# Automatic Correction of Current Imbalance due to Element Variations in Multi-Phase Ripple Controlled Converter

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# Research Objective

## Objective

Development of power supply with

- Automatic correction of current imbalance

  Due to element variations(L or C)

- Fast response
- Low output voltage ripple control

## Approach

- Constant on-time control method
- Multi-phase converter

# Contents

- Research background
- Constant on-time control
- Four-phase converter solution via saw-tooth wave circuit
- Simulation results
- Automatic correction technology for balance of element variation
- Conclusion

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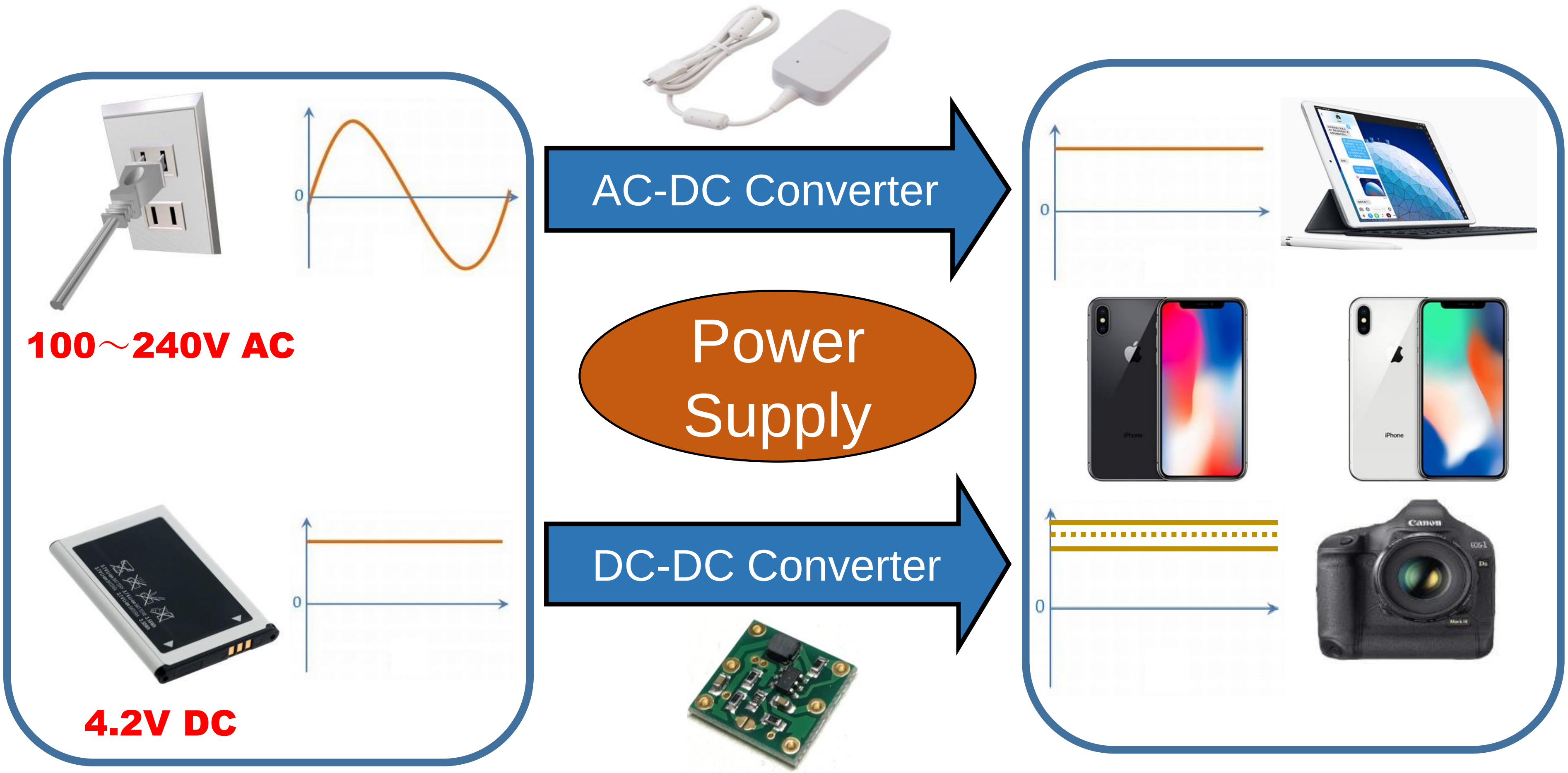
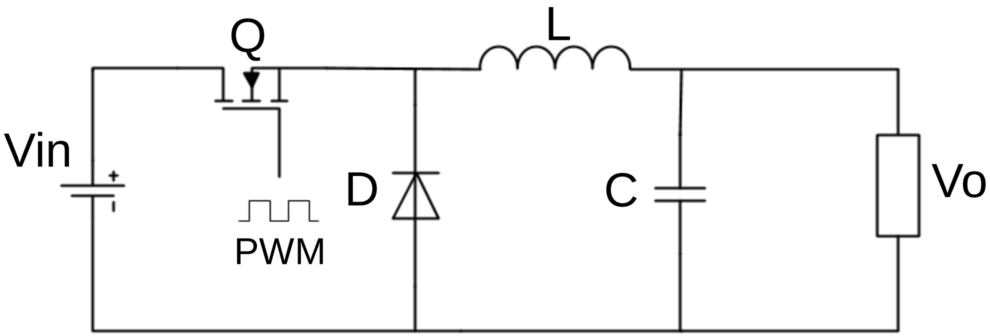
# Power Supplies Prevail Everywhere

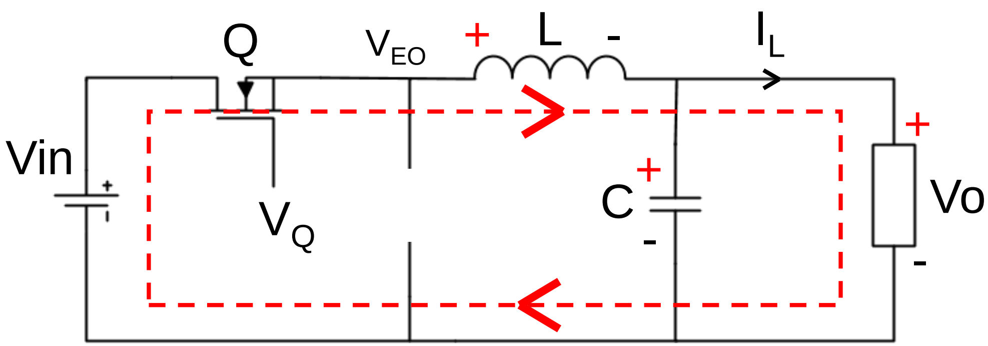



Power supply → demanded everywhere
to provide appropriate voltage for electronic device

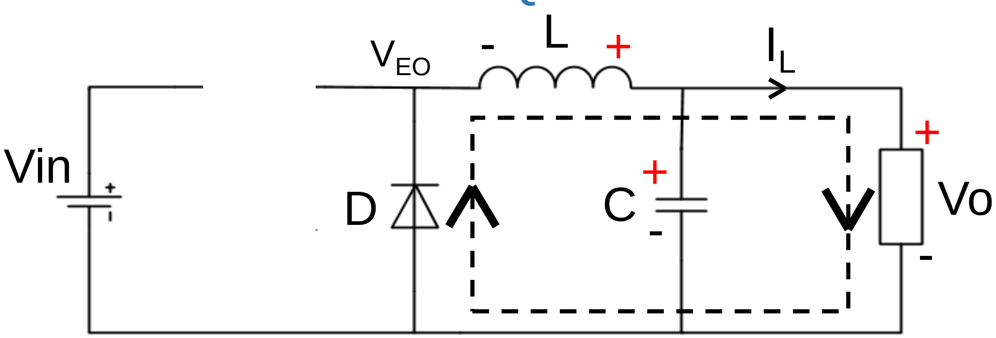
# Operation of Buck Converter



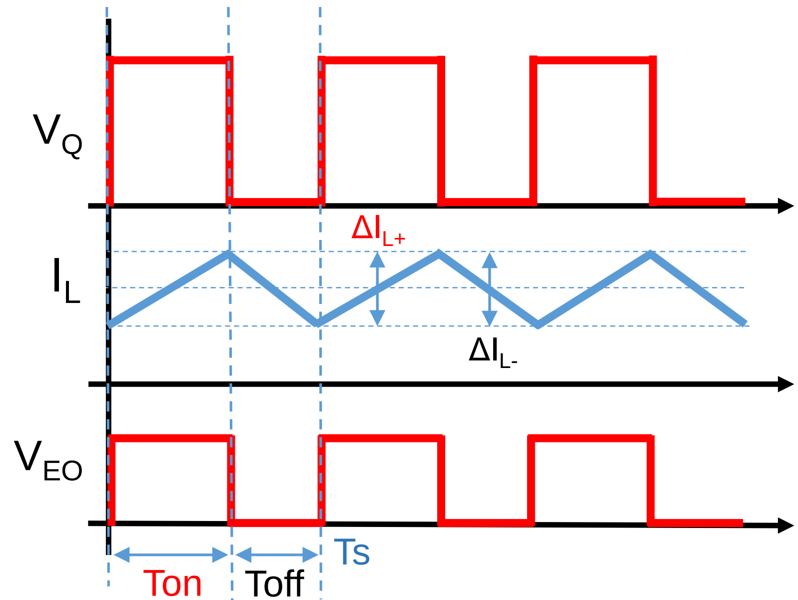

Buck Converter




On State: Q on D off




Off State: Q off D on




On State

$V_{Lon} = Vin - Vo = L\cdot(\Delta i_{L+}/\Delta t_{on})$

Off State

$V_{Loff} = -Vo = L\cdot(\Delta i_{L-}/\Delta t_{off})$

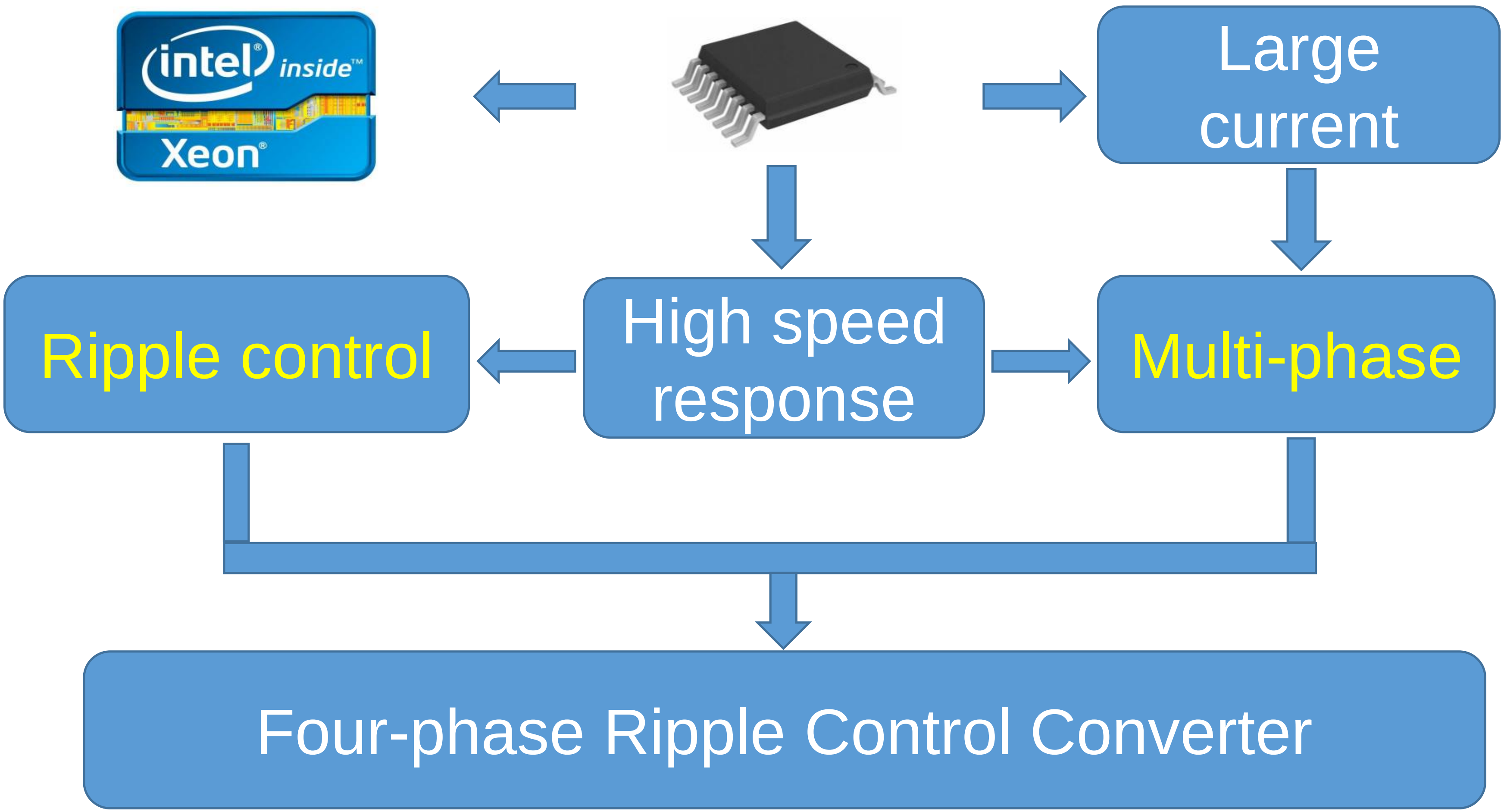
**Volt-second balance**

$\Delta i_{L+} = \Delta i_{L-}$

$$Vo = Vin\frac{T_{on}}{T_s}$$

# Demand for Power Supply of Process

| DC input | DC output | Max. output current | Max. output current step | Max. output current slew rate |
|---|---|---|---|---|
| 12V | 1.5V | 120A | 100A/us | 930A/us |



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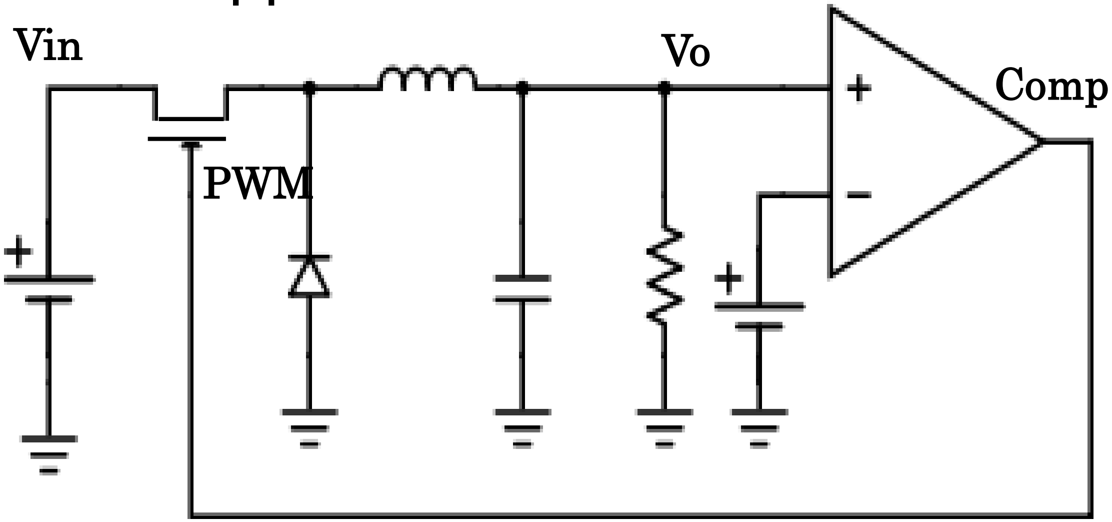
# Ripple Control Converter

## Basic Ripple Control Converter




No fixed clock signal

**Merit:**
①High-speed response
②Easy to obtain high frequency
③No Op-Amp

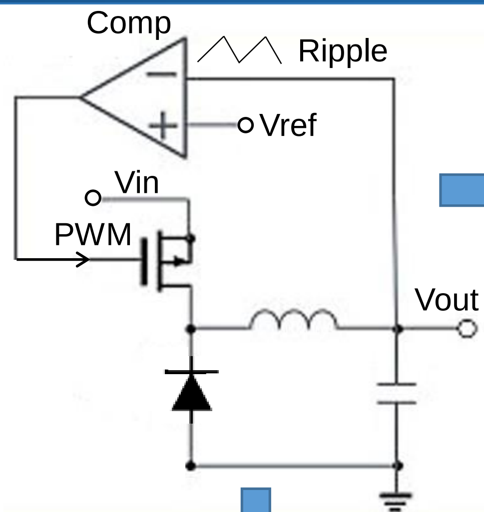
**Demerit:**
①Operation frequency is changed by the load current transient.
② Large noise

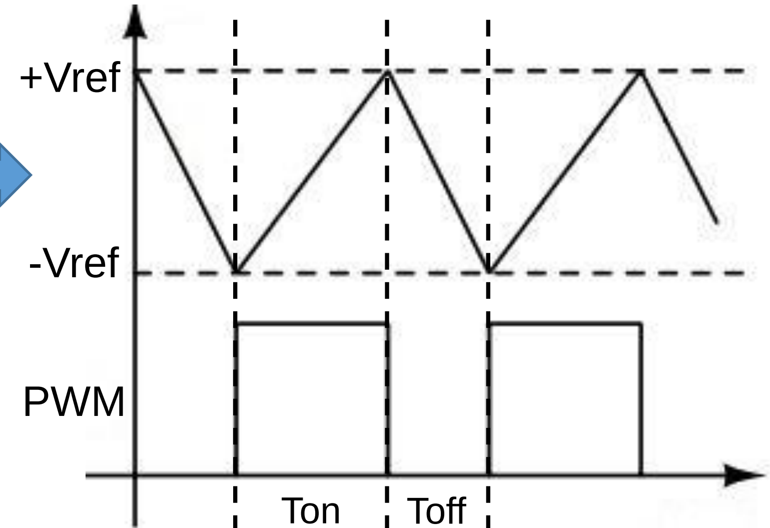
**Fop ≒ constant** — Low frequency / Stable operating frequency

→ Constant on-time control method

# Ripple Control with Constant on-time Method

## Ripple Control



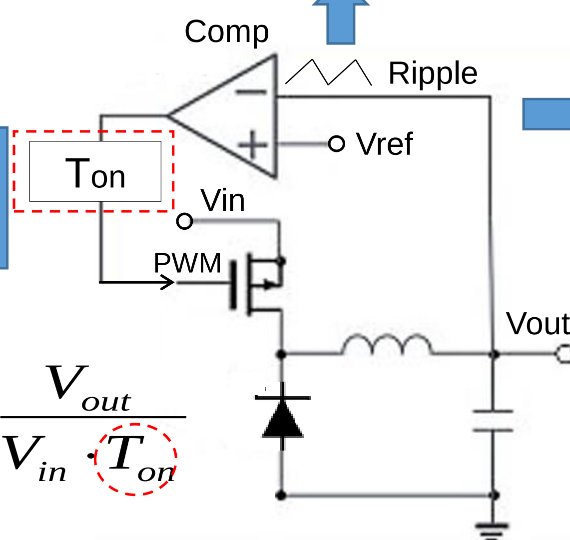

Hysteresis window control

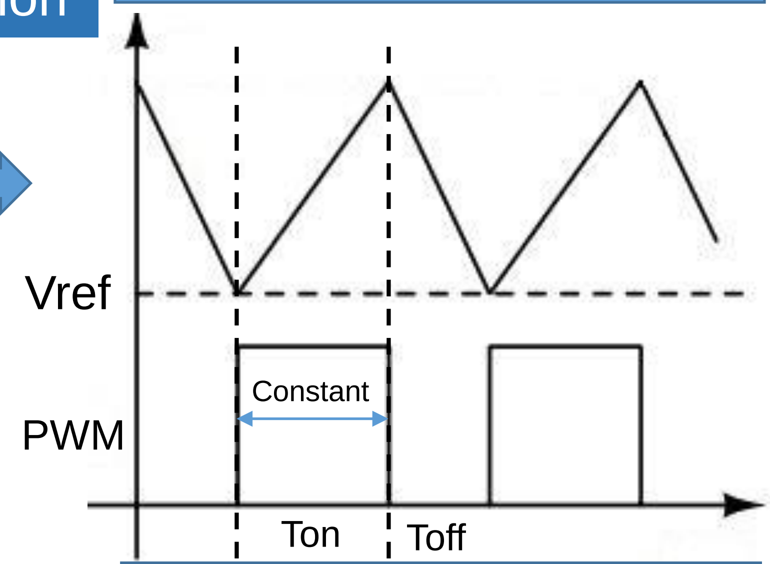
Extreme fast response

No phase compensation

Frequency swings usually

Constant on-time control




Frequency keeps stable

$$V_{out} = V_{in} \frac{T_{on}}{T_s}$$

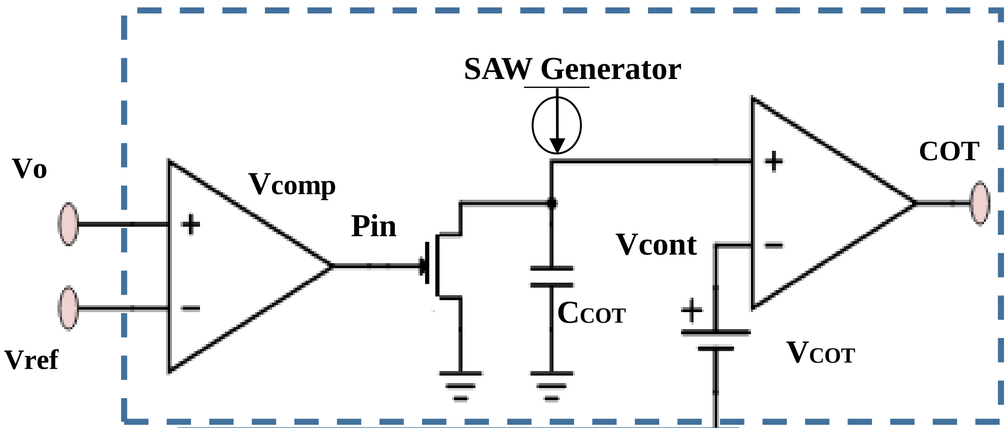
$$f_s = \frac{1}{T_s}$$

$$f_s = \frac{V_{out}}{V_{in} \cdot T_{on}}$$

# Operation of Proposed COT Generator

## Proposed COT Converter

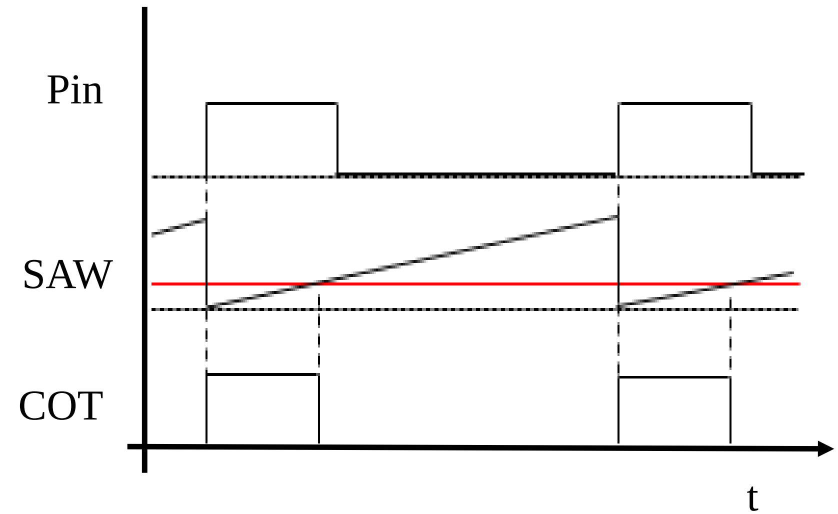
COT Generator of sub-converter




COT: Constant On-Time

No External Clock

## Operation waveform




SAW signal generator with Vcont

① Pin is supplied from the comparator
② Positive edge resets and restarts SAW generator
③ Gradient is decided with $I_o$ and $C_{COT}$
④ COT pulse is generated by comparing SAW signal and Vcont.

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- EMI reduction via pulse phase modulation
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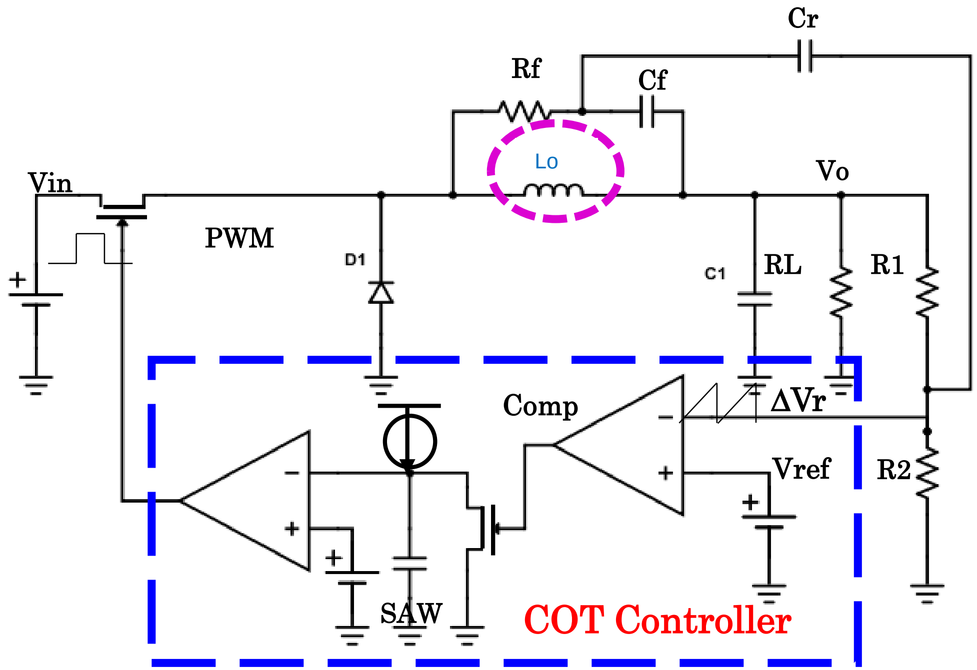
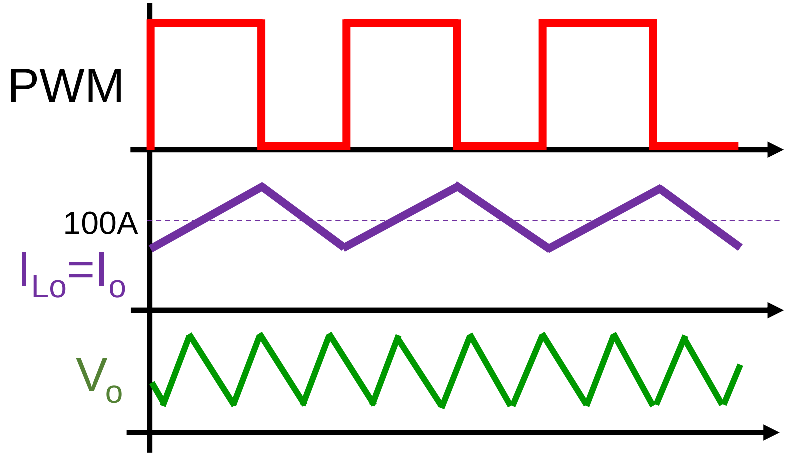
# Single-Phase Converter

## Ripple injection method




Large load
on inductor Lo

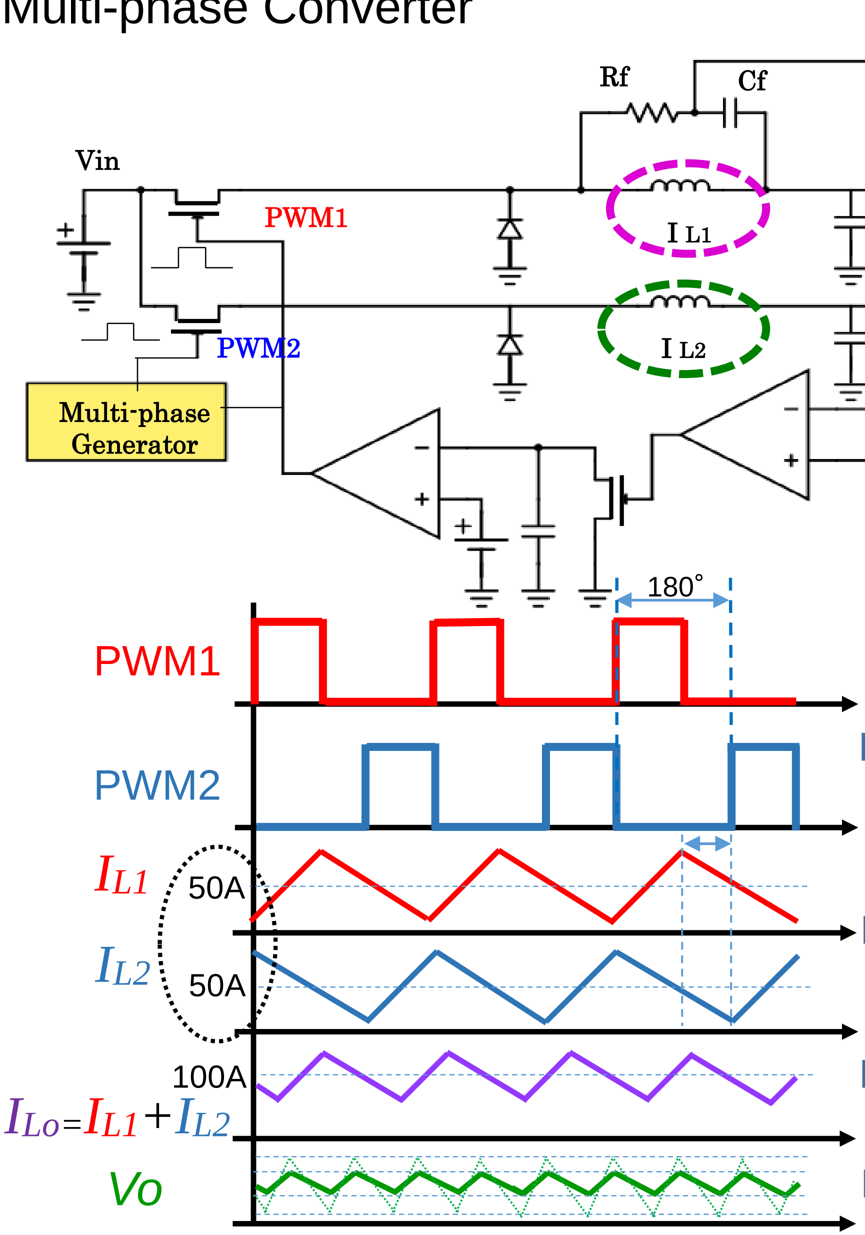
Io flows
only through inductor Lo

Lo large

body of coil is large

# Merit of Multi-Phase Converter

Multi-phase Converter




180° phase difference

Load of each phase's inductor halved

Simulative frequency multiplication

Low ripple by shifted two-phase peak current

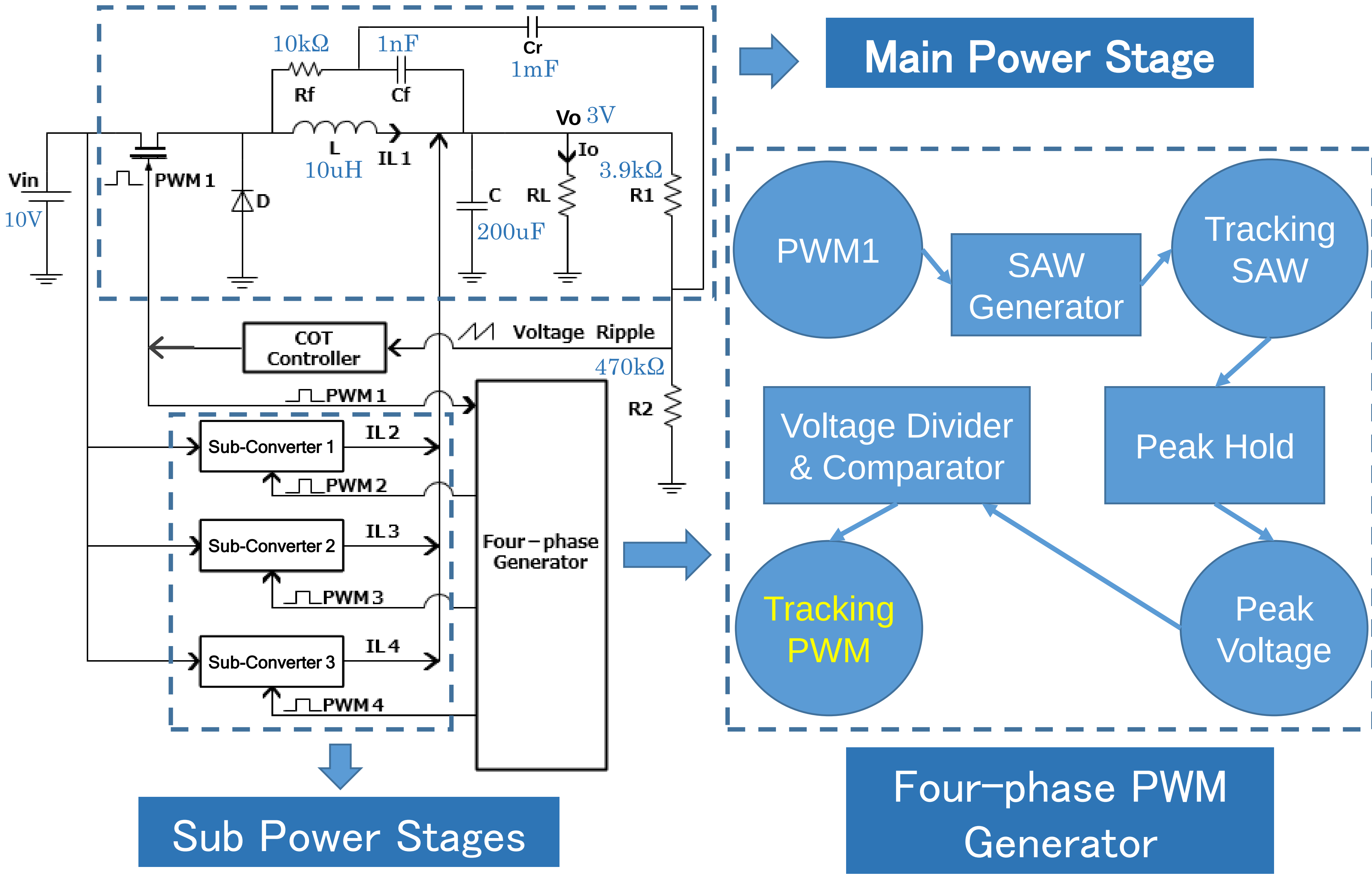
Tracking PWM2 with PWM1 without clock demand

Inductor L1 and L2 will go shares with Io

L1 and L2 small

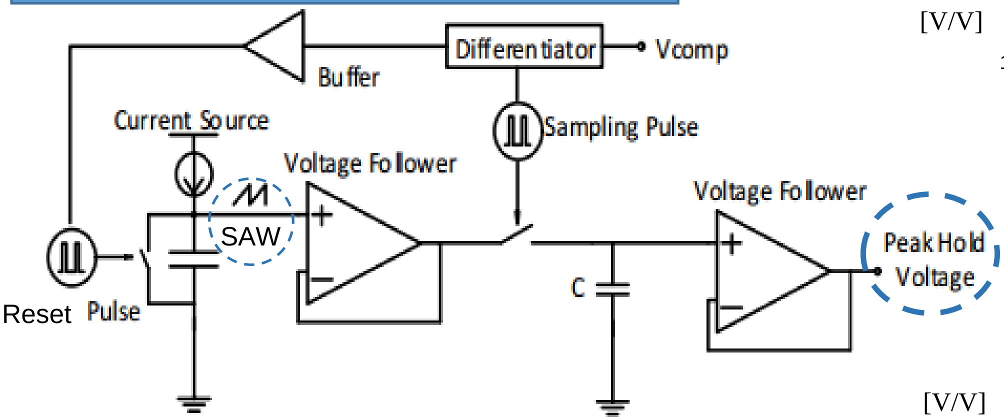
* Small body size, L1, L2
* High speed response
* Smaller output ripple

# Proposed Four-Phase Converter Solution

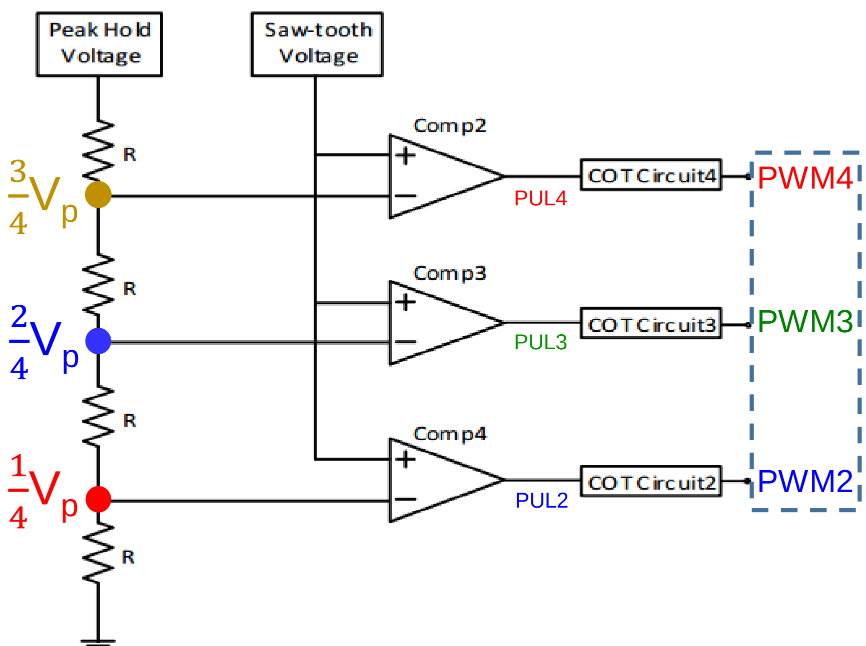


# Generation of Four-Phase PWM

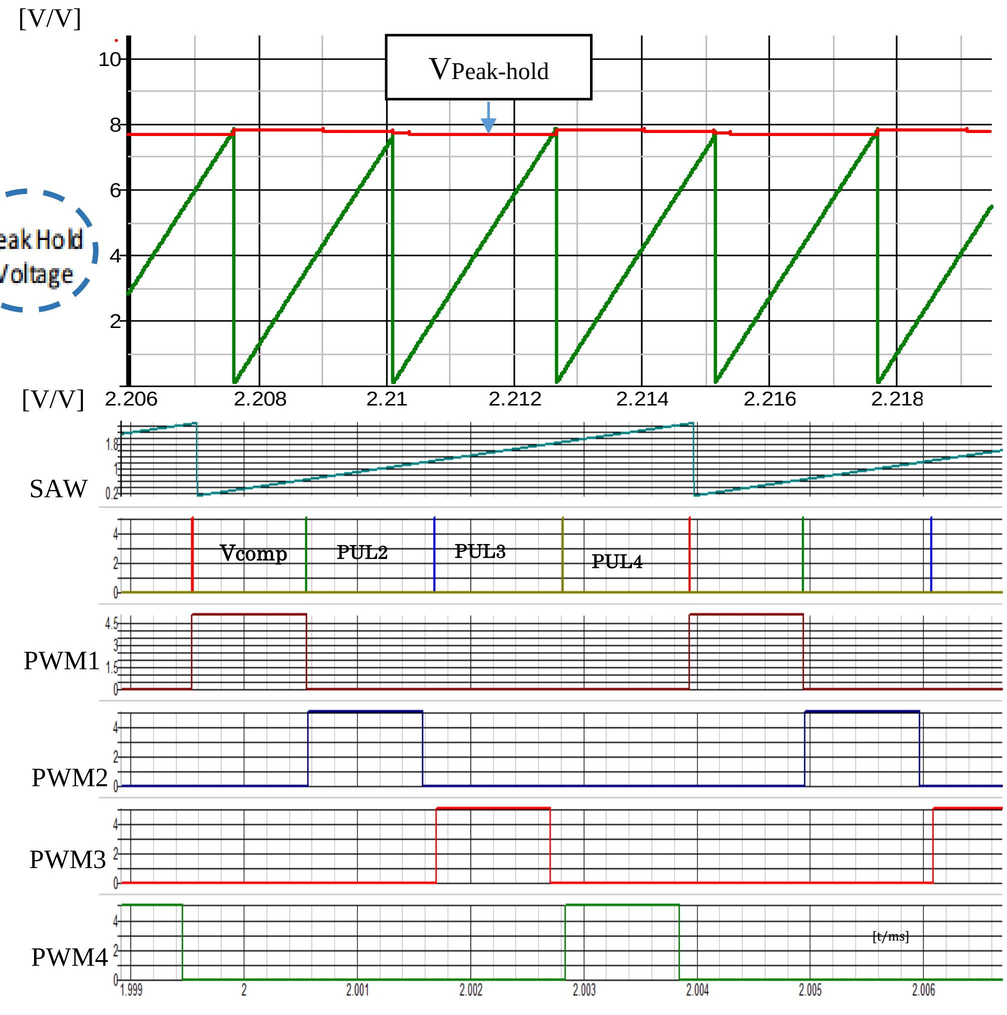
## SAW Generator & Peak Hold




## Voltage Divider & Comparator




## Operation waveform

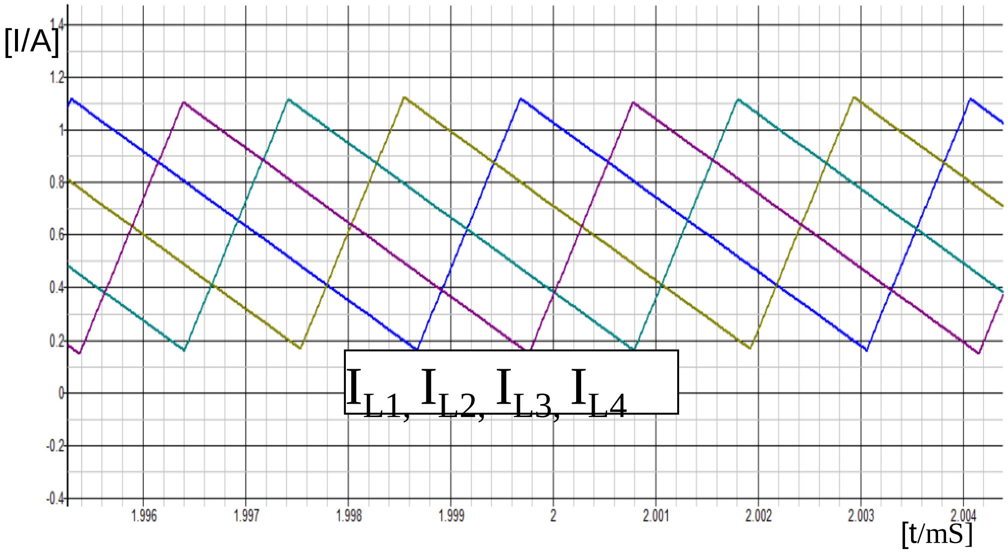


# Current Balance of four-phase Converter

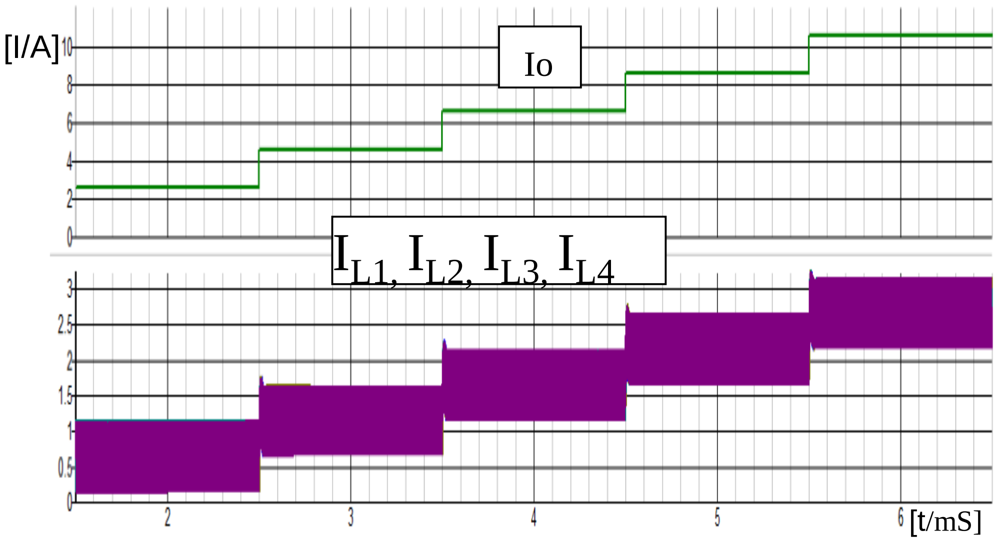
## ★Simulation Result

Without element variations

⊿L, ⊿$T_{COT}$(=⊿C), ⊿$V_{S/H}$




**Good current balance**




**Large load current achieved**

**Good current balance during transient response**

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  for balance of element variation**
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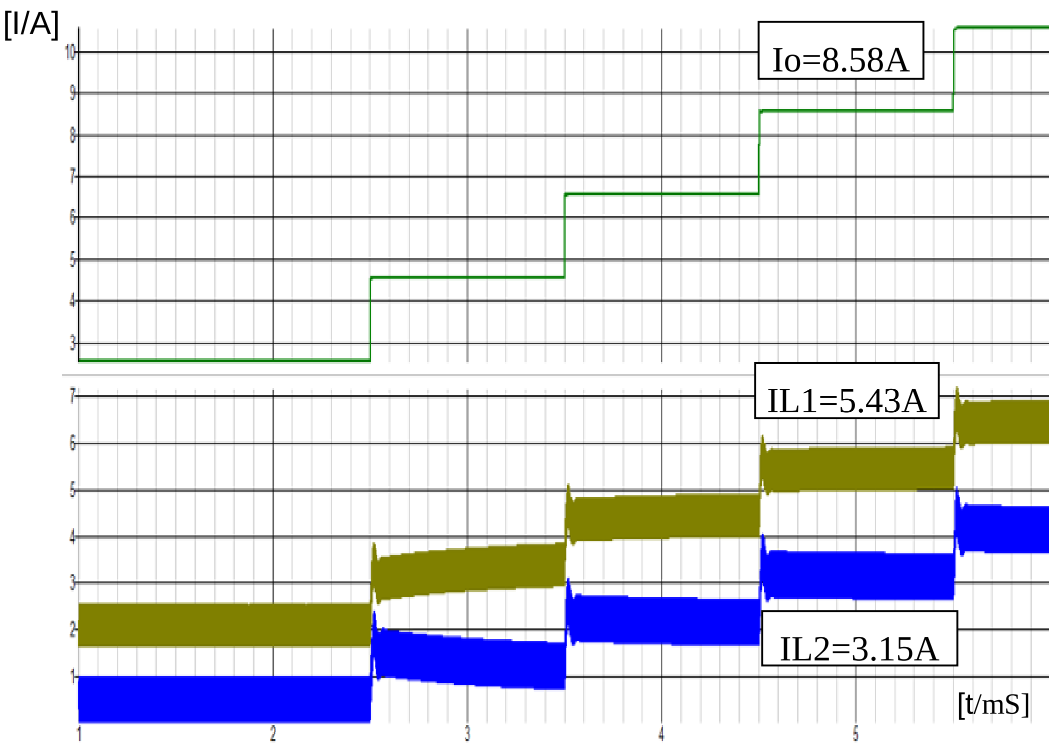
# Imbalance current (Inductance variation)

● Two Phase: With element variation (Inductance)




**Imbalance result for two-phase current**


10μH ⇨ 11μH

**+ 10%**

Main power supply

$I_o$ = 8.58A

$I_{L1}$ =5.43A , $I_{L2}$ =3.15A

$\Delta I_L = (I_{L1} - I_{L2})$

$= |5.43-3.15| = 2.28A$

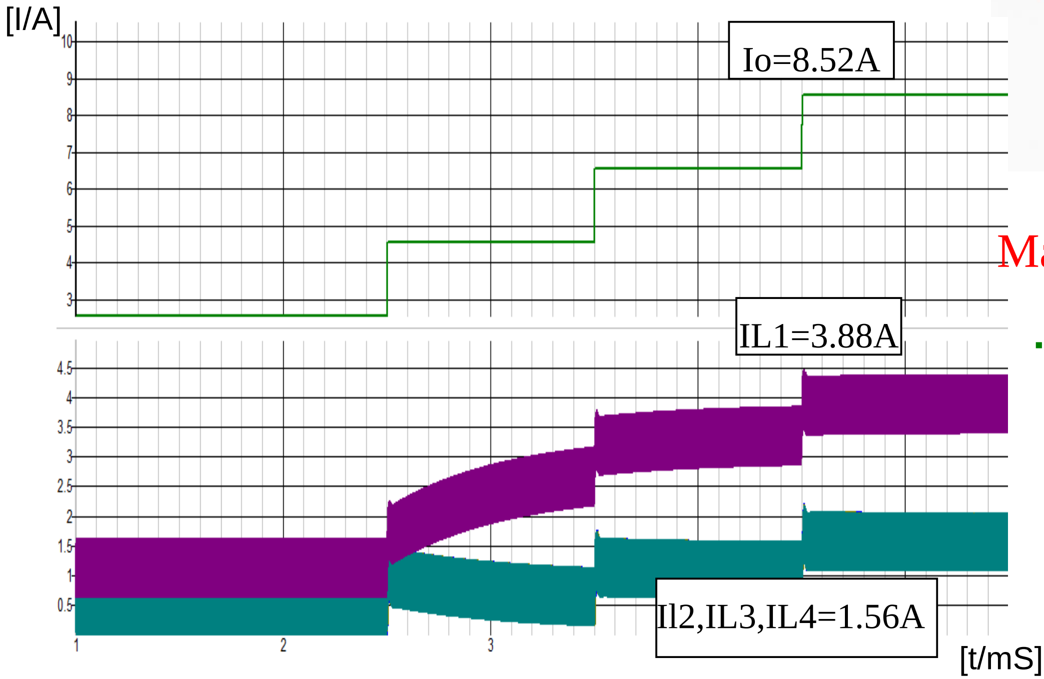
Error Ratio:

$\delta = (Io/2-In)/Io/2$

$=(4.29-3.15)/4.29 \Rightarrow 27\ \%$

# Imbalance current(Capacitance variation)

● Four Phase: With element variation (Capacitance in COT generator)




500pF ➡ 495pF

**- 1%**

Capacitance

Main power supply

High Sensitivity

Io = 8.52A

$I_{L1}$ =3.88A ,

$I_{L2}$ = $I_{L3}$ = $I_{L4}$ =1.56A

**Imbalance result for four-phase current**

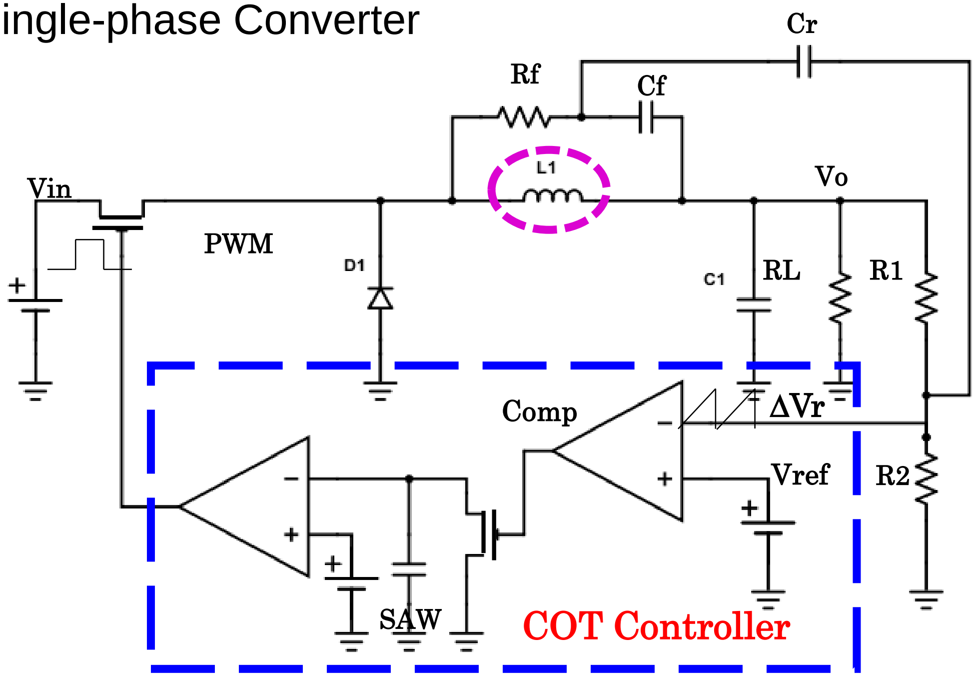
δ 1= (3.88-2.31)/2.13 => 82%

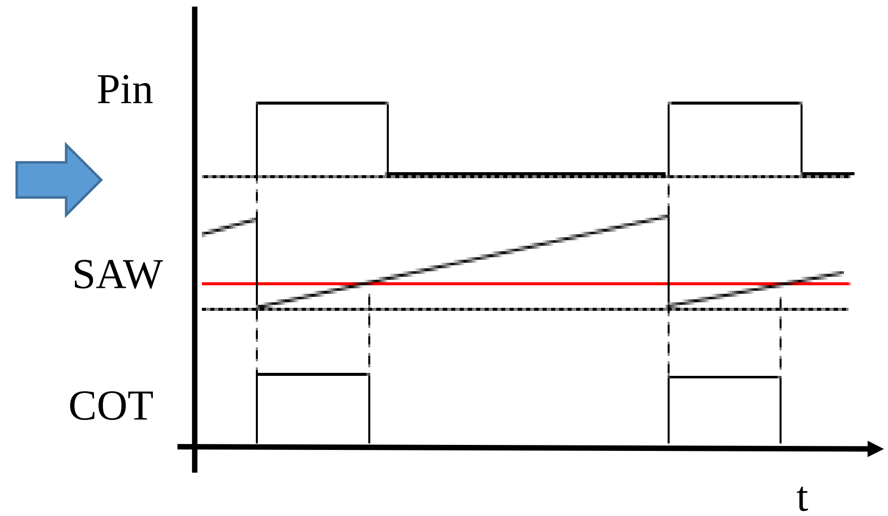
δ 2= (2.13-1.56)/2.13 => 27%

☹

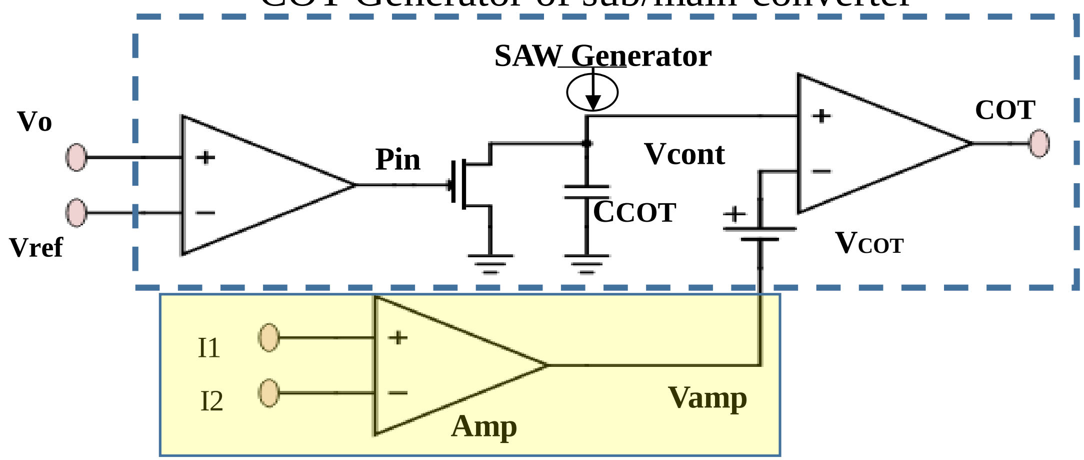
# Proposed Current Balance Modulation

Single-phase Converter




COT Generator of sub/main-converter



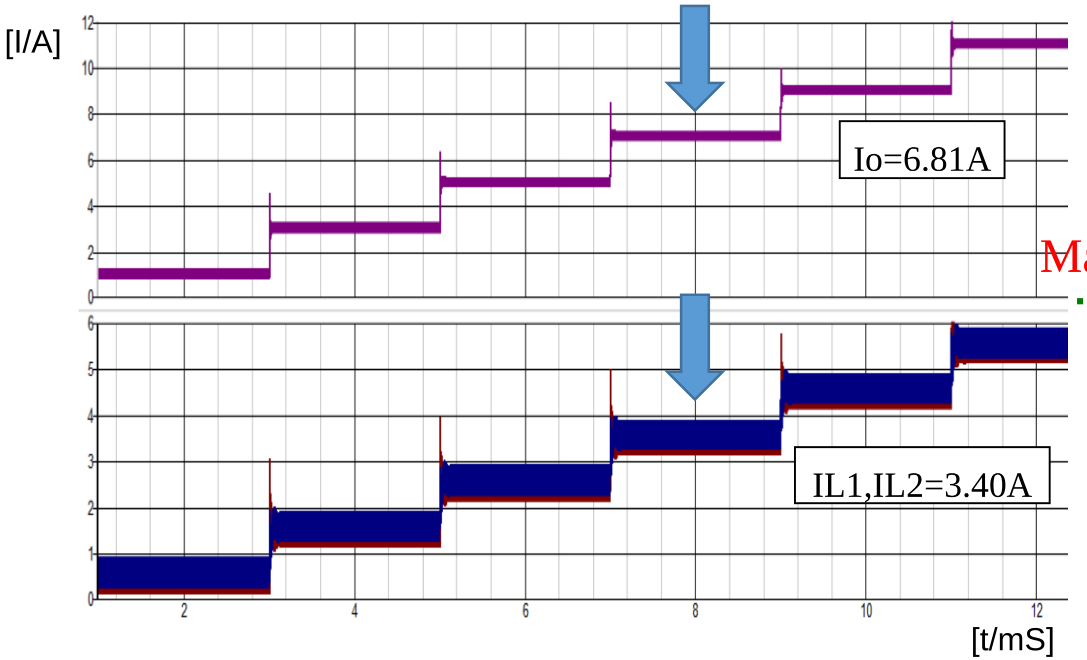

$$T_{COT} = k \cdot V^{-}$$
$$= k \cdot (V_{COT} + V_{amp})$$
$$= T_{COT} + \Delta T_{COT}$$

**Modulation Ratio:**

$$\alpha = \Delta T_{COT} / T_{COT}$$
$$= V_{amp} / V_{COT}$$

# Balance current (Inductance variation)

● Two Phase ：Result of proposed method with good current balance




Inductor

Main power supply

10µH ➡ 11µH

**+ 10%**

**Good current balance**

Io = 6.81A

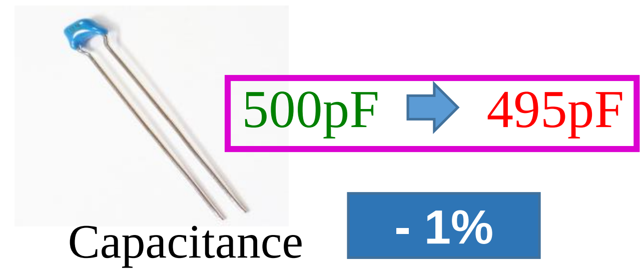
$I_{L1} = I_{L2} = 3.40A$

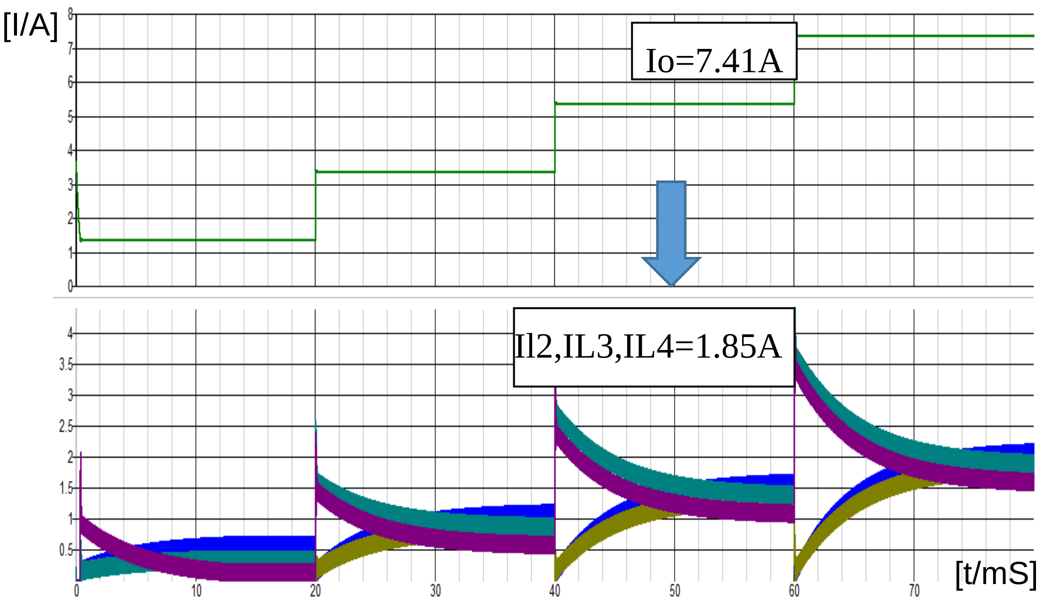
**Balance result for tow-phase current**

★ Even if capacitance varies,
the current balance can be secured in the same way

# Balance current (Capacitance variation)

● Four Phase: Result of proposed method with good current balance




**Balance result for four-phase current**

**Good current balance**

Io = 7.41A

$I_{L1} \fallingdotseq I_{L2} \fallingdotseq I_{L2} \fallingdotseq I_{L2} \fallingdotseq 1.85A$

# Merits of Proposed Method

- When L or C for COT pulse is varied, inductor current of each sub-converter is automatically kept in good balance.
- There is no need to select L and C values, so the cost is reduced.
- Even if L or C values change due to temperature change, the current balance can be automatically maintained

by the proposed system.

# Conclusion

- The current imbalance due to inductance and capacitor variations is well improved.

- Current balance is very good even at large output current.

# Thank you for your attention

# Q&A

- Q1:Is the automatic current balancing technique for ripple-controlled power supplies suitable for conventional four-phase buck converter power supplies?
- A1: I have never thought of it before, but I think it is applicable.

- Q2:Can the correction be made even if the current of each phase varies due to the variation in the conduction resistance of the switch?
- A2:Whatever the reason, the current balance correction can be performed using the proposed technology if the current in each phase varies.

- Q3:How did you determine the gain of the current sense amplifier?
- A3:The negative feedback control can suppress the current variation to (1 / loop gain). Even if the loop gain is made quite large, it is easy to keep stable, so we determined the value of gain by experiments.

# Classifications of DC-DC Converter