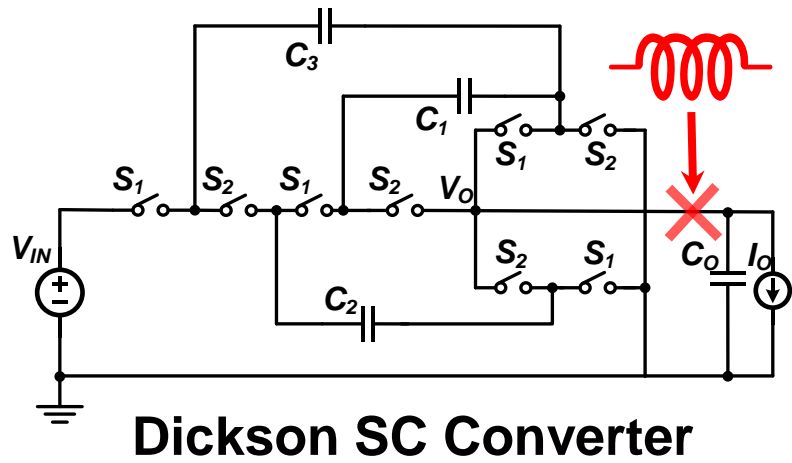
# Construction Summary 1

## L Replacement in SC Converters

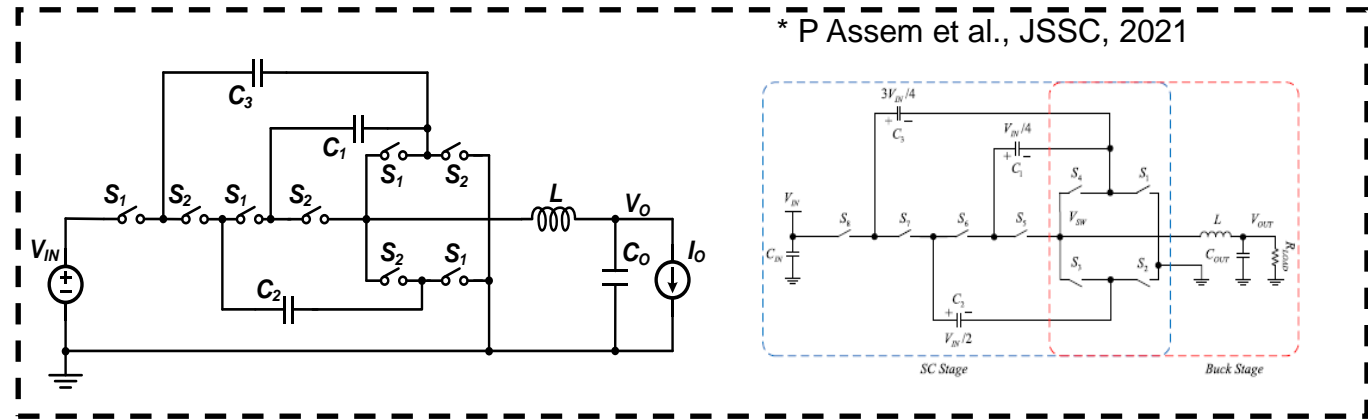


# Construction Summary 2

## L Insertion in SC Converters



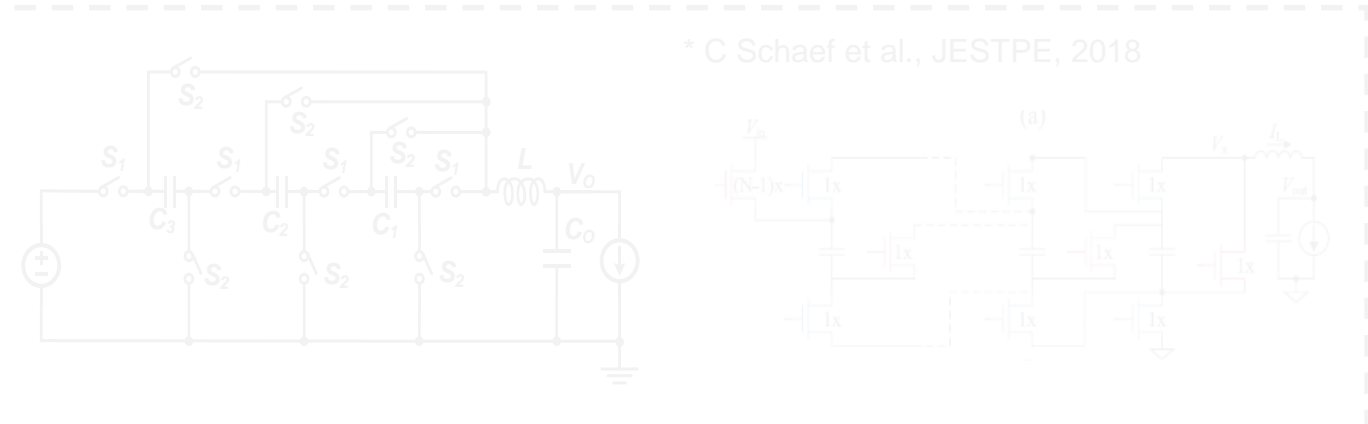
Insert



## Hybrid Dickson Converter

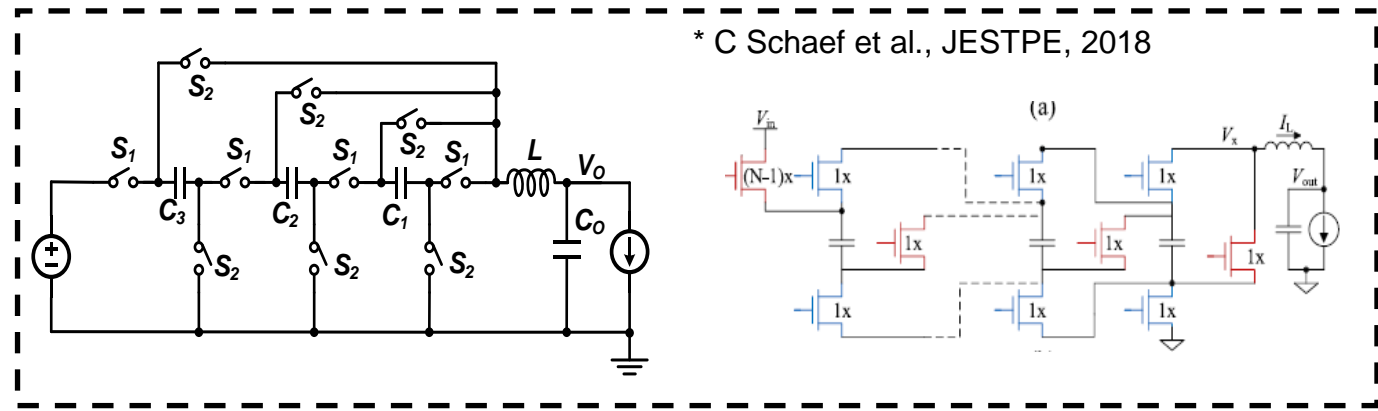
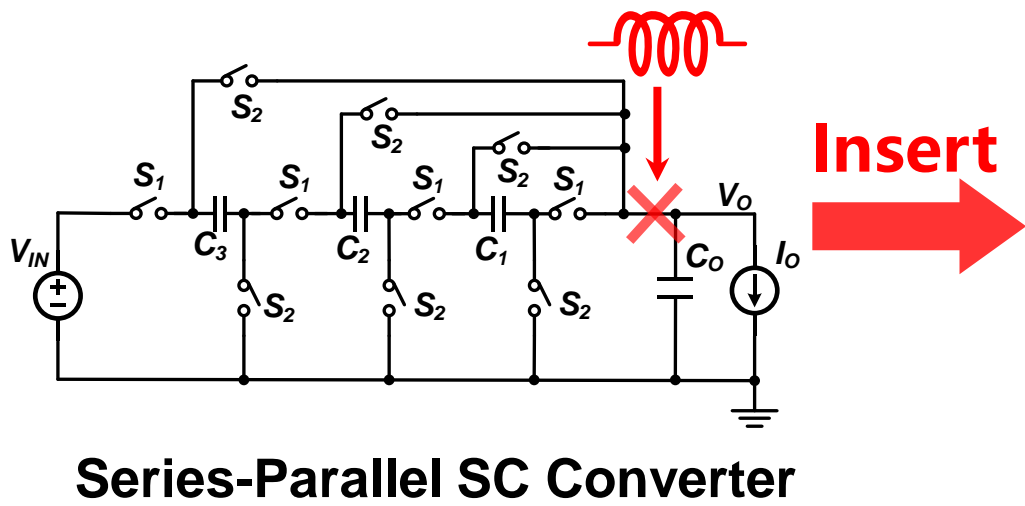
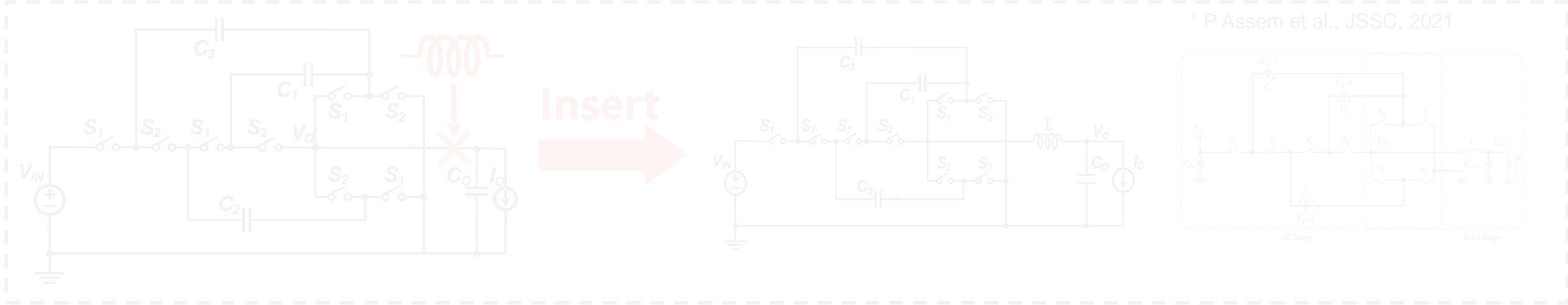


Insert



# Construction Summary 2

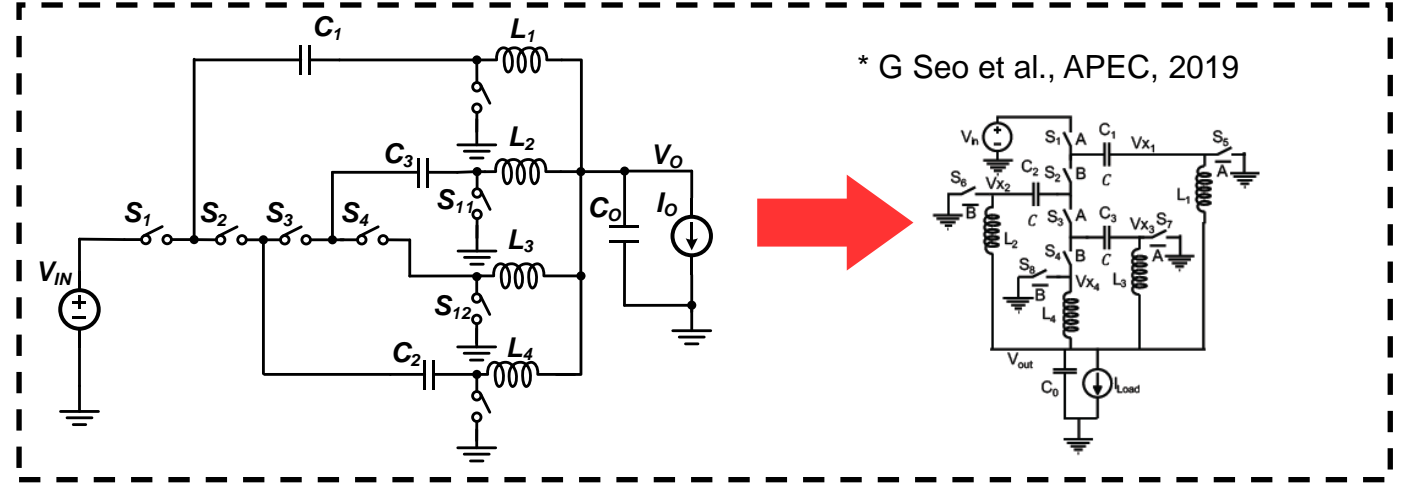
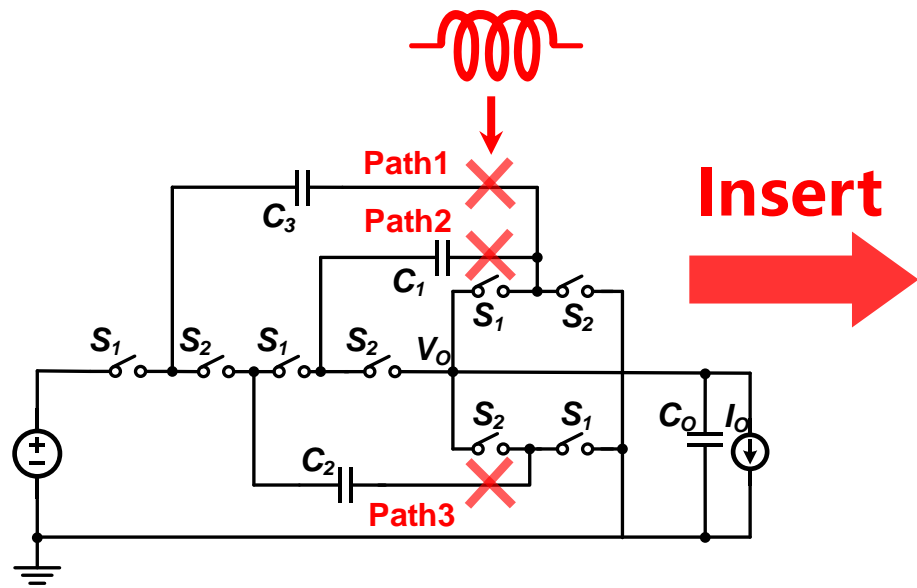
## L Insertion in SC Converters



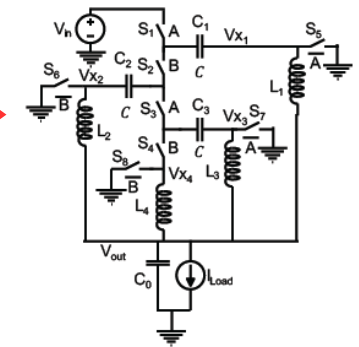
## Hybrid Series-Parallel Converter

# Construction Summary 2

## L Insertion in SC Converters



\* G Seo et al., APEC, 2019



# Construction Summary 3

## Buck Type

\* N Tang et al., ISSCC, 2019

\* Y Huh et al., JSSC, 2019

\* K Hata et al., APEC, 2020

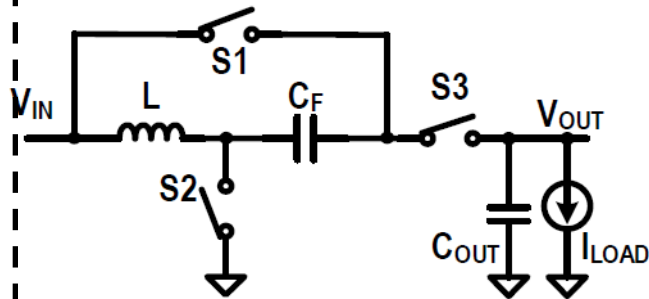
\* S Zhen et al., ISCAS, 2021

Inductor replacement and insertion still **NOT ENOUGH!**

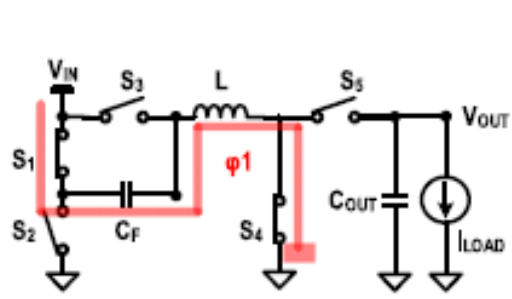


Summary 1 and 2 cannot guide the following designs.

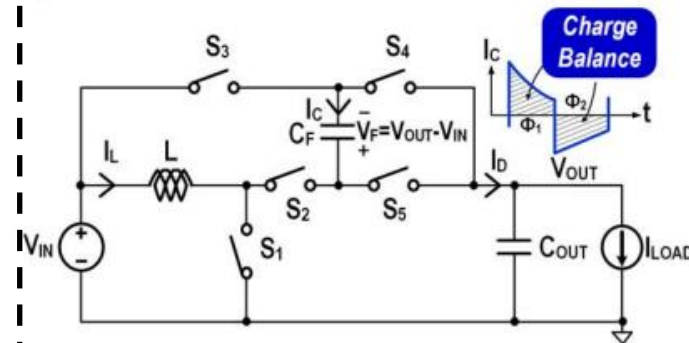
\* Y Lin et al., ISSCC, 2021



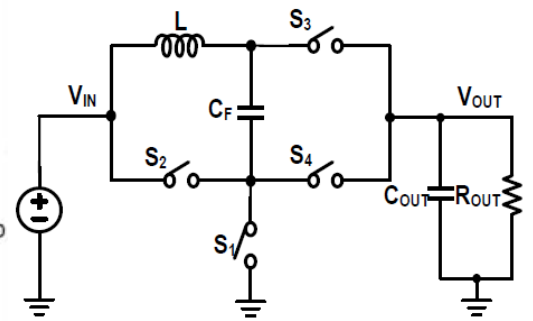
\* Si Li et al., JSSC, 2023



\* S Shin et al., ISSCC, 2018



\* J Jin et al., ISSCC, 2023

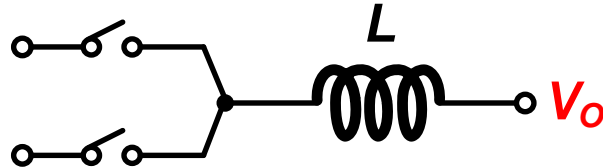


# Construction Summary 3

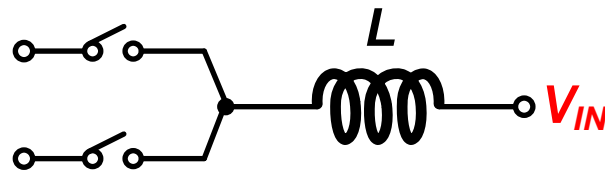
## $L + C$ Combinations

### ■ Assumption: one of the inductor ports connects to DC

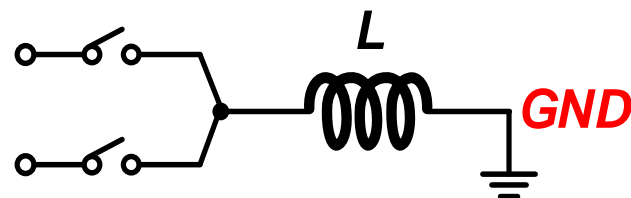
- Connect to  $V_O$



- Connect to  $V_{IN}$



- Connect to Ground

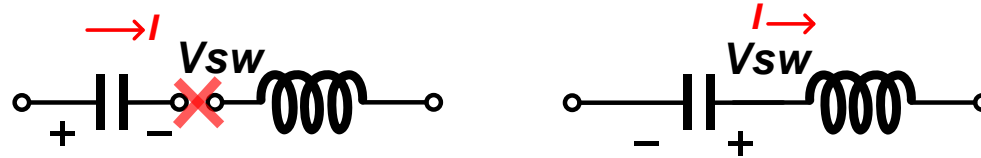


# Construction Summary 3

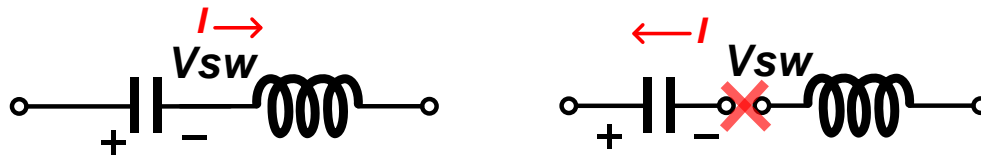
## L + C Combinations

### ■ Cap charge/discharge in three conditions:

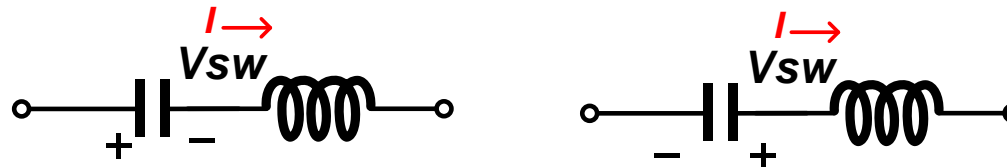
- Charge without  $L$ , discharge with  $L$



- Charge with  $L$ , discharge without  $L$

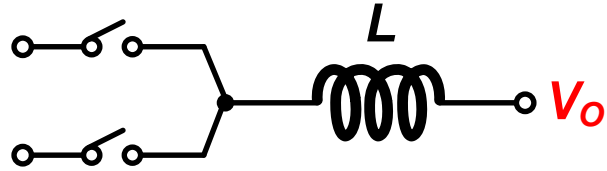


- Charge and discharge both with  $L$

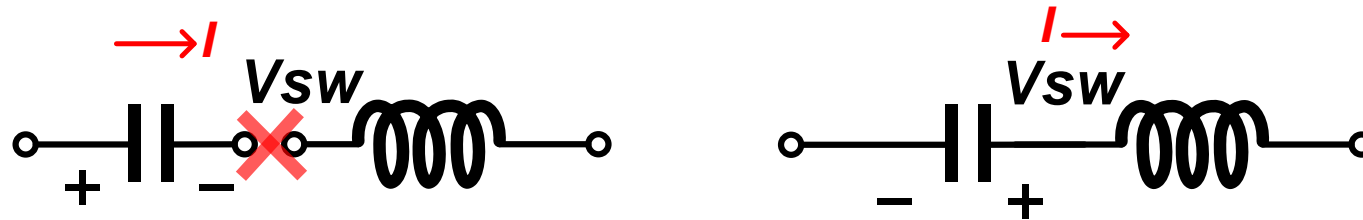


# Construction Example

- Assumption: One of  $L$  ports connects to output
  - Connect to  $V_o$



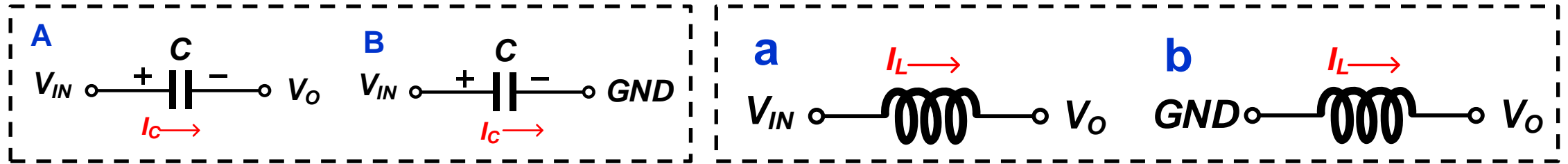
- Cap charge/discharge conditions
  - Charge without  $L$ , discharge with  $L$



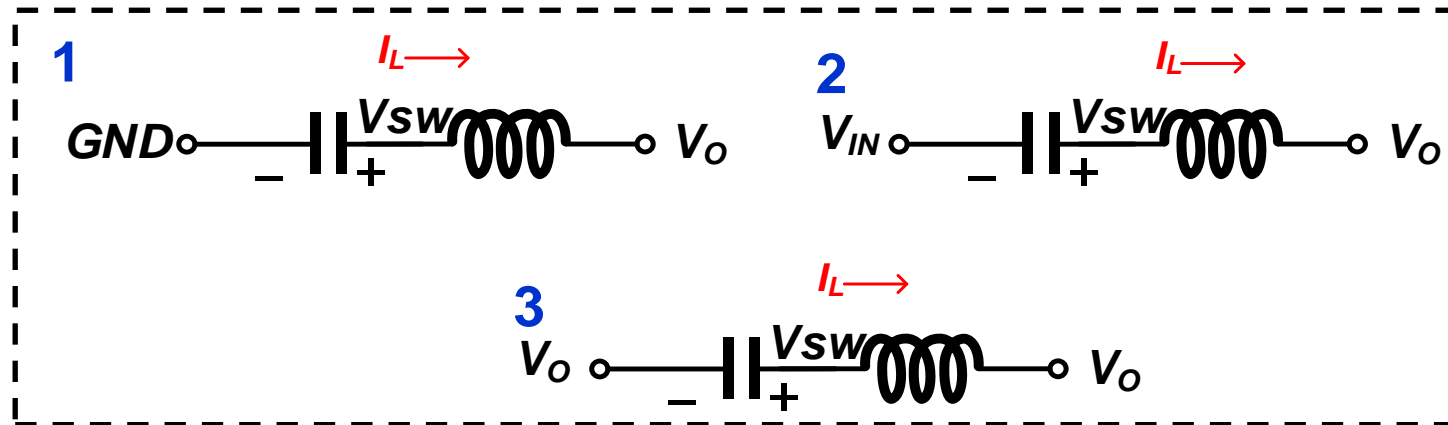


# Construction Example (2 phase)

## ■ $\Phi_1$ : Cap charge without $L$

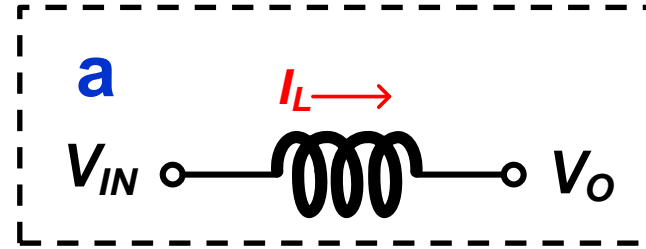
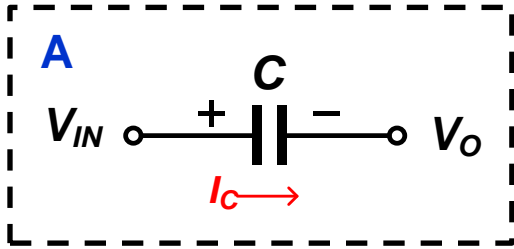


## ■ $\Phi_2$ : Flying Cap Discharge with $L$

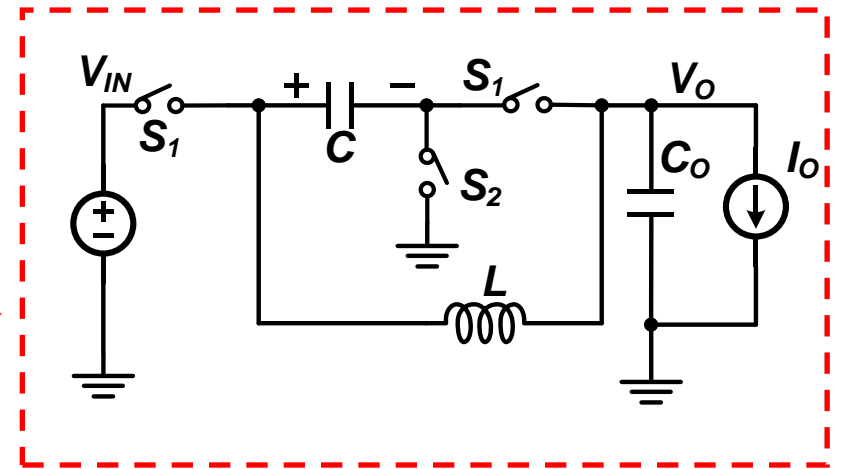
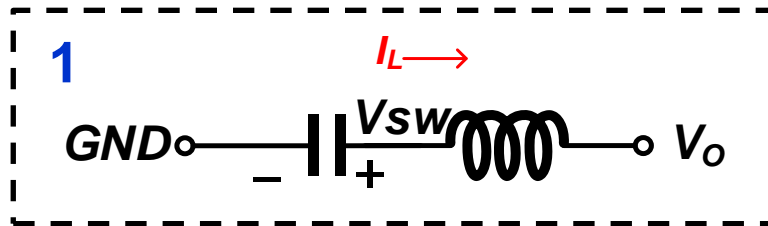


# Construction Example

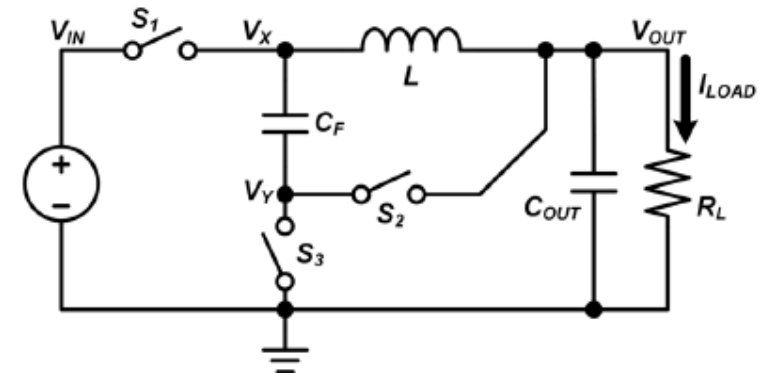
- $\Phi_1$ : Select “A” and “a”



- $\Phi_2$ : Select “1”

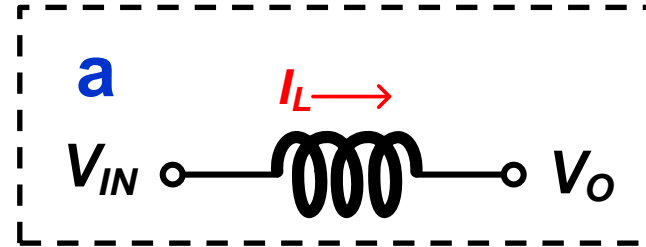
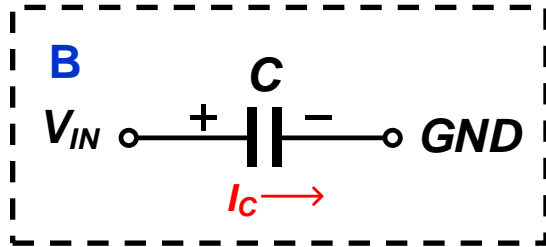


\* Y Huh et al., JSSC, 2019

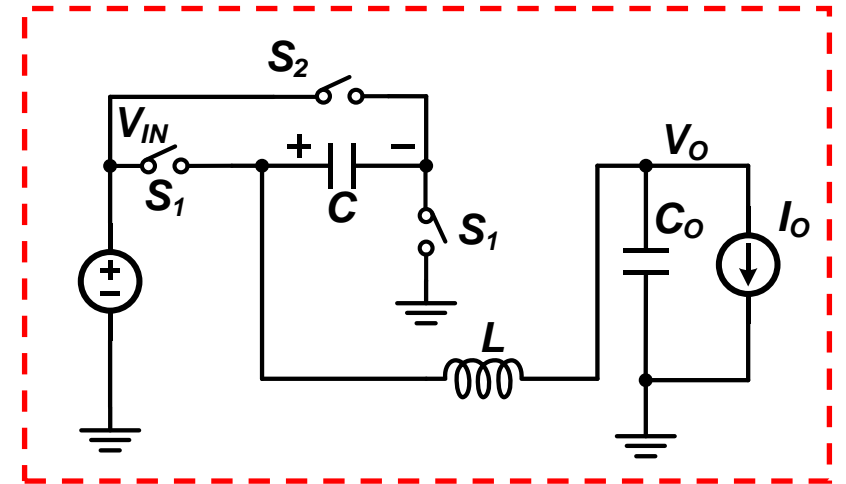
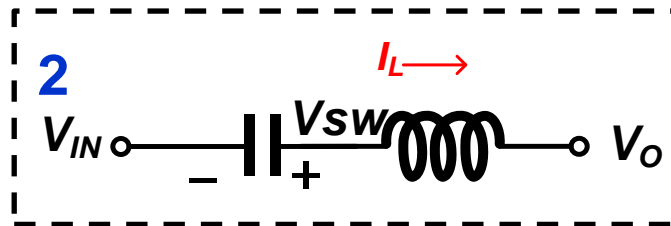


# Construction Example

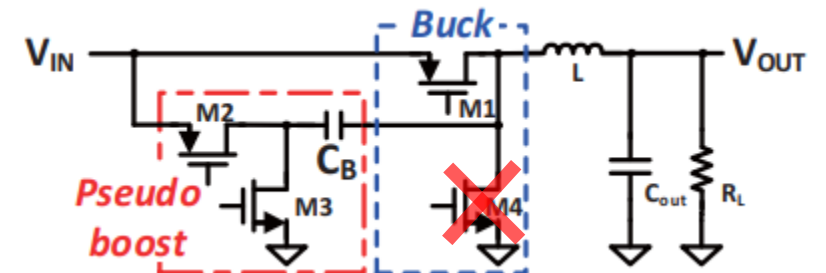
- $\Phi_1$ : Select “B” and “a”



- $\Phi_2$ : Select “2”

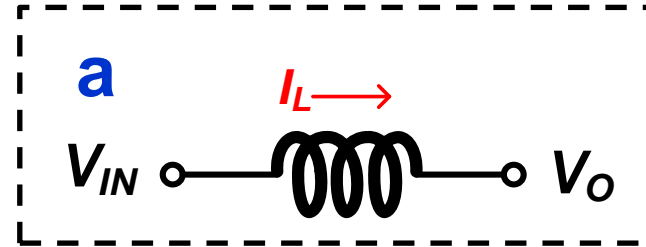
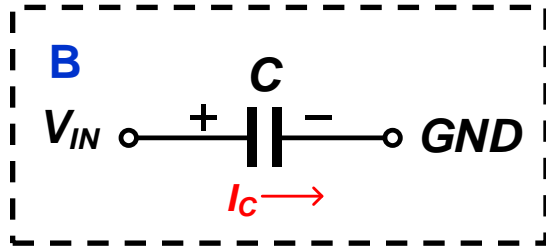


\* Y Lin et al., VLSI, 2019

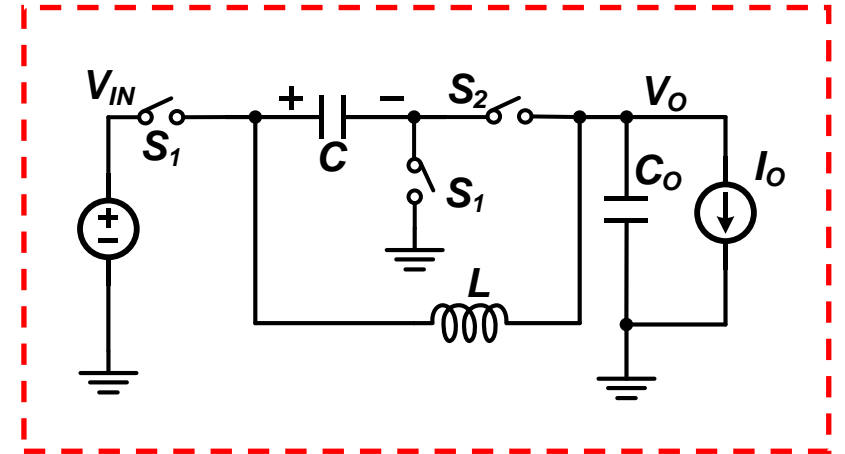
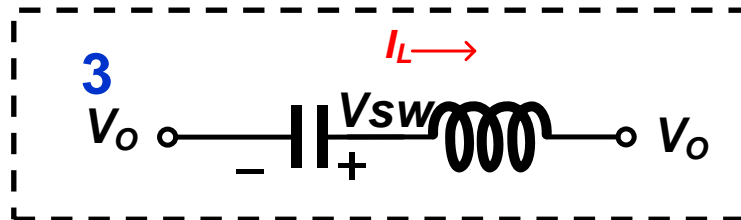


# Construction Example

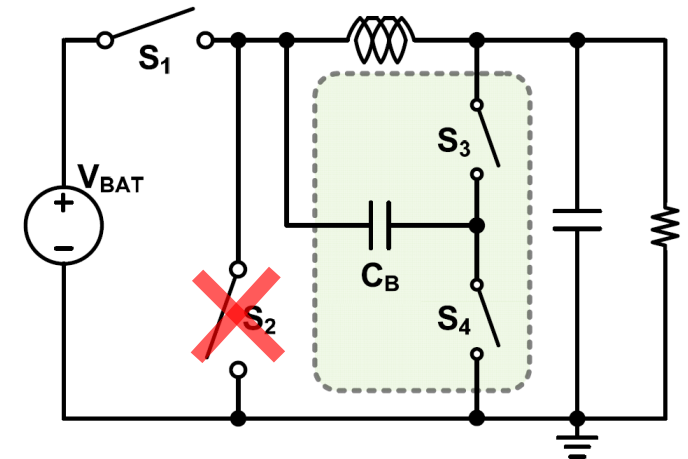
- $\Phi_1$ : Select “B” and “a”



- $\Phi_2$ : Select “3”



\* Y Ju et al., ISSCC, 2017



**$L + C$  combination scheme renders  
a less intuitive but more complete strategy.**

## ■ Summary of Hybrid Converters Constructions

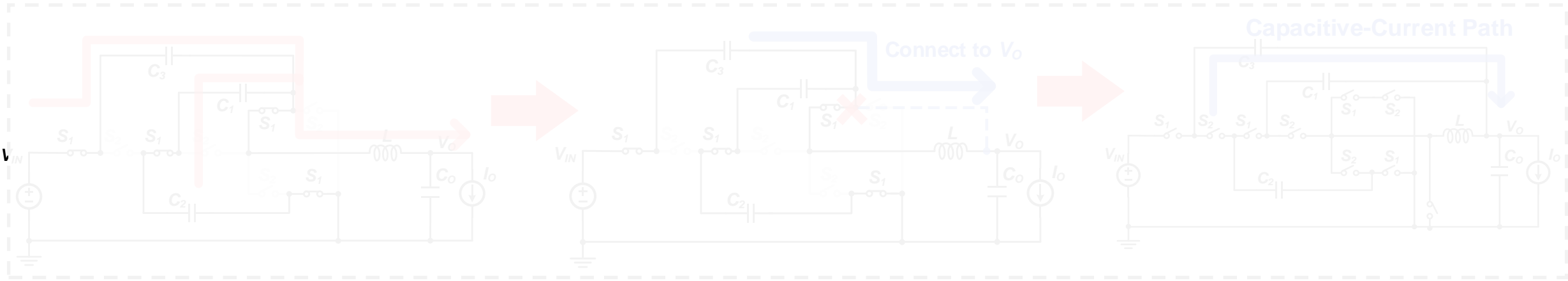
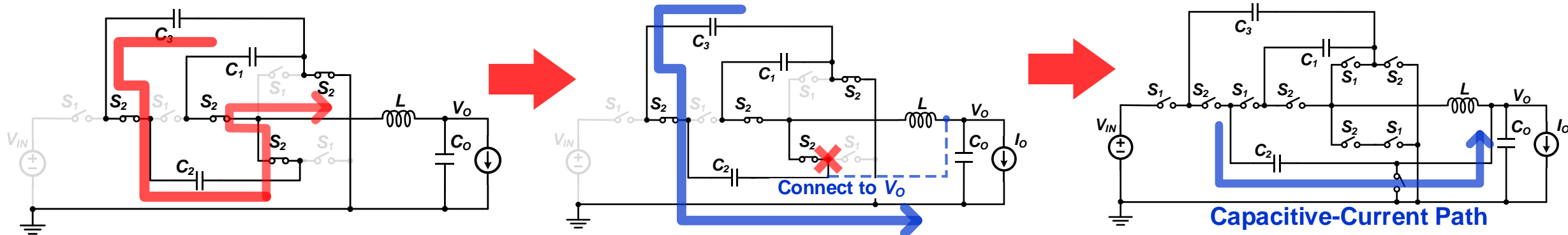
- $L$  Replacement in SC Converters
- $L$  Insertion in SC Converters
- $L + C$  Combinations
- Other Extensions

## ■ 12V/1V Hybrid DC-DC Converter

- Prior 12V/1V Hybrid Converters
- Proposed 12V/1V DPSC Converter

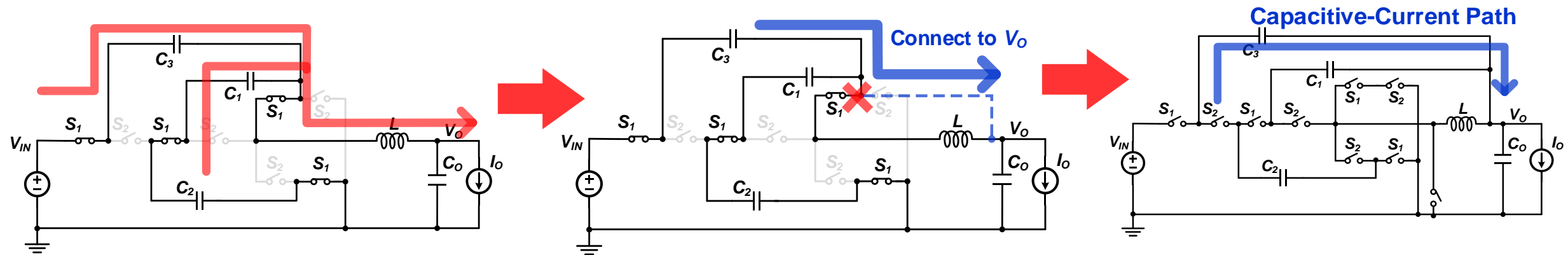
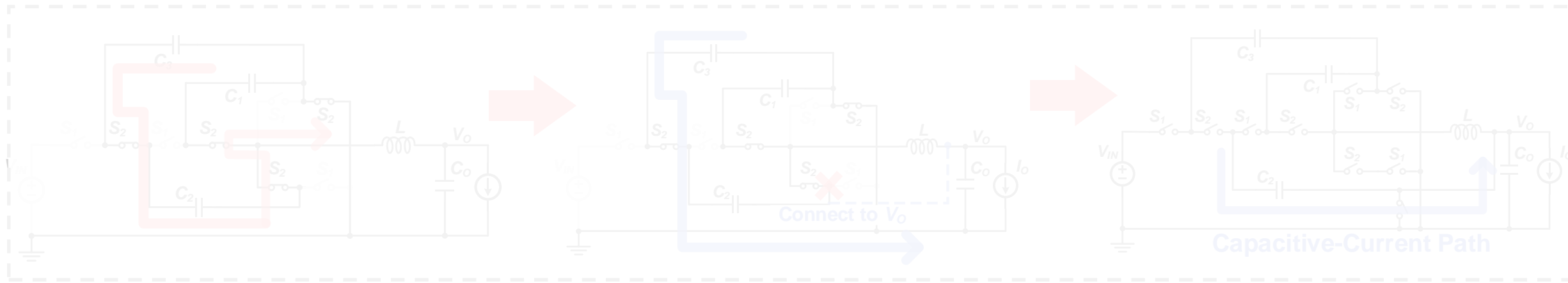
# Ext-1: Dual-Path Hybrid Converter

## Ext-1: Capacitive-Current Path Directly Connect to Output



# Ext-1: Dual-Path Hybrid Converter

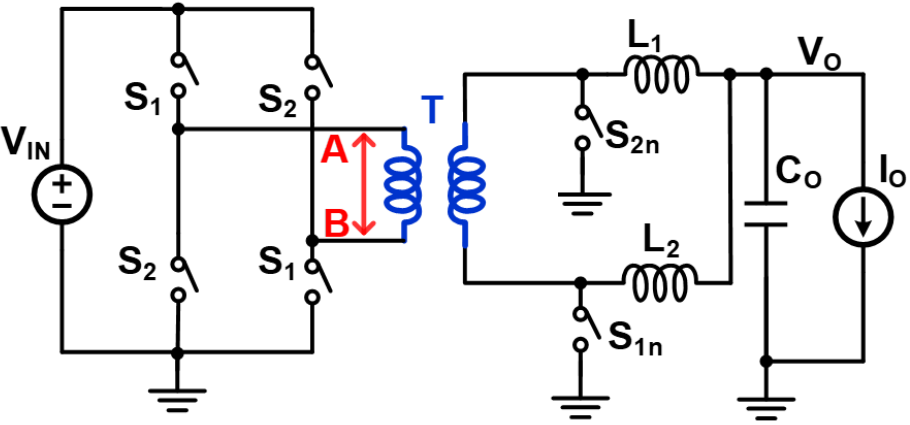
## Ext-1: Capacitive-Current Path Directly Connect to Output



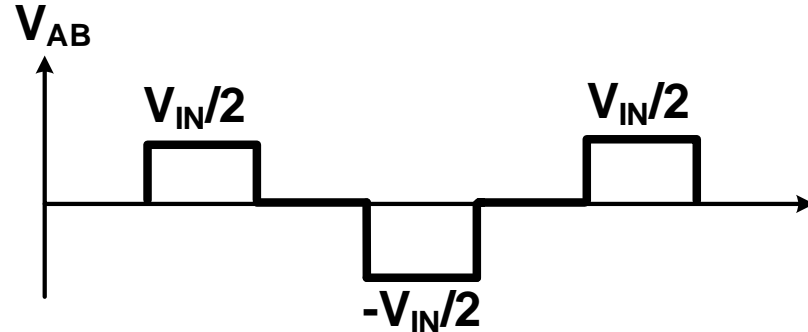
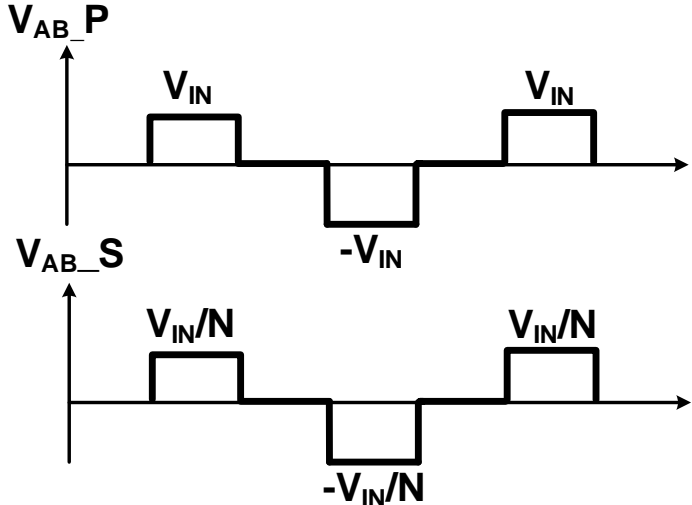
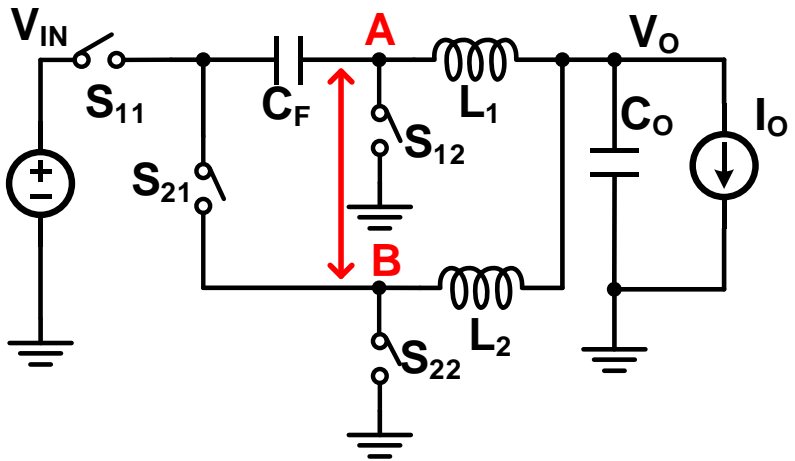


# Ext-2: Isolated Hybrid Converter

Full Bridge Converter



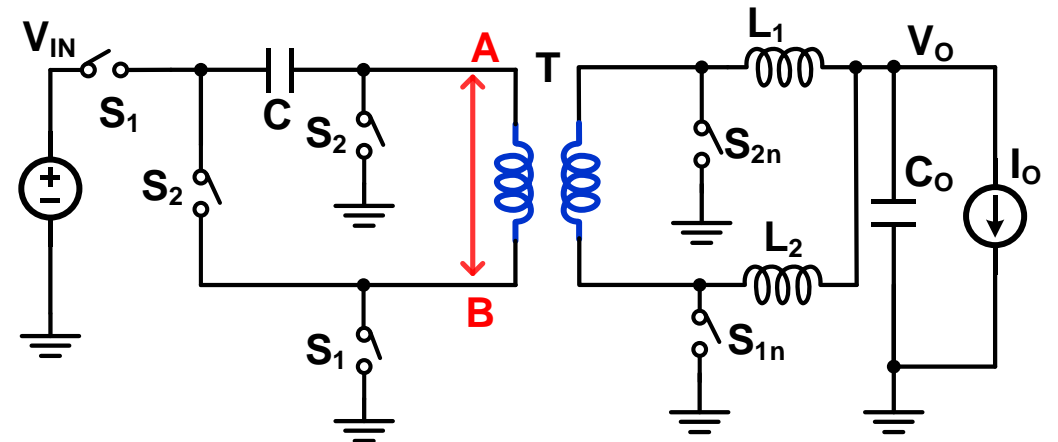
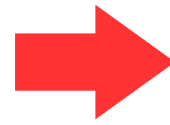
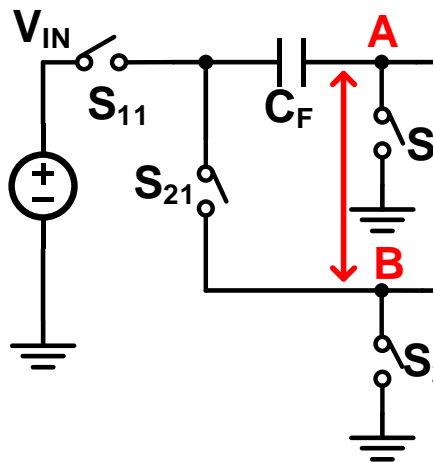
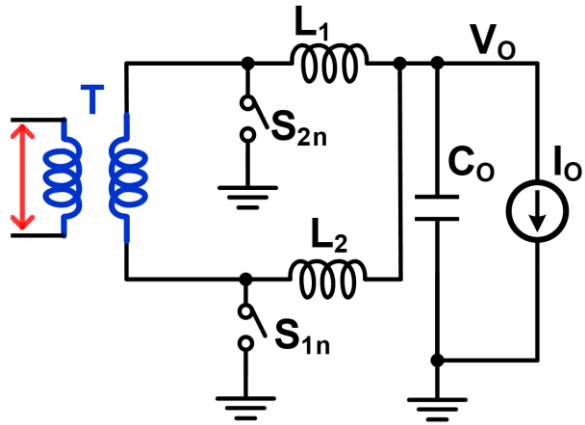
Series-Capacitor Converter



Same voltage swings

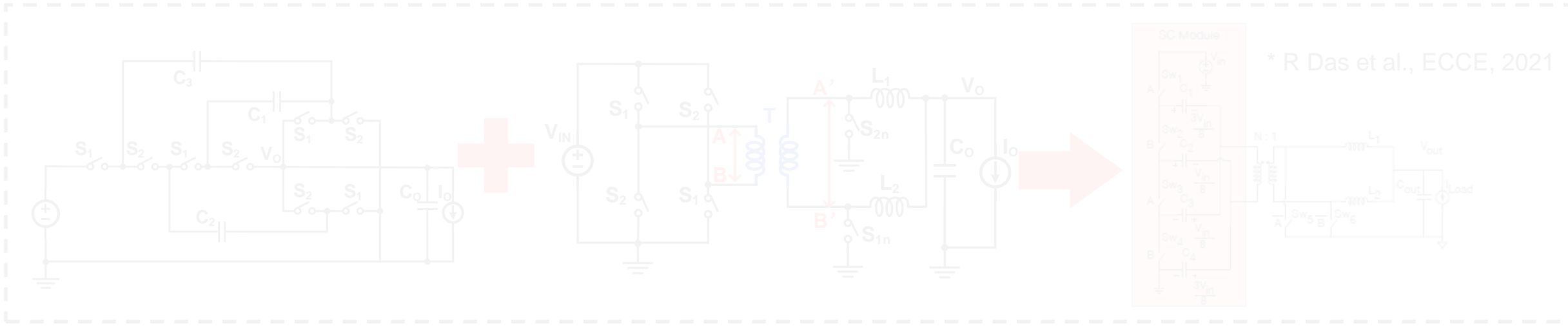
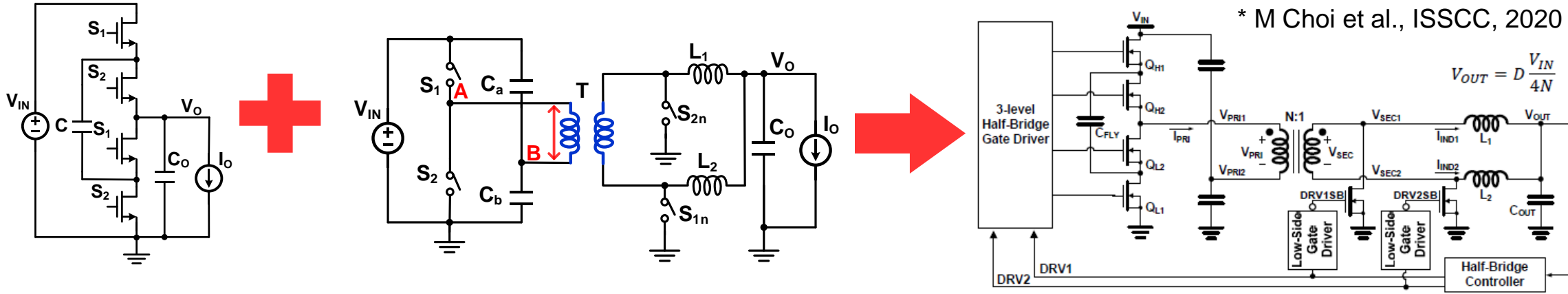
# Ext-2: Isolated Hybrid Converter

## Ext-2: SC Converter Replace Primary Switches

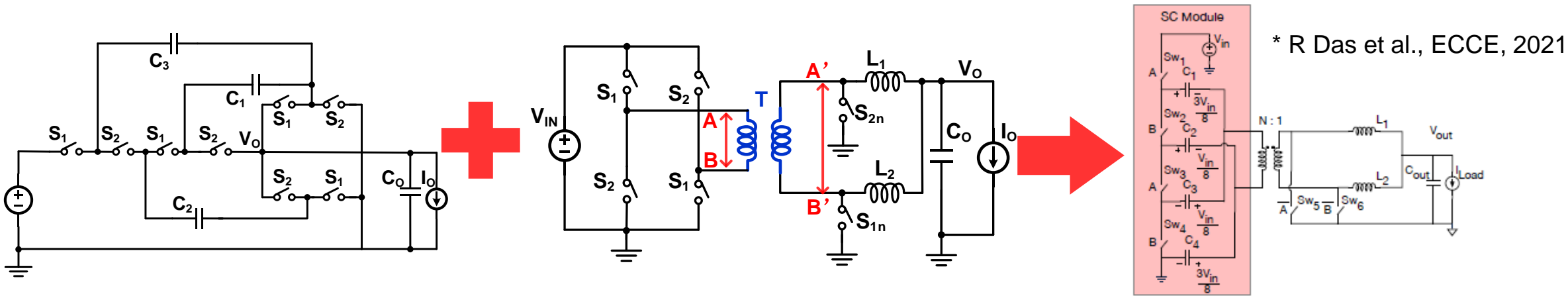
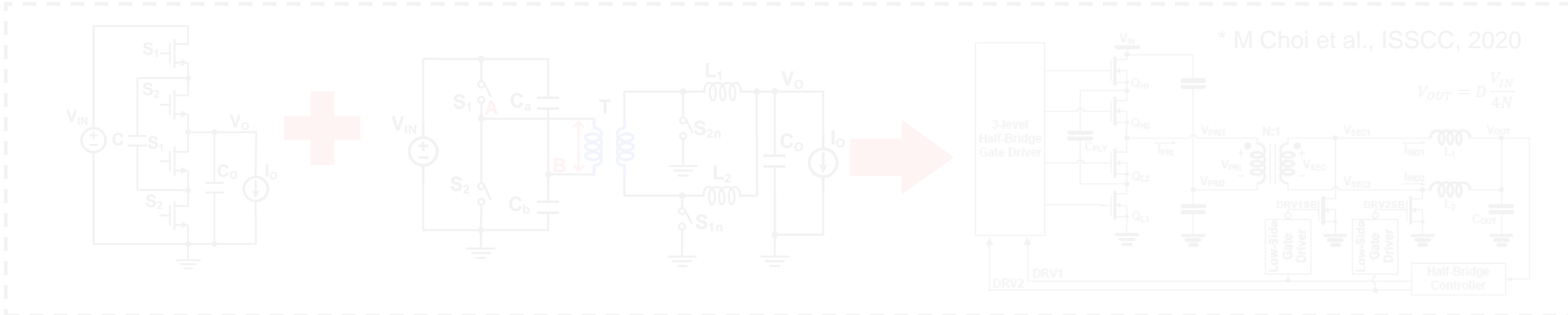


**Full Bridge Isolated Hybrid Converter**

# Ext-2: Isolated Hybrid Converter



# Ext-2: Isolated Hybrid Converter



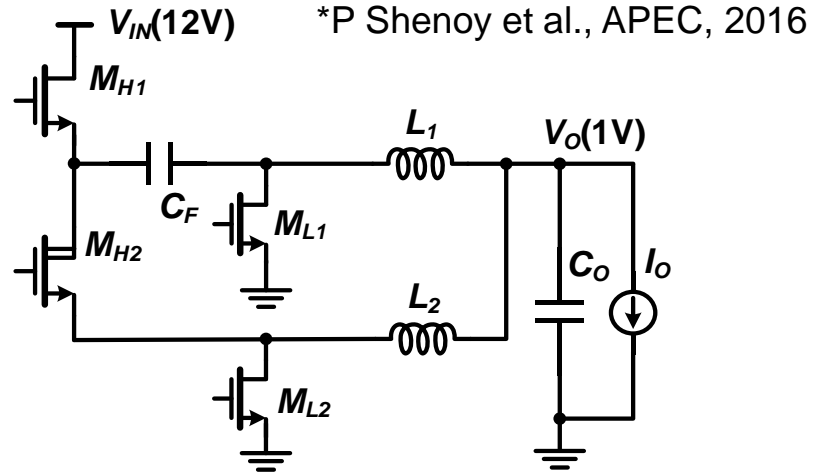
## ■ Summary of Hybrid Converters Constructions

- $L$  Replacement in SC Converters
- $L$  Insertion in SC Converters
- $L + C$  Combinations
- Other Extensions

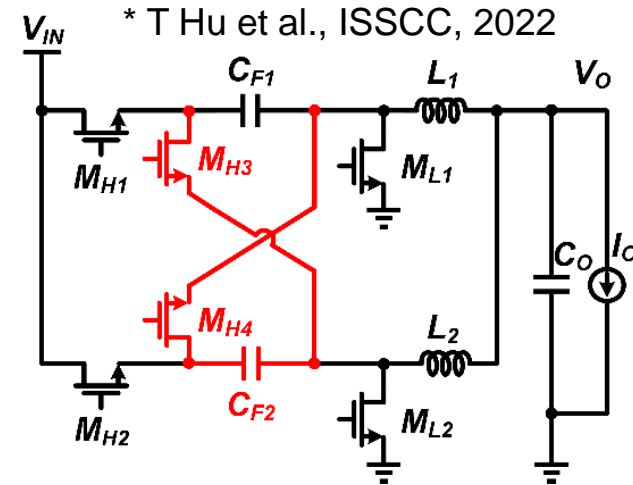
## ■ 12V/1V Hybrid DC-DC Converter

- Prior 12V/1V Hybrid Converters
- Proposed 12V/1V DPSC Converter

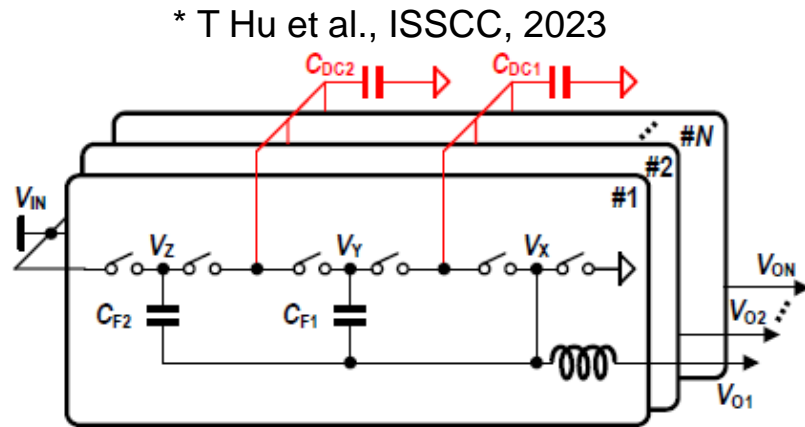
# Prior 12V/1V Hybrid PMIC



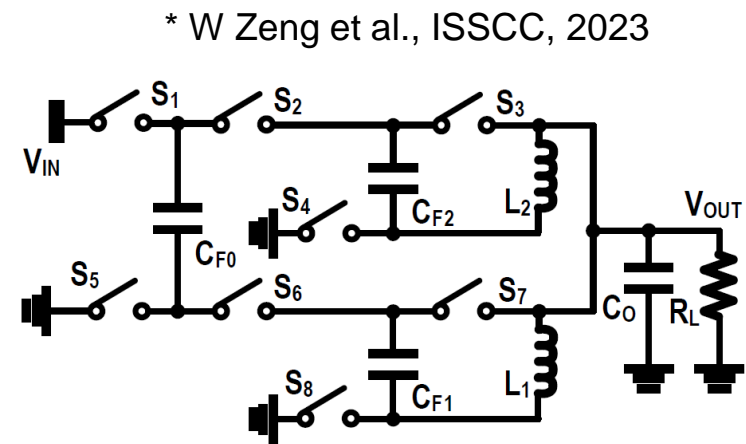
**Series-Capacitor Converter**



**Capacitor Cross-Connected Converter**

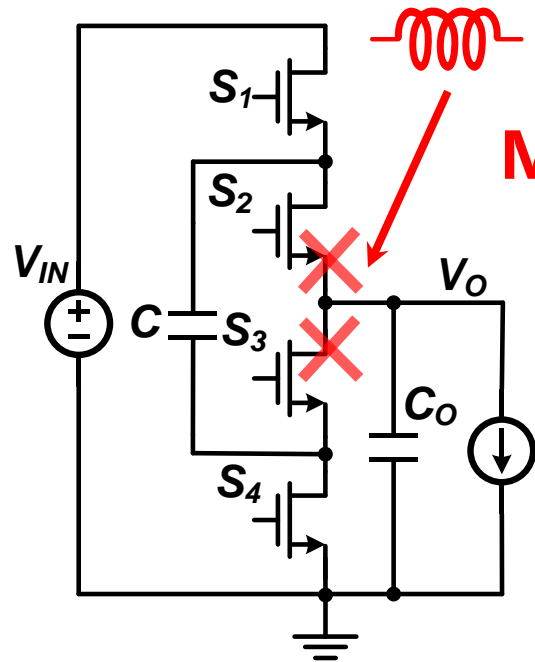


**Quad-Output SC Converter**

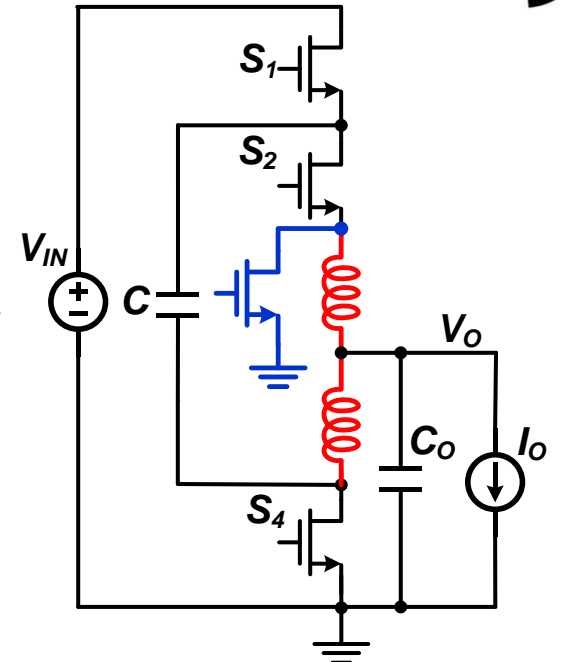
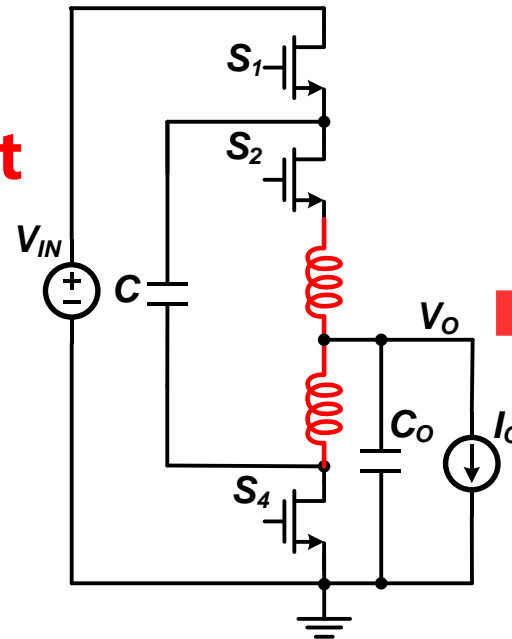


**Dual-Inductor Quad-Path SC Converter**

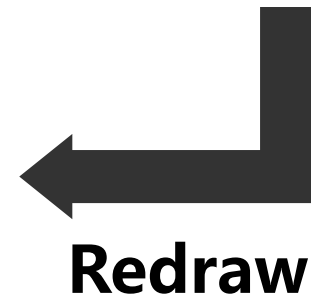
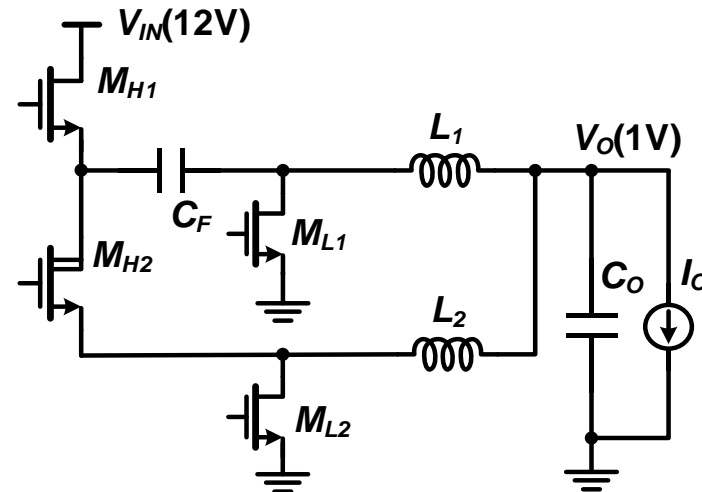
# Series-Capacitor Converter



Make both current path inductive

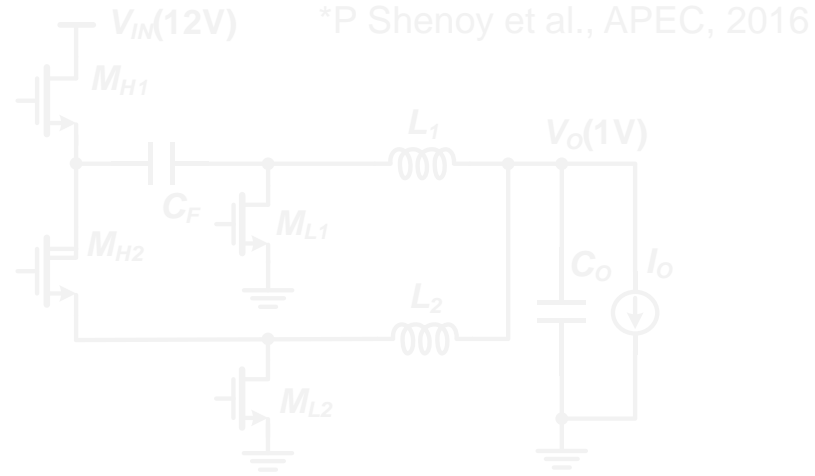


- Auto Current Balance
- Low Voltage Stress
- Double Duty Cycle

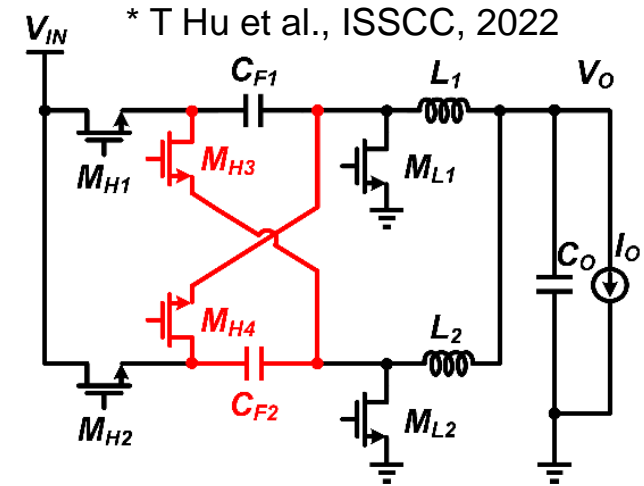


Series-Capacitor Converter

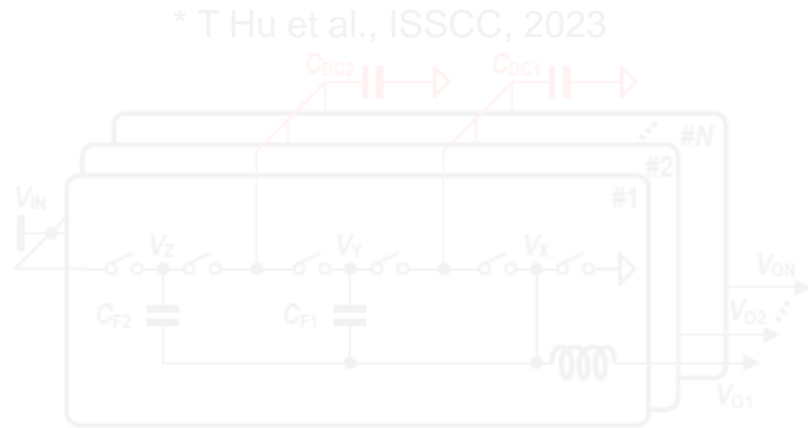
# Prior 12V/1V Hybrid PMIC



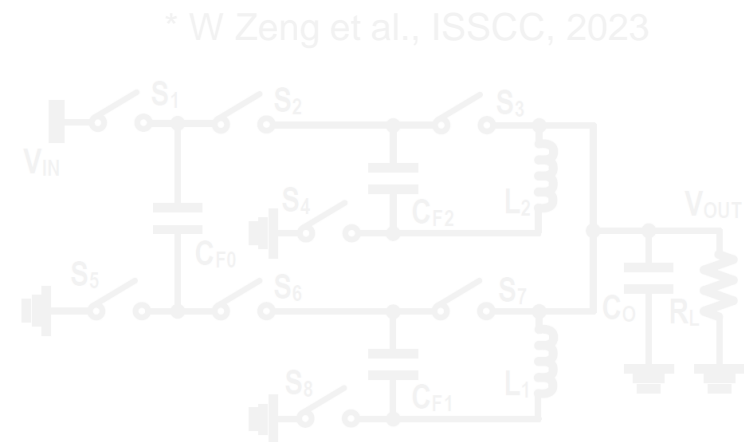
Series-Capacitor Converter



Capacitor Cross-Connected Converter



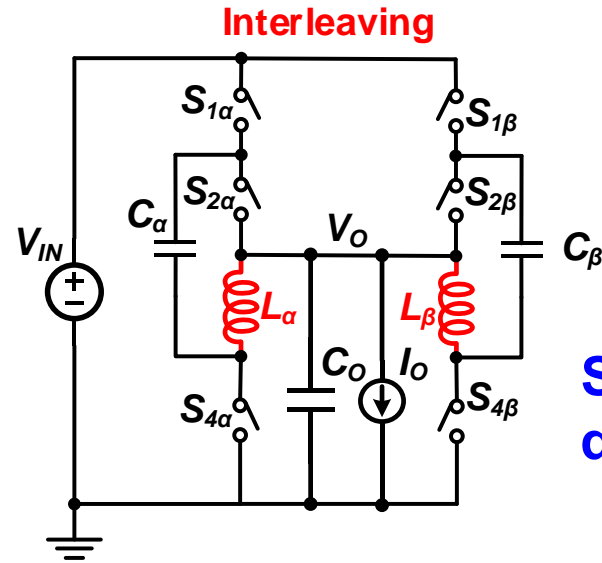
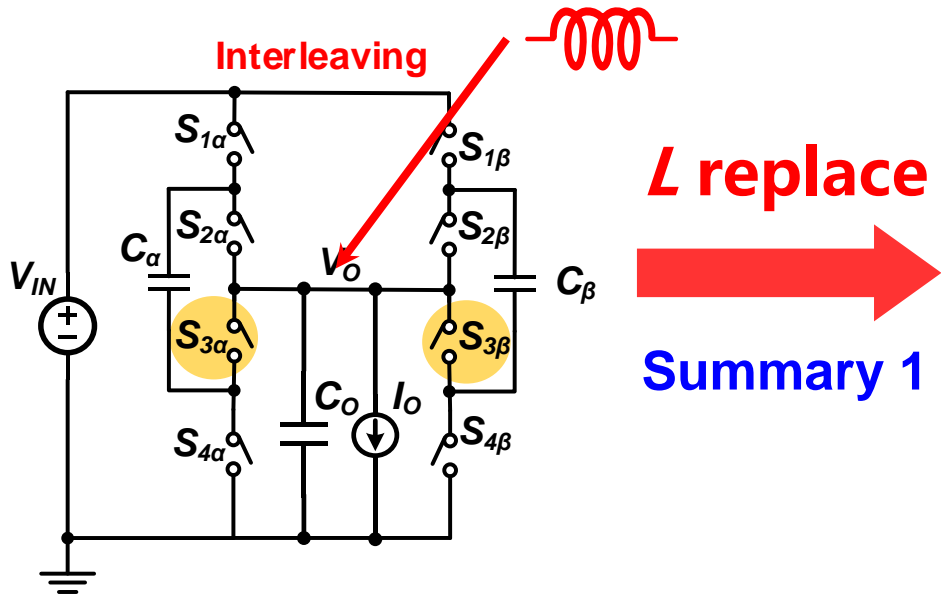
Quad-Output SC Converter



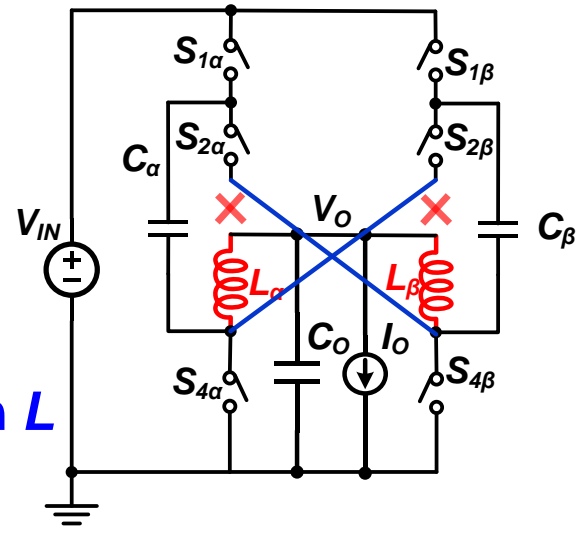
Dual-Inductor Quad-Path SC Converter



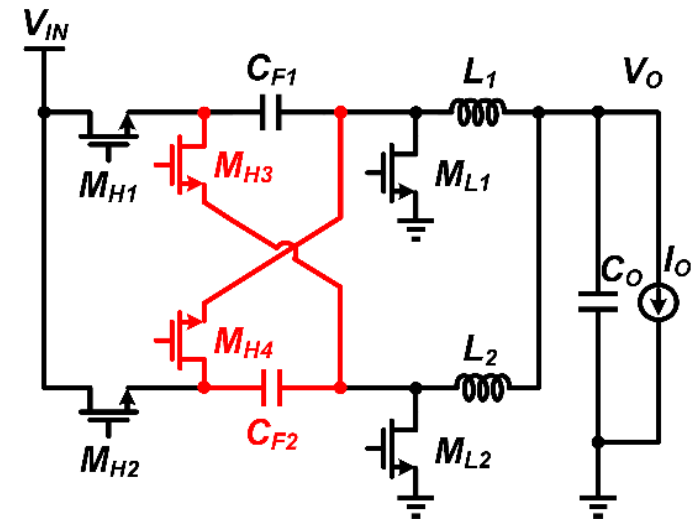
# Capacitor Cross-Connected Converter



**Summary 3:**  
discharge with  $L$

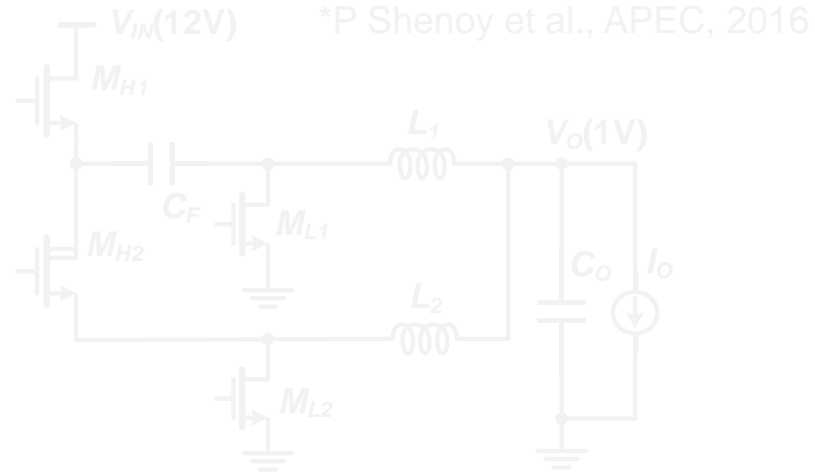


- Balance Voltage Stress
- $D > 0.5$  During Transient
- Auto Current Balance

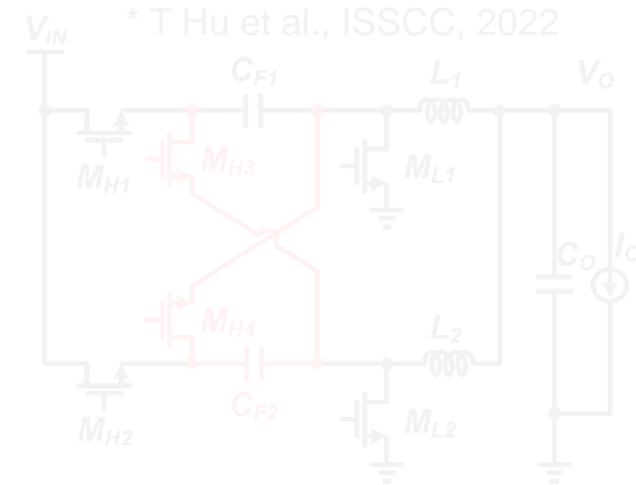


Capacitor Cross-Connected Converter

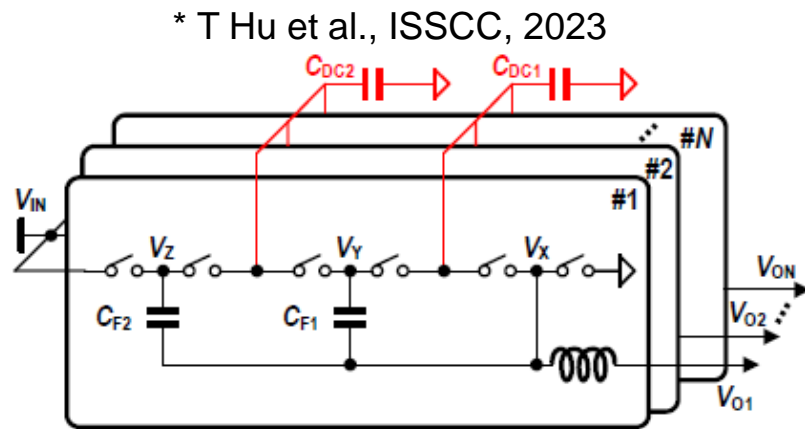
# Prior 12V/1V Hybrid PMIC



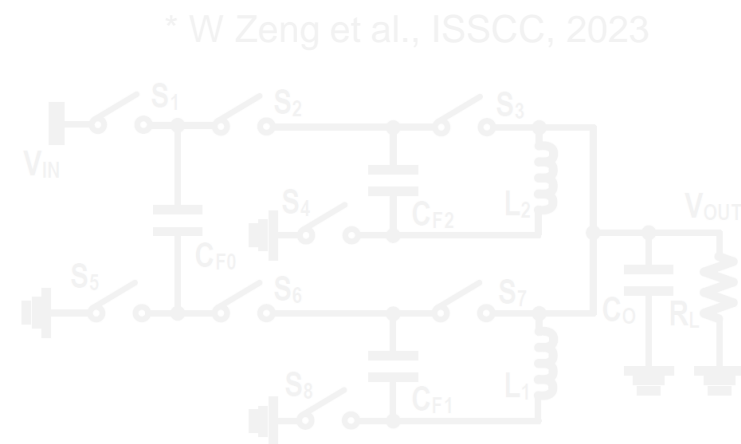
Series-Capacitor Converter



Capacitor Cross-Connected Converter

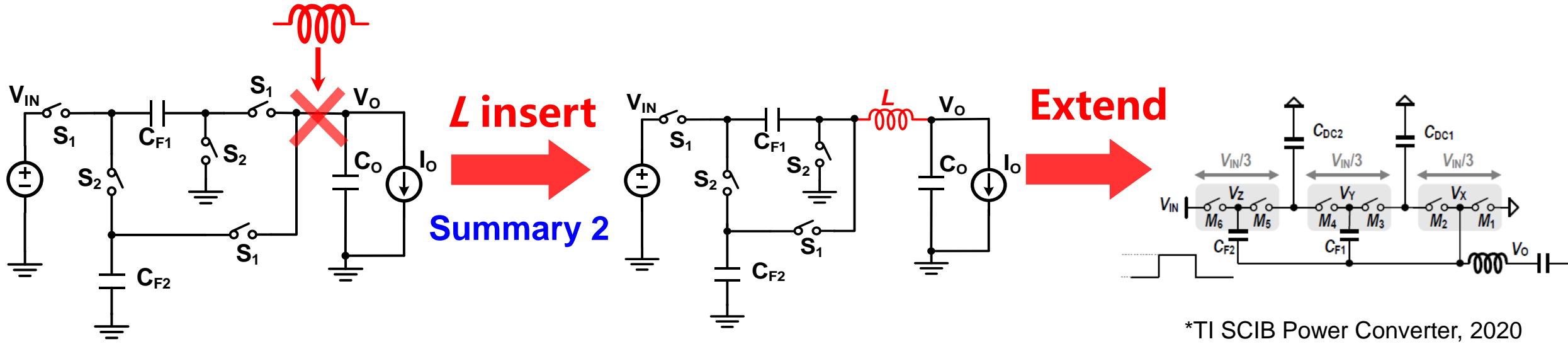


Quad-Output SC Converter

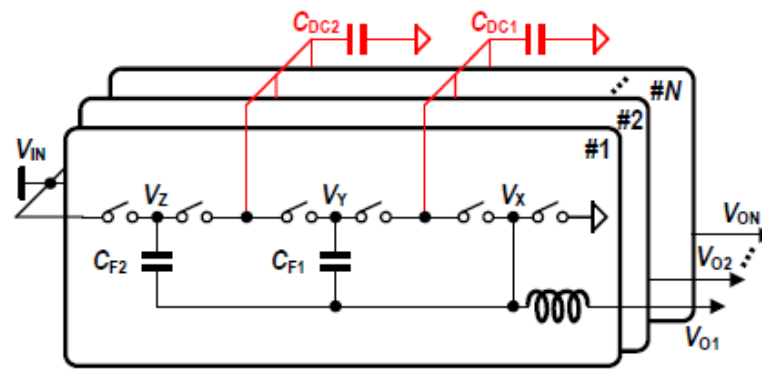


Dual-Inductor Quad-Path SC Converter

# Quad-Output SC Converter



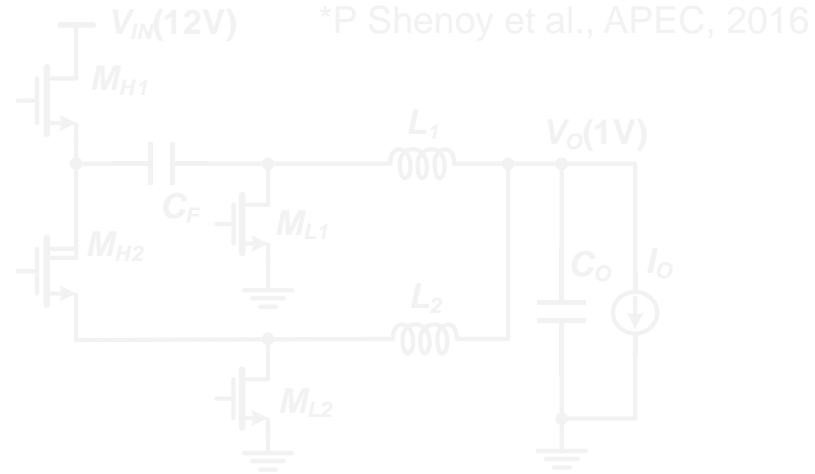
- Single Inductor
- Shared DC Capacitor
- Multi-Output Voltage



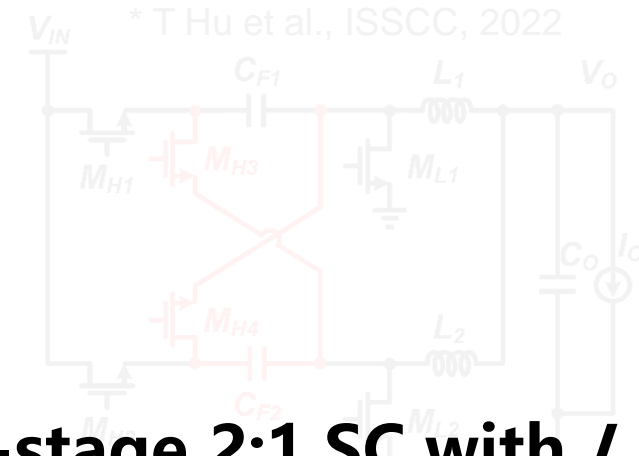
Quad-Output SC Converter

**Multi-Phase**

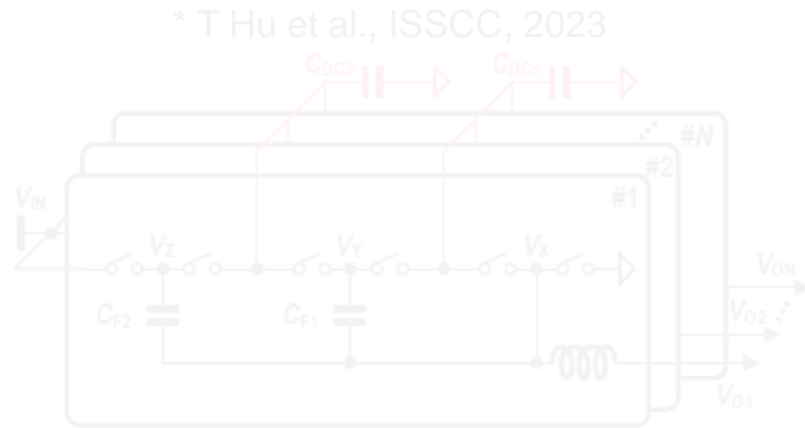
# Prior 12V/1V Hybrid PMIC



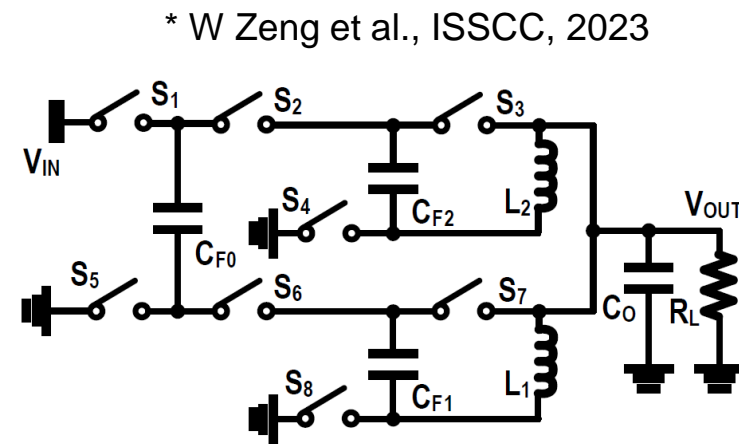
Series-Capacitor Converter



Two-stage 2:1 SC with  $L$  replace  
Capacitor Cross-Connected Converter  
(summary 1) and switch reuse



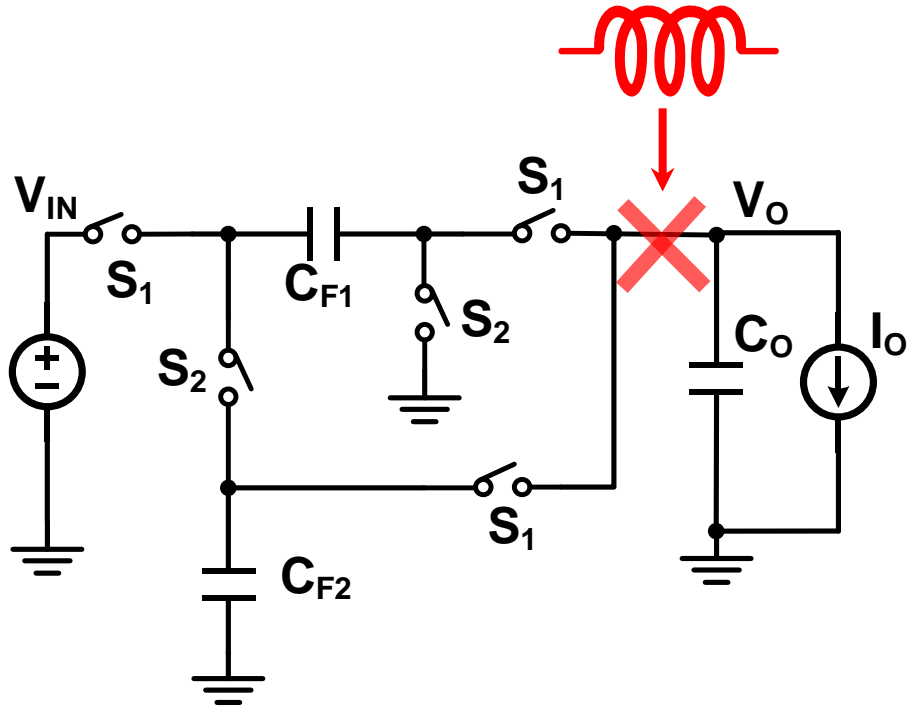
Quad-Output SC Converter



Dual-Inductor Quad-Path SC Converter

## Dual-Path Series-Capacitor (DPSC) Converter

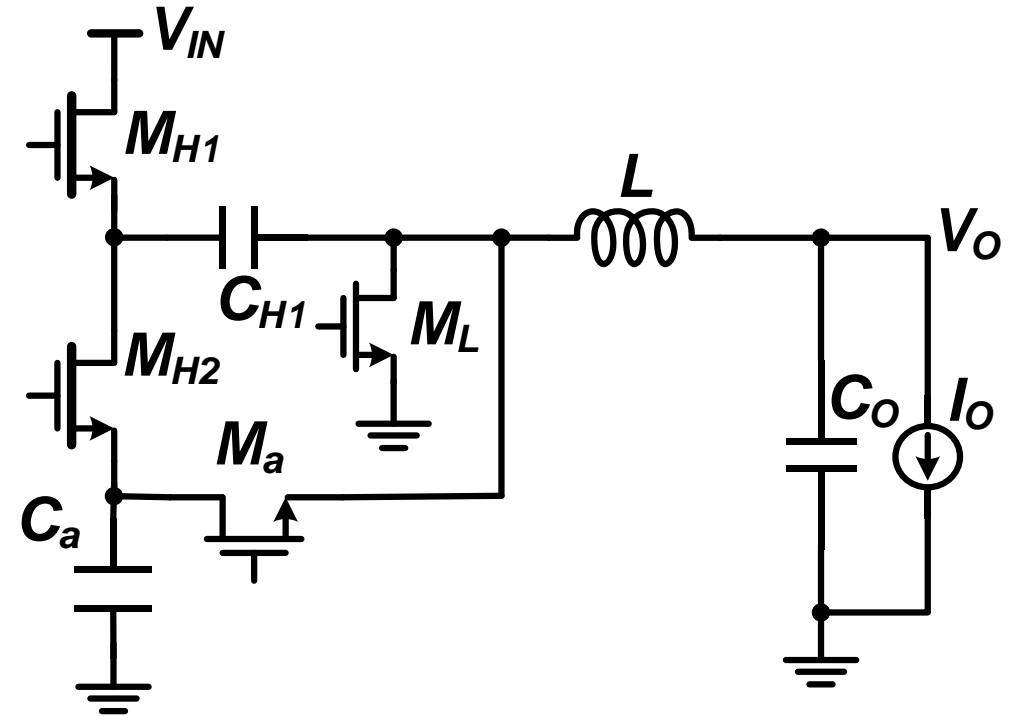
# Construction of DPSC Converter



**L insert**

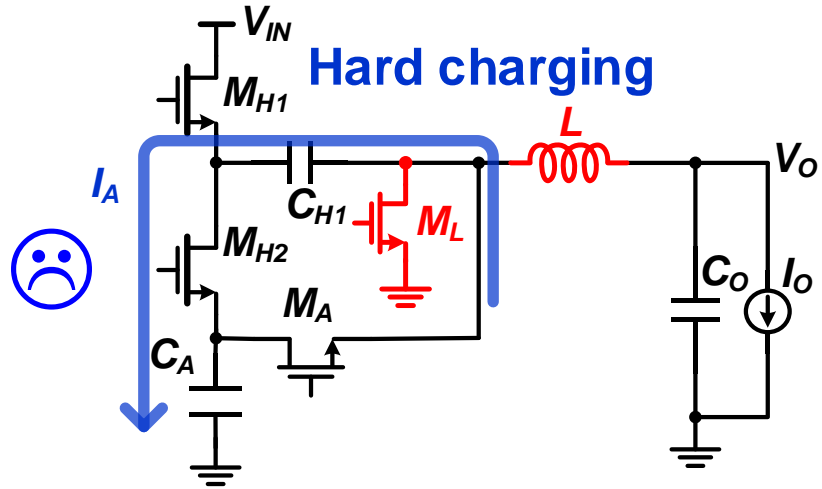


**Summary 2**

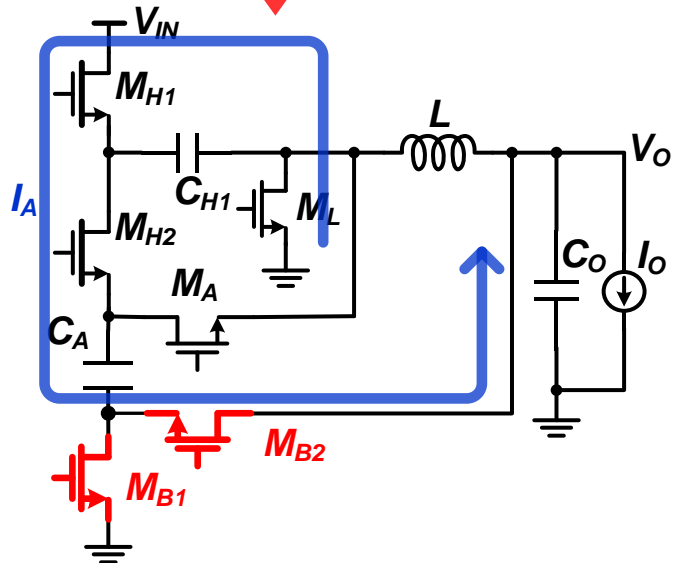


- Same Voltage Stress
- Single Inductor
- Full-range Duty Cycle

# Construction of DPSC Converter

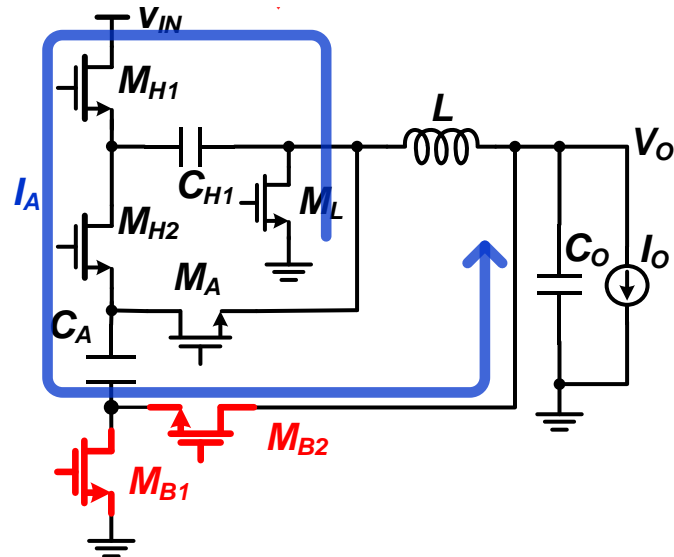


Use Ext-1 Dual Path



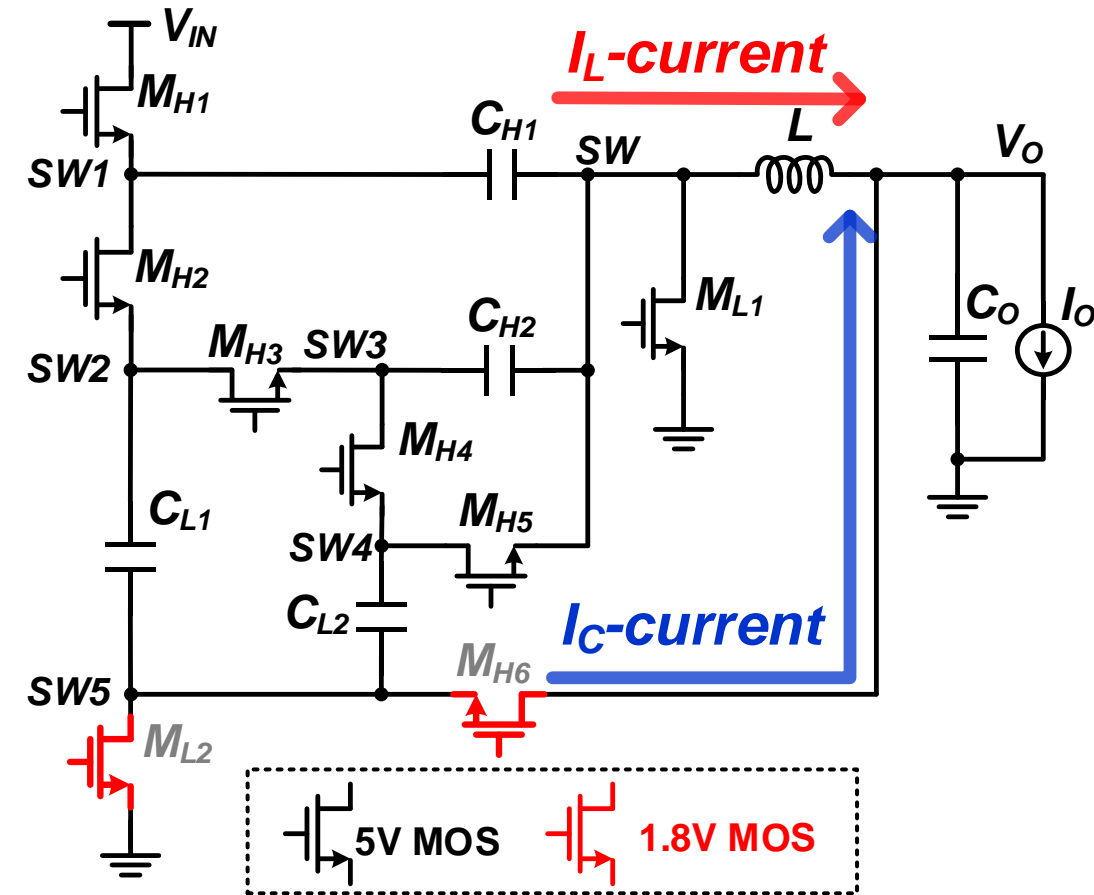
# Construction of DPSC Converter

- Low Voltage Stress
- Dual-Path Current
- Full-range Duty Cycle



Extend

X. Yang et al., ISSCC, 2023



Dual-Path Series-Capacitor Converter



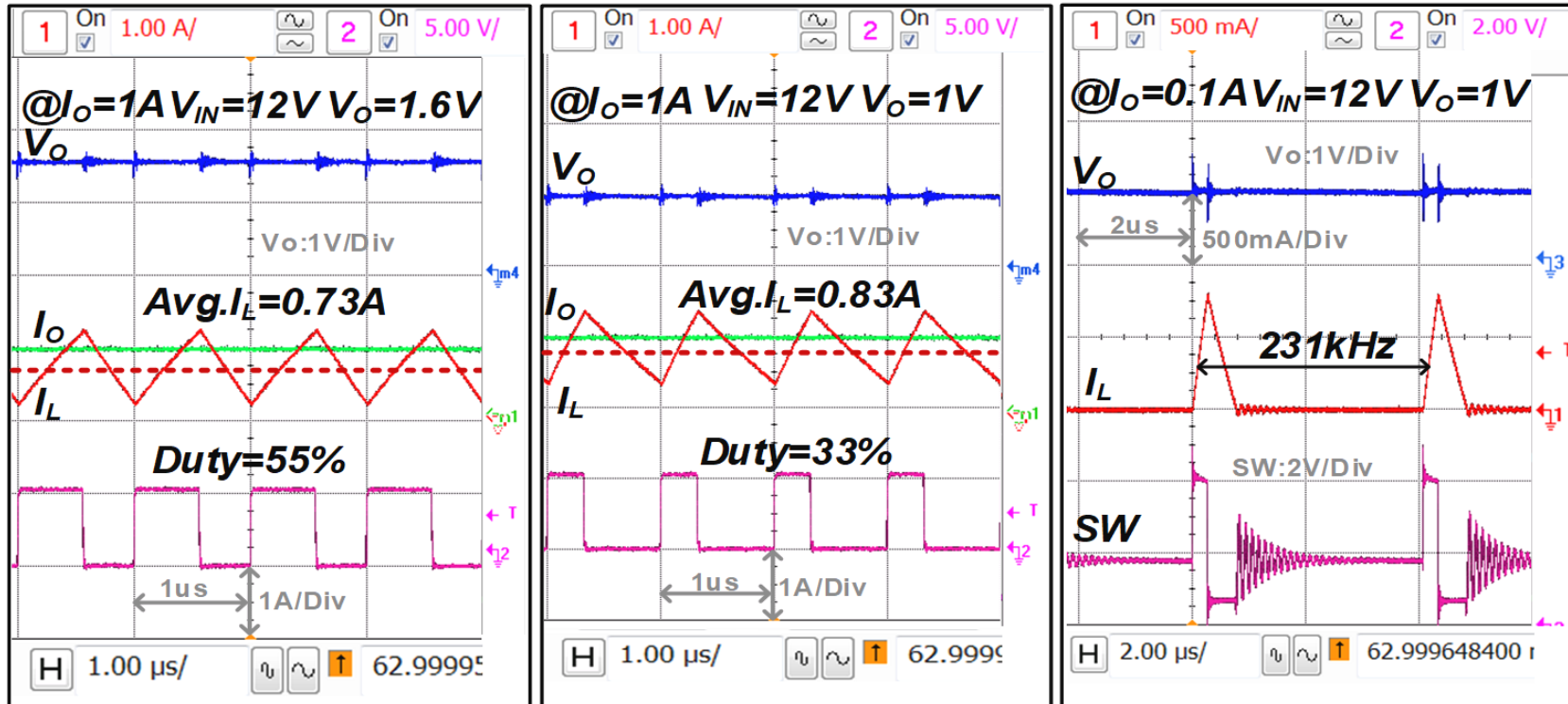
# Measurements

- TSMC 180nm BCD
- 9V~16V Input, 0.6V~1.2V Output
- Maximum 5A Load Current, 1MHz Switching Frequency

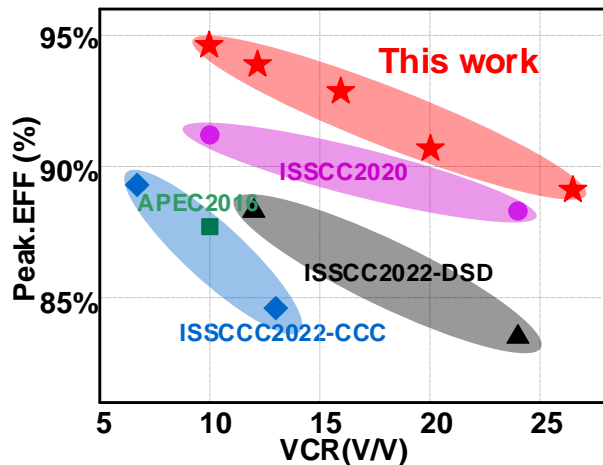
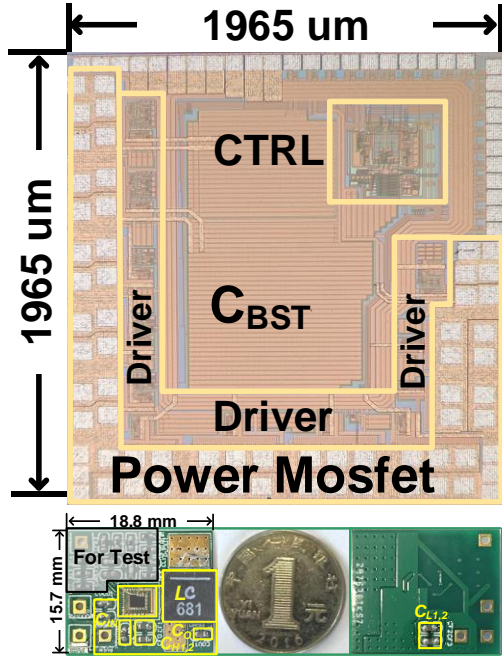
D>0.5

D<0.5

ZCD



# Comparison



	APEC2016	ISSCC2022	ISSCC2020	ISSCC2022	This Work
Topology	DSD	CCC	Tri-State DSD	DSD	DPSC
Process	NA	180nm BCD	180nm BCD	180nm BCD	180nm BCD
$V_{IN}$	12V	12V	12V/24V	12V/24V	9V~16V
$V_O$	1.2V	0.9V~1.8V	1V	1V	0.6V~1.6V
Max.Load	10A	4A	3A	4A	5A
Flying Cap	2.2 $\mu$ F	2.2 $\mu$ F $\times$ 2	1 $\mu$ F $\times$ 2	4.7 $\mu$ F	10 $\mu$ F $\times$ 4
Frequency	2~5MHz	2MHz	1MHz	1MHz	1MHz
Inductor	0.22 $\mu$ H $\times$ 2	0.74 $\mu$ H $\times$ 2	0.56 $\mu$ H $\times$ 2	1.8 $\mu$ H $\times$ 2	0.68 $\mu$ H
Output Cap	350 $\mu$ F	10.6 $\mu$ F	10 $\mu$ F	10 $\mu$ F	22 $\mu$ F
Peak.EFF@ $V_O$	87.7%@1.2V	86.8%@1.2V	91.2%@1.2V	88.3%@1V	94.5%@1.2V
EFF@Heavy $I_O$	80.1%@10A*	81.5%@4A*	70.2%@3A*	84.5%@4A*	84.4%@5A
EFF@Light $I_O$	70%@0.2A*	67.5%@0.2A*	74%@0.1A*	52.5%@0.1A*	89.2%@0.1A
Chip Current Density	NA	0.42A/mm <sup>2</sup> *	0.48A/mm <sup>2</sup> *	1.08A/mm <sup>2</sup> *	1.30A/mm <sup>2</sup>
Current Path	L	L	L	L	L+C
$D > 0.5$	NO	NO	NO	NO	YES

\* Estimated from graph

## ■ Make a summary of Hybrid Converter Constructions

- $L$  Replacement in SC Converters
- $L$  Insertion in SC Converters
- $L + C$  Combinations
- Other Extensions

## ■ Still complicated, further refinement required

## ■ Applications in high density designs using new passives and packages are promising