電気学会
電子回路研究会
（岡山県立大）

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# デルタシグマ変調を用いた DC-DC変換器制御の検討

◎ 高 虹，美和俊介，小堀康功，邢 林
小林春夫，高井伸和，新津葵一 （群馬大学）
大森武志, 小田口貴宏, 中西功, 根本謙治
（AKMテクノロジー株式会社）
松田順一（旭化成パワーデバイス株式会社）

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- Research Background and Objective
- PWM and ΔΣ Controllers in DC-DC Converter
- Feedforward-type ΔΣ Controller in DC-DC Converter
- ΔΣ Controller for
  Single-Inductor Dual-Output DC-DC Converter
- Conclusion

# Research Background



- Rapid advances of Power Devices
  → Fast switching speed

↓

Application of ΔΣ modulator
to DC-DC converter controller becomes feasible.

- Expected advantages
  - Fast transient response
  - High efficiency at low load
  - Spread spectrum of switching noise

# Research Objective

- To show advantages of feed-forward-type ΔΣ controller over feedback-type in DC-DC converter.

  Feedback-type ΔΣ controller → one clock signal delay

  Feed-forward type → no signal delay

  - small ripple
  - fast response

- To investigate applicability of ΔΣ controller in single-inductor dual-output DC-DC converter.

# Contents

# Trade-off of Fast Response and Efficiency

Faster Transient Response → Inductor charged and discharged at high speed

↓

High Switching Frequency

High Efficiency → Lower Switching Loss

↓

Reduction of Switch Operation

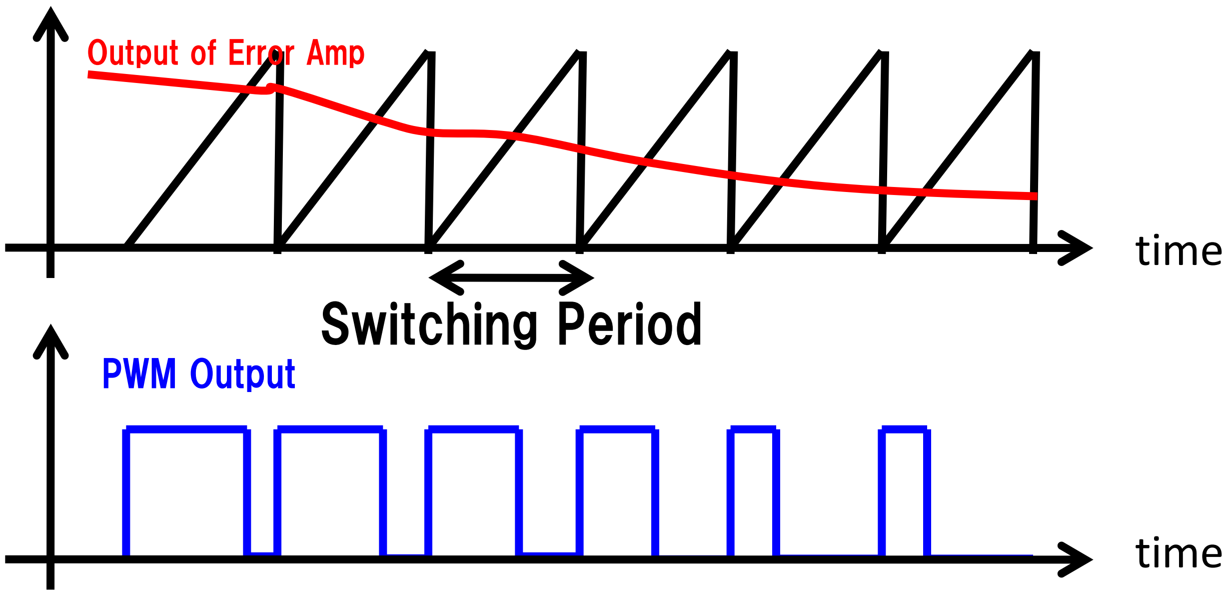
↓

Low Switching Frequency

# Problems of PWM Controller

## DC-DC converter with PWM controller

Switching frequency ➡ determined by sawtooth wave




Difficult to meet simultaneously both of

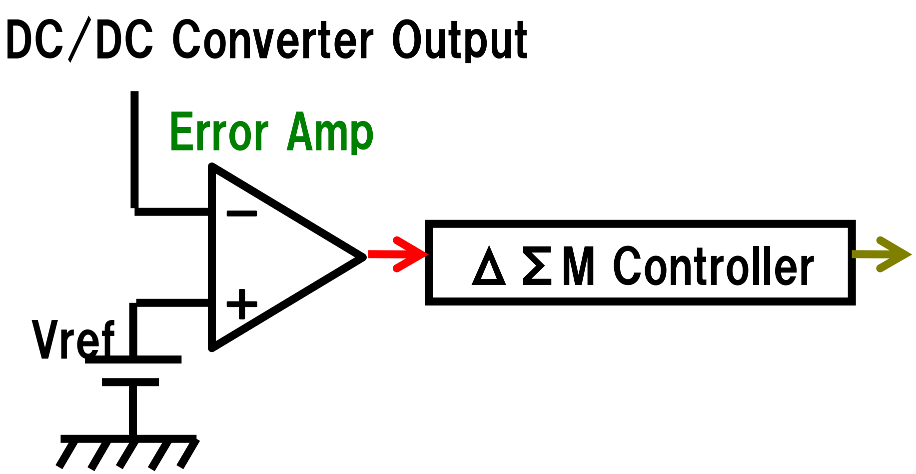
- Fast Transient Response
- High Efficiency

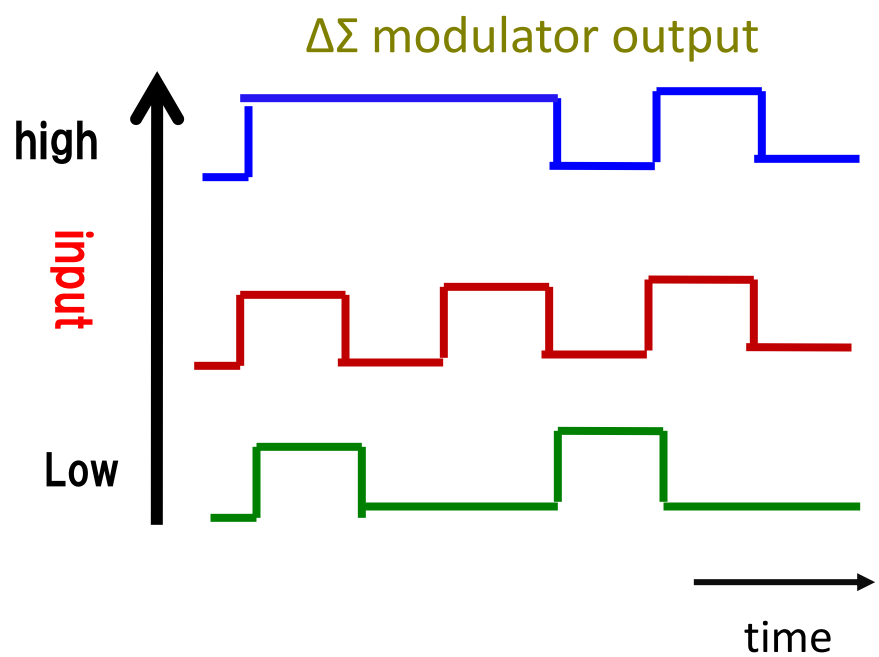
# ΔΣ Modulator Controller

Fast transient Response: High input (at transient state) ⇒ Dense Pulse Stream (High switching frequency)

Can meet both

High efficiency: Low input (at steady state) ⇒ Sparse Pulse Stream (Low switching frequency)



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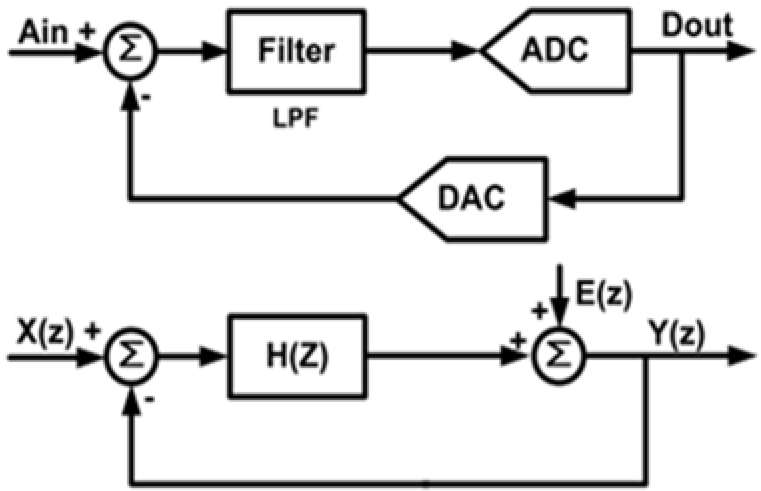
# Feedback-type ΔΣ Modulator




$$Y(z)=\frac{H(z)}{1+H(z)}\cdot X(z)+\frac{1}{1+H(z)}\cdot E(z)$$

$$H(z)=\frac{z^{-1}}{1-z^{-1}} \rightarrow STF(z)=z^{-1} \quad NTF(z)=1-z^{-1}$$

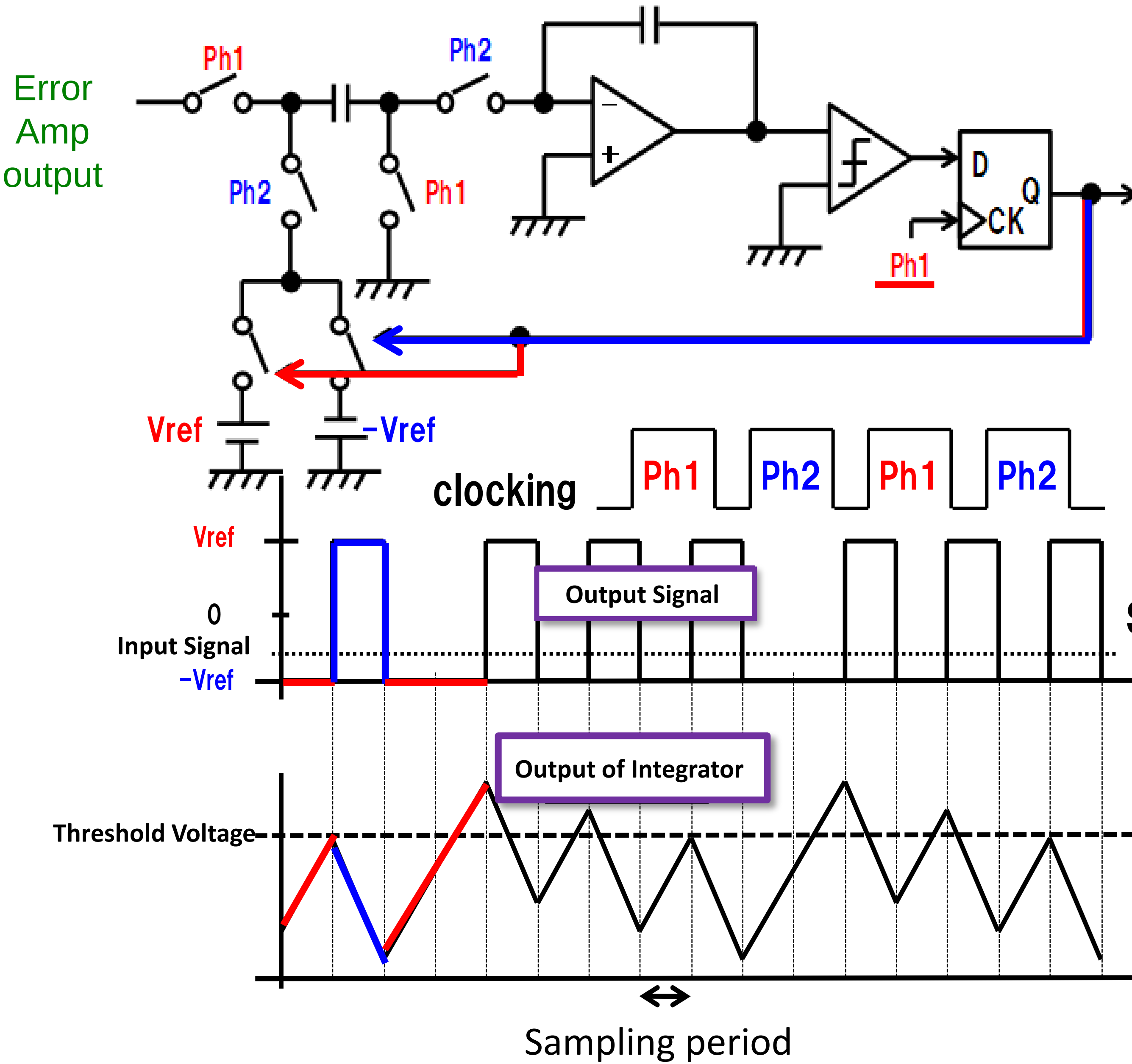
Signal Transfer Function

Noise Transfer Function

**One-clock delay**

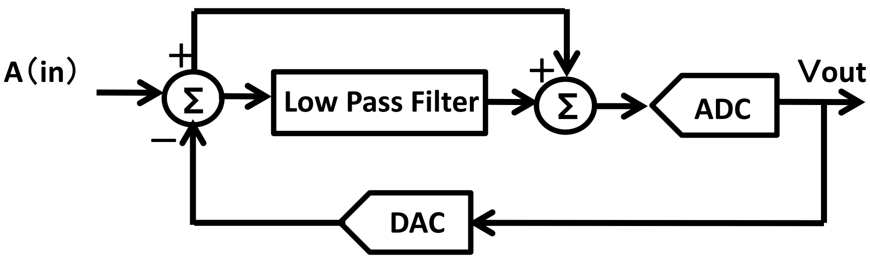
**Differentiation=Noise Shaping**

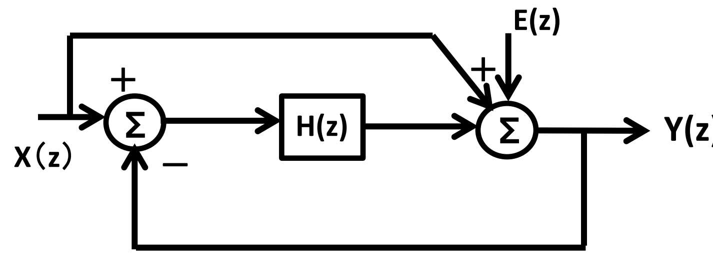
# Feedback-type ΔΣ Modulator and Operation

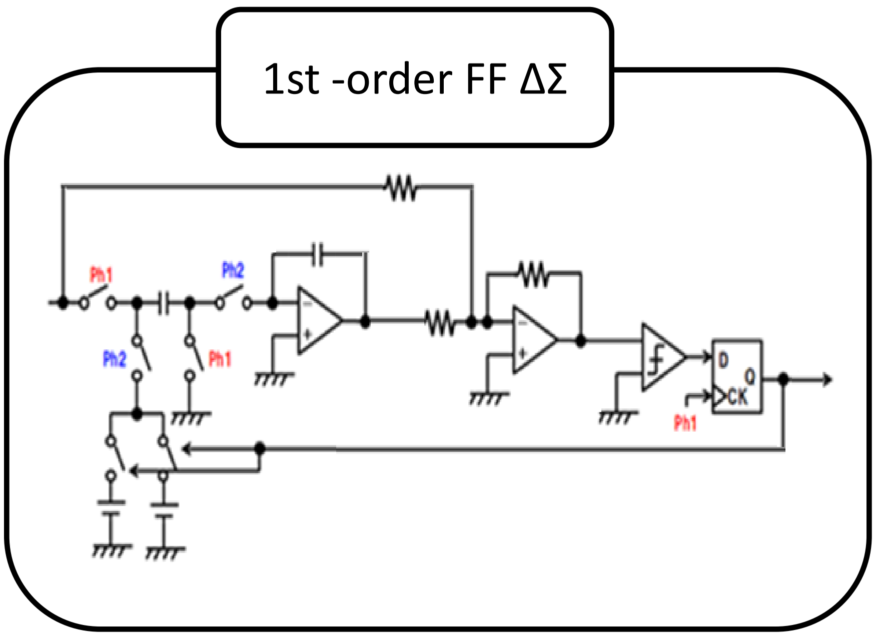



Sampling Frequency ∝ Number of Pulses

# 1st-order Feedforward ΔΣ Modulator




$$Y(z) = X(z) + \frac{1}{1 + H(z)} \cdot E(z)$$

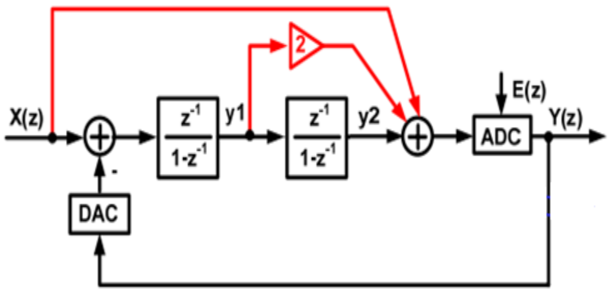
$$H(z) = \frac{z^{-1}}{1 - z^{-1}}$$

$$STF = 1 \qquad NTF = 1 - z^{-1}$$

**No Delay**

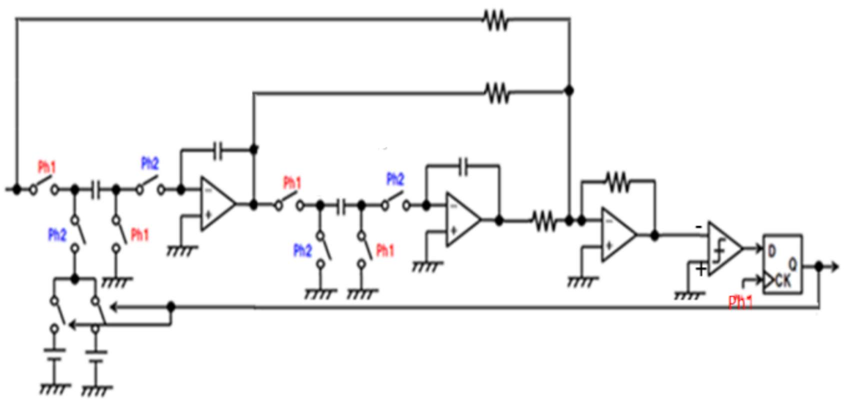
**Differentiation=Noise Shaping**

# 2nd-order Feedforward-type ΔΣ Modulator




$$Y(z) = X(z) + \left(1 - z^{-1}\right)^2 E(z)$$

2nd-order FF ΔΣ

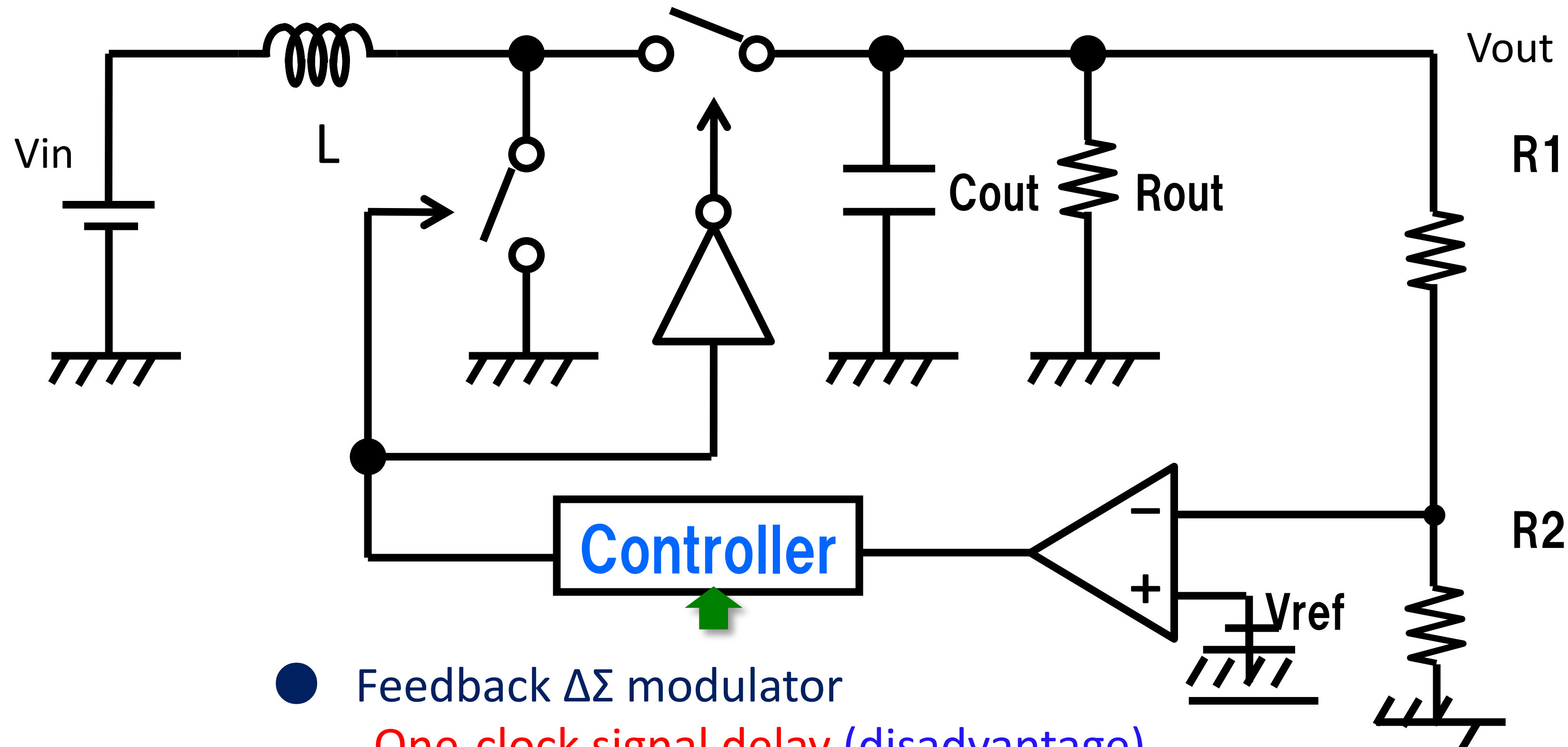


STF = 1 NTF= $(1 - z^{-1})^2$

No Delay

2nd-order Differentiation

# ΔΣ Modulator as DC-DC Converter Controller

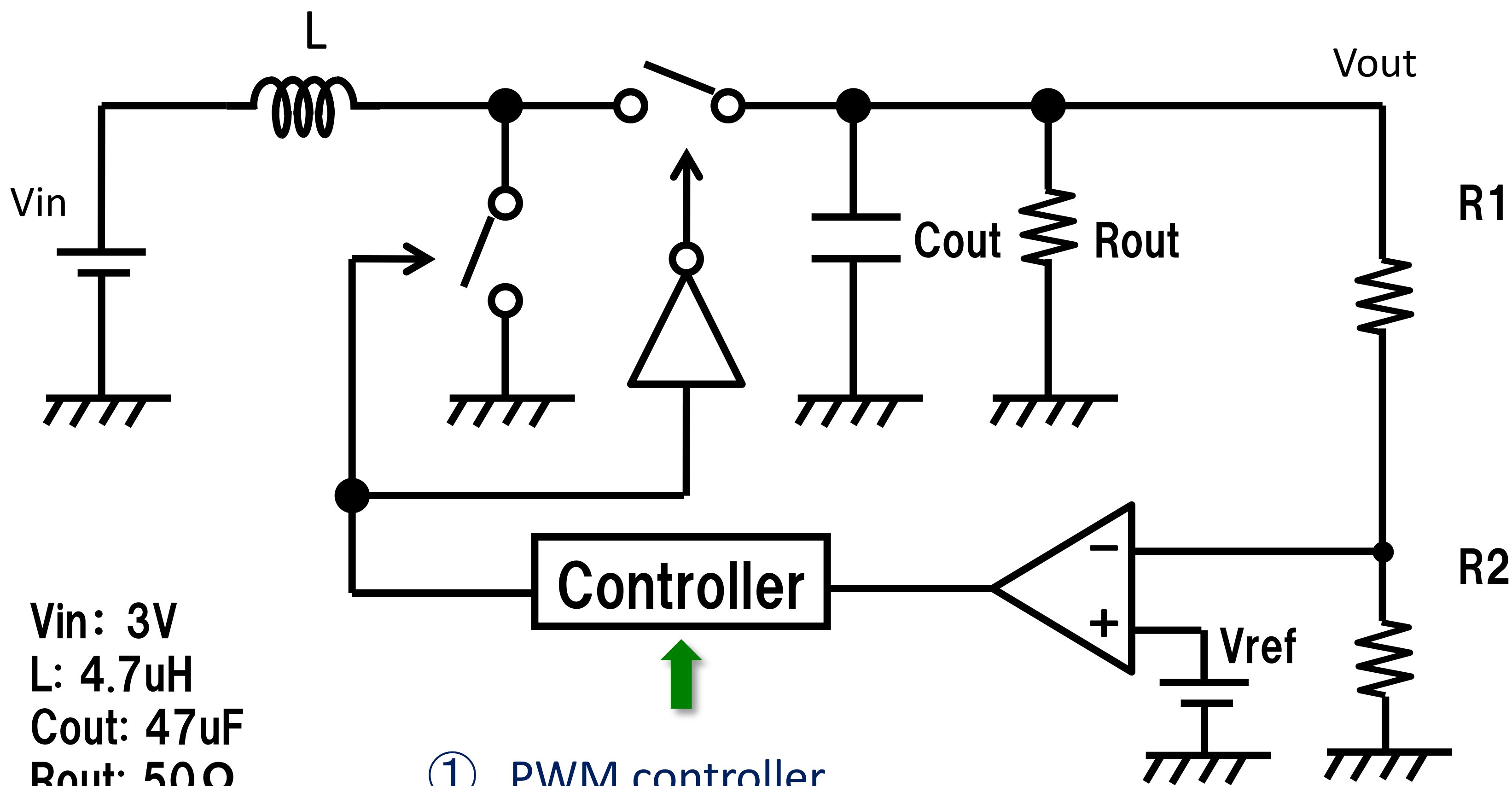



- Feedback ΔΣ modulator
  One-clock signal delay (disadvantage)
- Feedforward ΔΣ modulator
  No signal delay (advantage)

We expect → phase & gain margin improvement
small ripple
fast transient response

# Simulation Condition

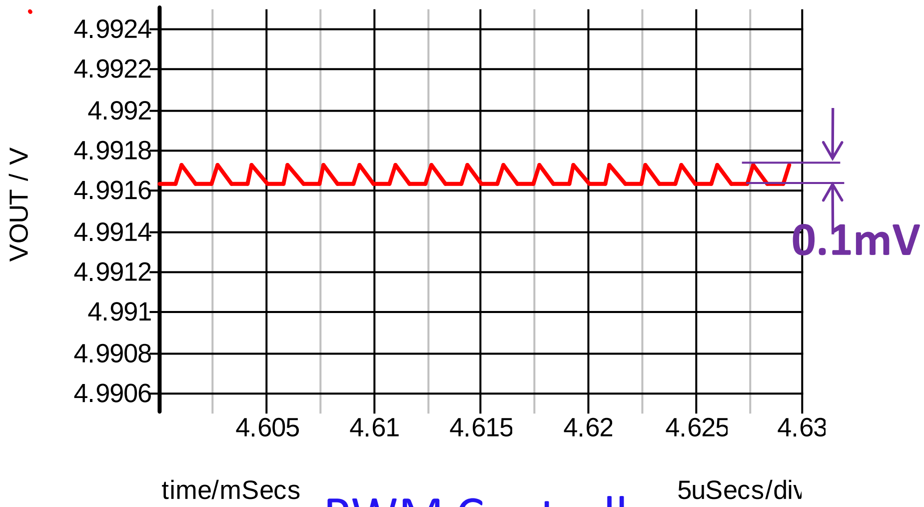
Boost DC-DC Converter



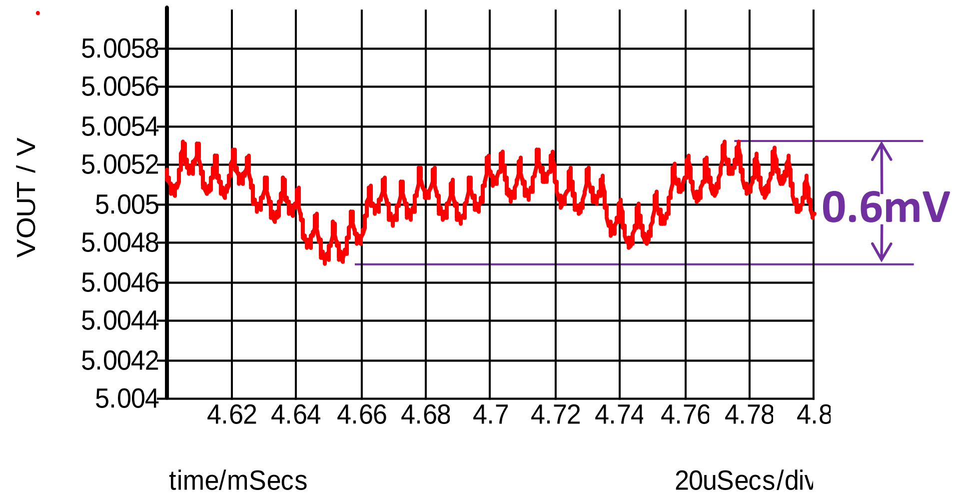

Vin: 3V
L: 4.7uH
Cout: 47uF
Rout: 50Ω
Vref: 600mV
Fs: 400kHz (PWM)
Fs: 800kHz (ΔΣ)

① PWM controller
② 1st-order feedback ΔΣ modulator
③ 1st-order feedforward ΔΣ modulator
④ 2nd-order feedfoward ΔΣ modulator

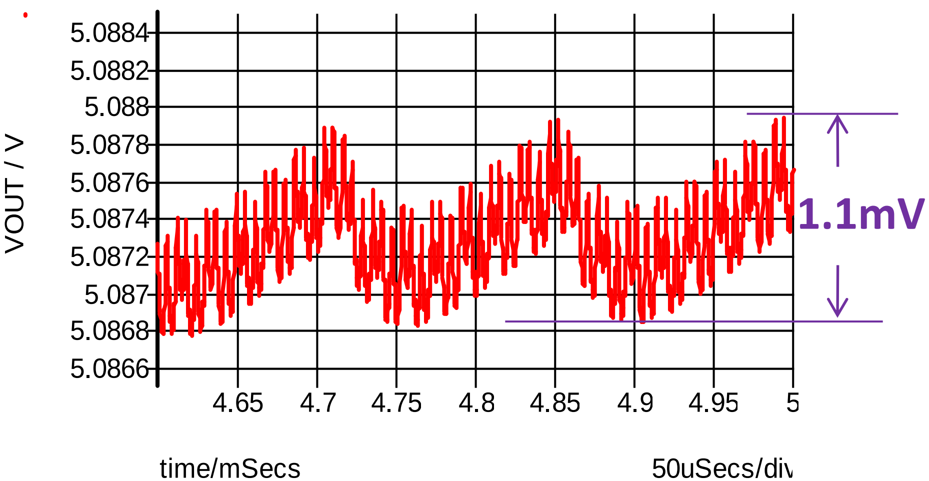
# Output Ripple Voltage (Simulation Results)



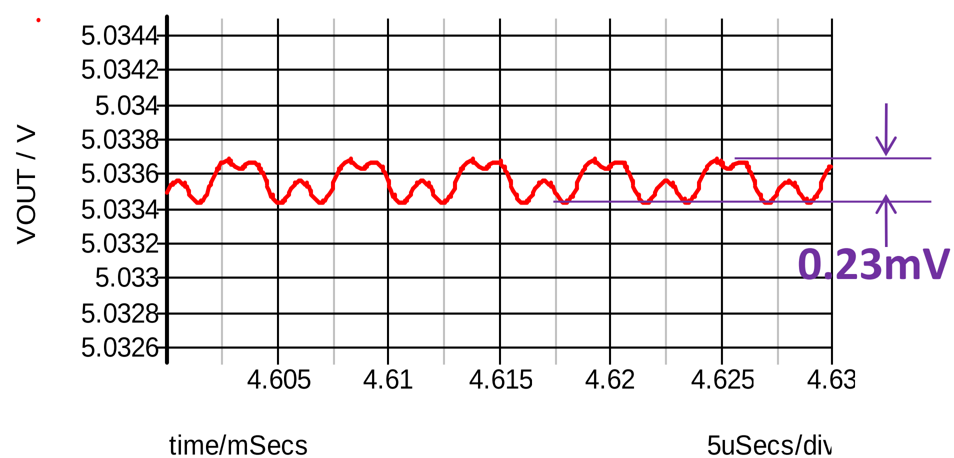

PWM Controller




1st-order Feedforward ΔΣ modulator

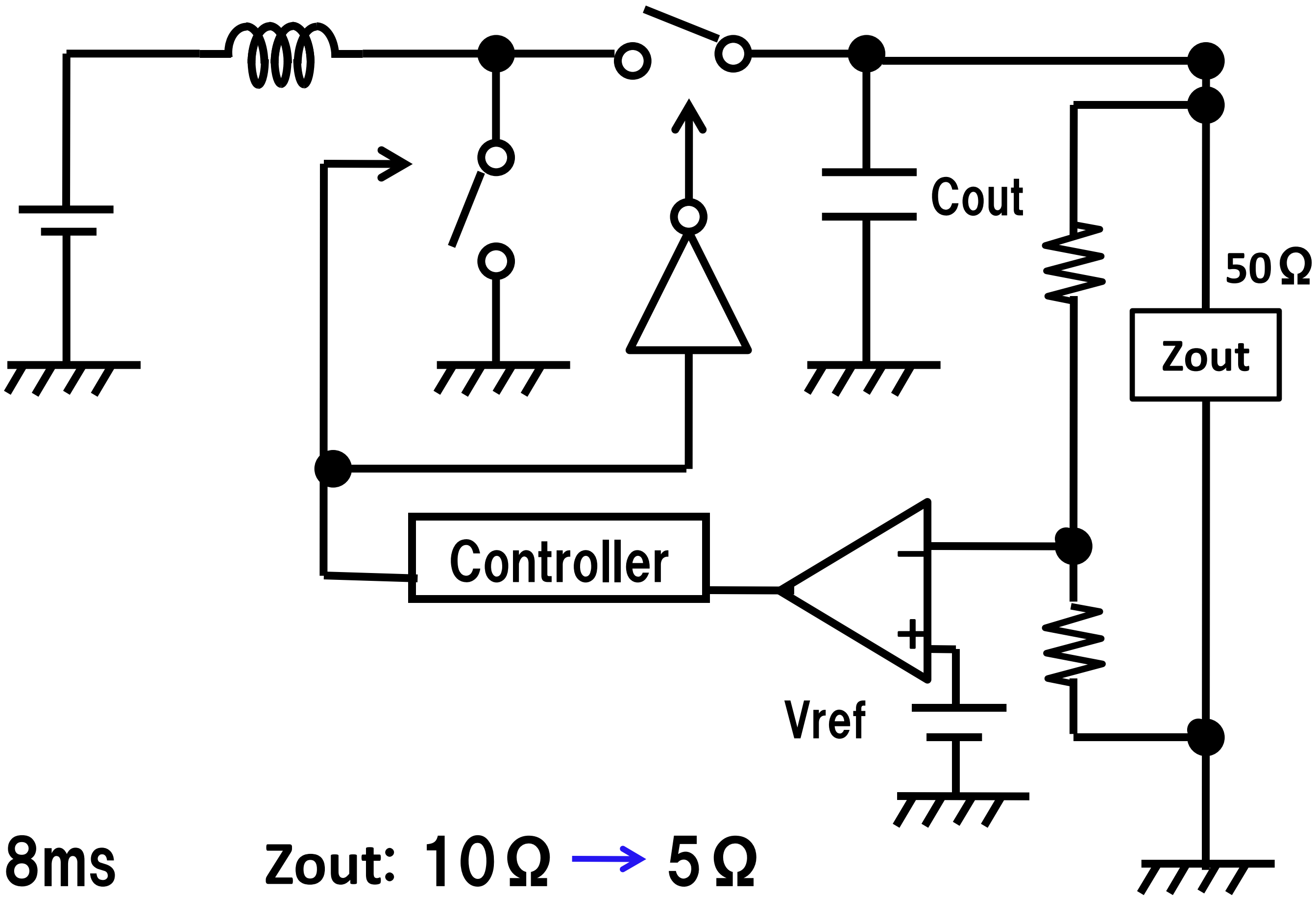



1st-order Feedback ΔΣ modulator



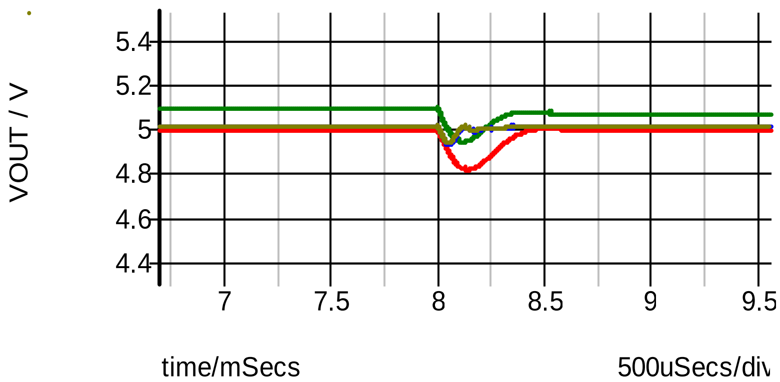

2nd-order Feedforward ΔΣ modulator

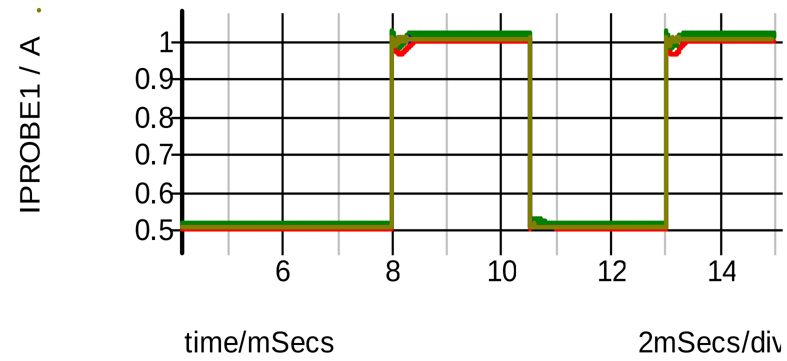
# Transient Response Simulation




At 8ms Zout: 10Ω → 5Ω
At 10.5ms Zout: 5Ω → 10Ω

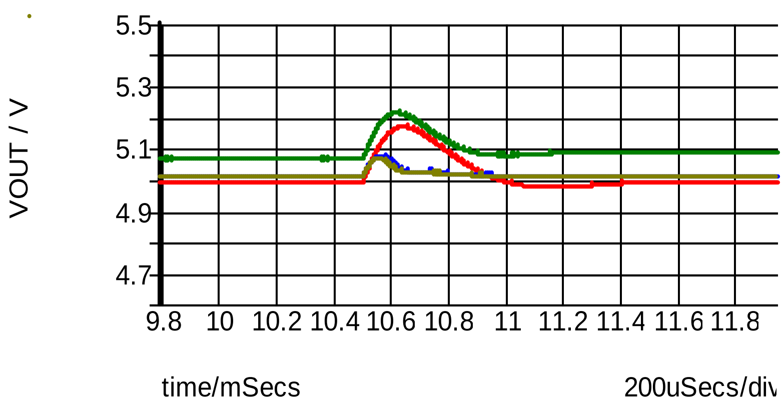
# Transient Response Simulation




Output Current **Iout**

**At 8ms** **Zout**: 10Ω → 5Ω
(**Iout**: 0.5A → 1A)




PWM
$1^{st}$- order Feedback ΔΣ modulator
$1^{st}$-order Feedforward ΔΣ modulator
$2^{nd}$- order Feedforward ΔΣ modulator

**At 10.5ms** **Zout**: 5Ω → 10Ω
(**Iout** : 1A → 0.5A)

# Simulation Results Summary

| State \ Modulator | | PWM | 1st-order Feedback ΔΣ | 1st-order Feedforward ΔΣ | $2^{nd}$-order Feedforward ΔΣ |
|---|---|---|---|---|---|
| Steady State | Ripple | 0.1mV ① | 1.1mV ④ | 0.6mV ③ | 0.23mV ② |
| Transient State(fall) | Ripple | 0.18V ④ | 0.15V ③ | 0.083V ② | 0.074V ① |
| | Time | 0.68ms ④ | 0.55ms ③ | 0.28ms ① | 0.28ms ① |

PWM controller case: steady state ripple ➡ smallest
but transient response ➡ slowest

2nd-order feedforward ΔΣ modulator is the best among 3 ΔΣ modulators.
This is due to

- No signal delay
- Noise is $2^{nd}$-order shaped
- High-frequency noise is reduced by LC circuit

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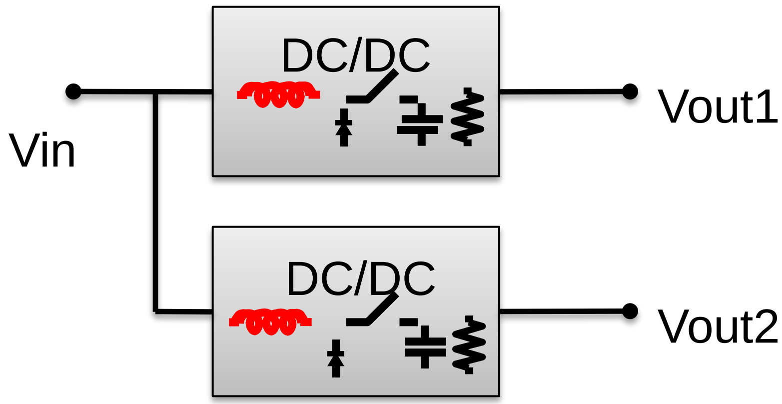
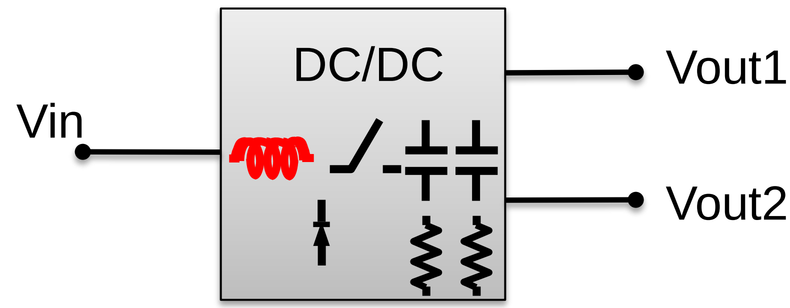
# Background of Single-Inductor Dual-Output DC-DC Converter

**Conventional Dual-output Converter**




**Inductor L×2**
**Bulky, expensive**

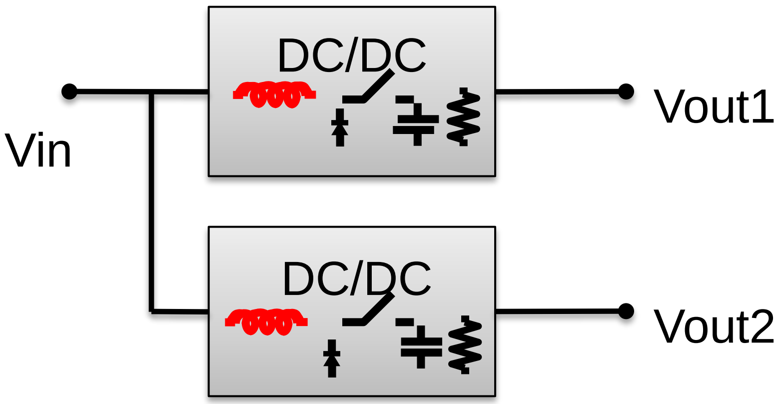
**Signal-Inductor Dual-Output Converter**




**Inductor L×1**
**Small, cheap**

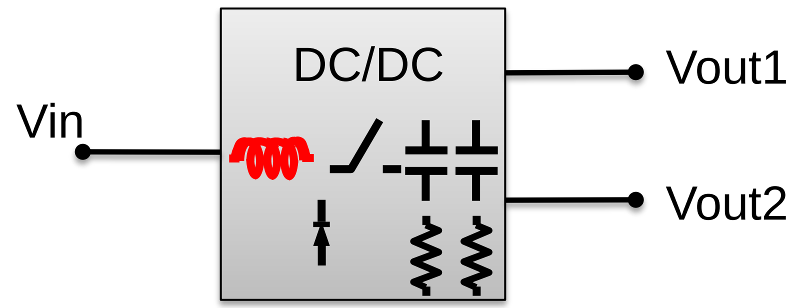
# Background of Single-Inductor Dual-Output DC-DC Converter

**Conventional Dual-output Converter**




**Inductor L×2**
**Bulky, expensive**

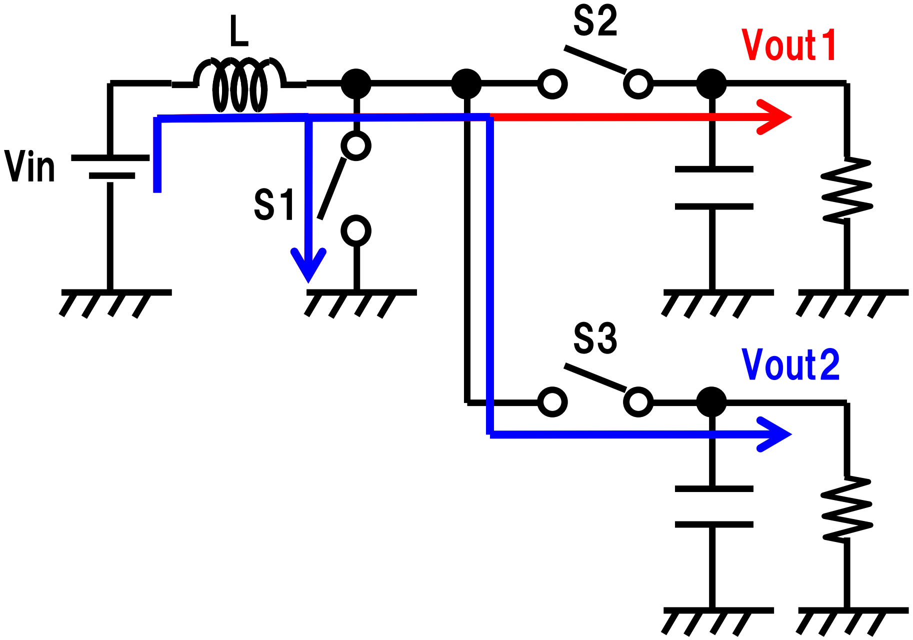
**Signal-Inductor Dual-Output Converter**



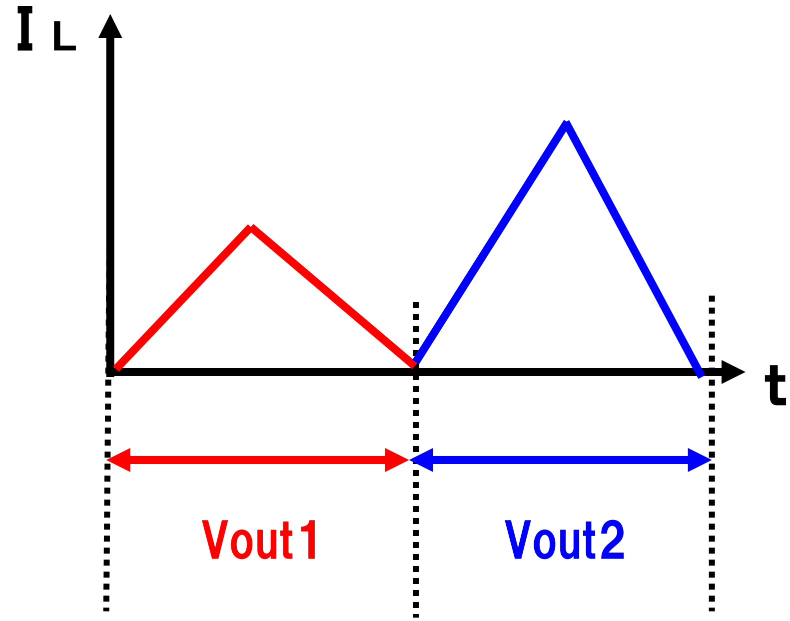

**Inductor L×1**
**Small, cheap**

Hot Research Topic

# Operation Principle of SIDO



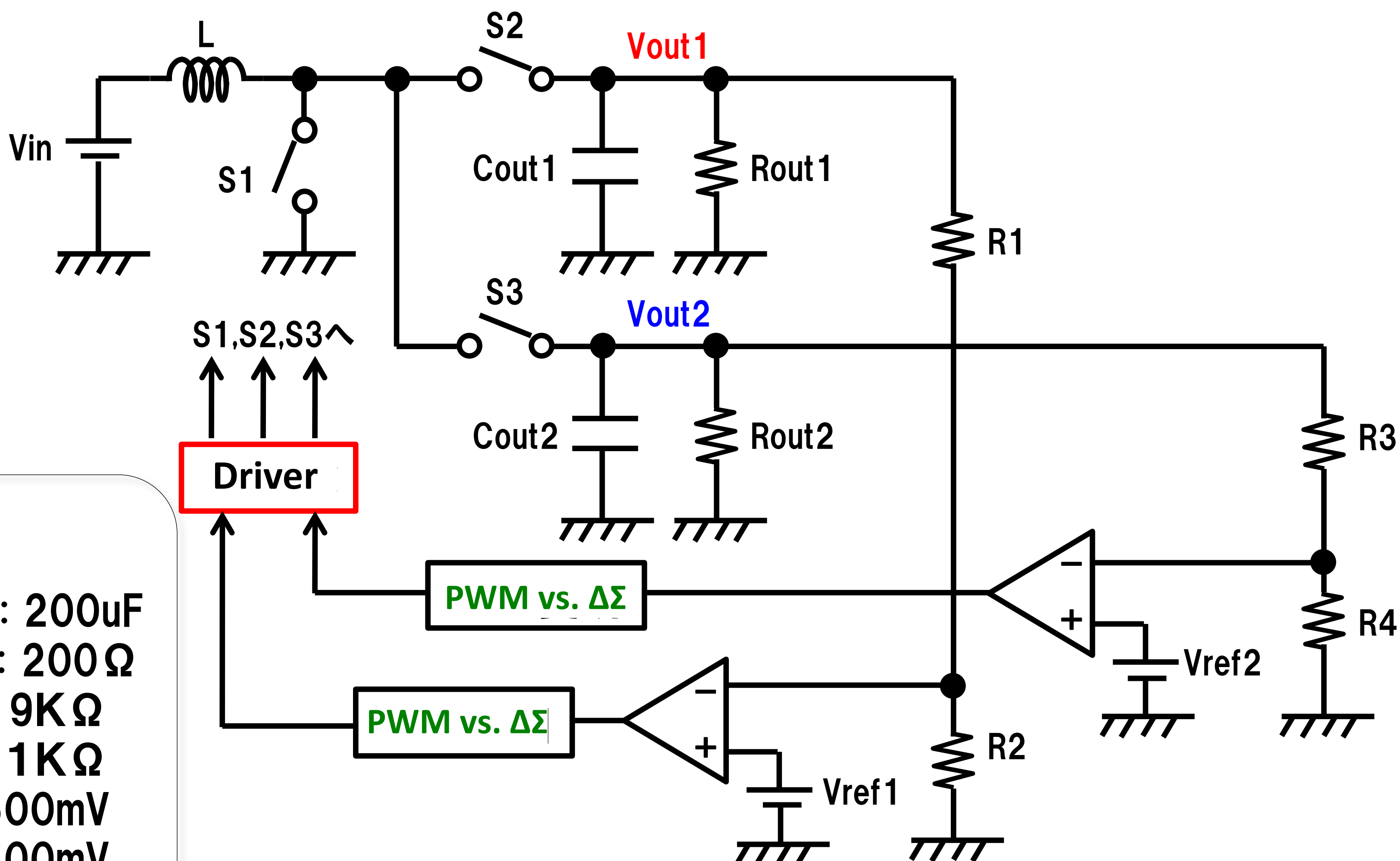

Dual-boost converter




Inductor Current

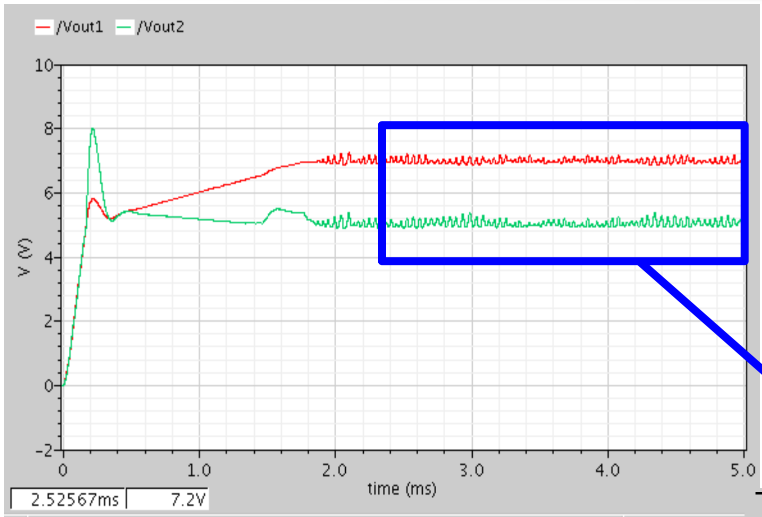
**Dual outputs by time-division usage of inductor**

# Simulation Condition



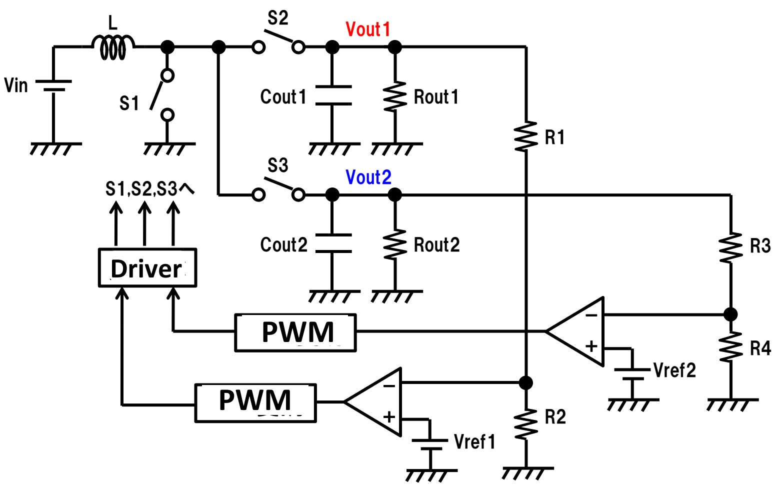

Vin： 3V
L: 1uH
Cout1,2: 200uF
Rout1,2: 200Ω
R1, 3: 9KΩ
R2, 4: 1KΩ
Vref1: 500mV
Vref2: 700mV
Fs:1MHz (PWM)
Fs: 5MHz (ΔΣ)

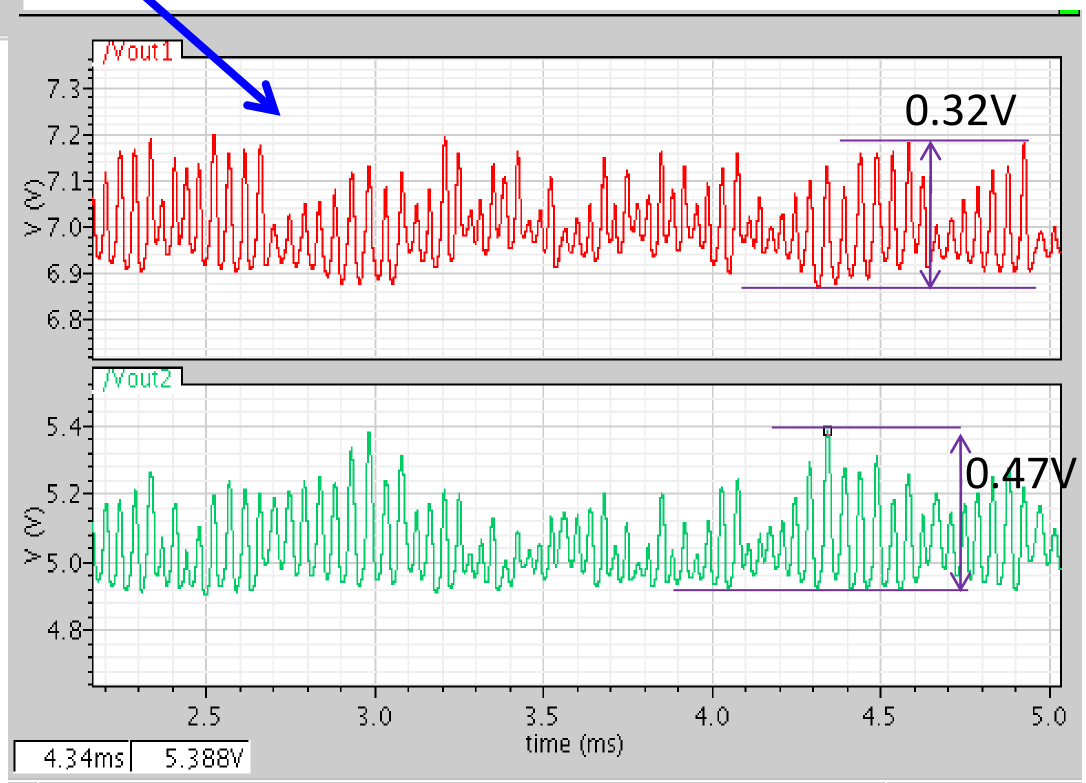
# Simulation Results with PWM Controller



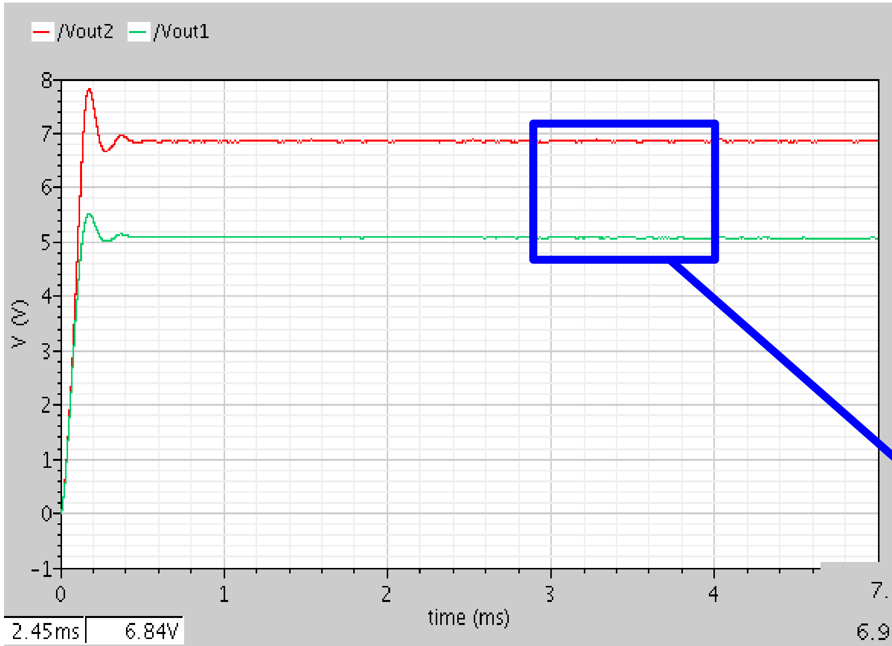

Vout1 (Vref1=7.0V)

Vout2 (Vref2=5.0V)



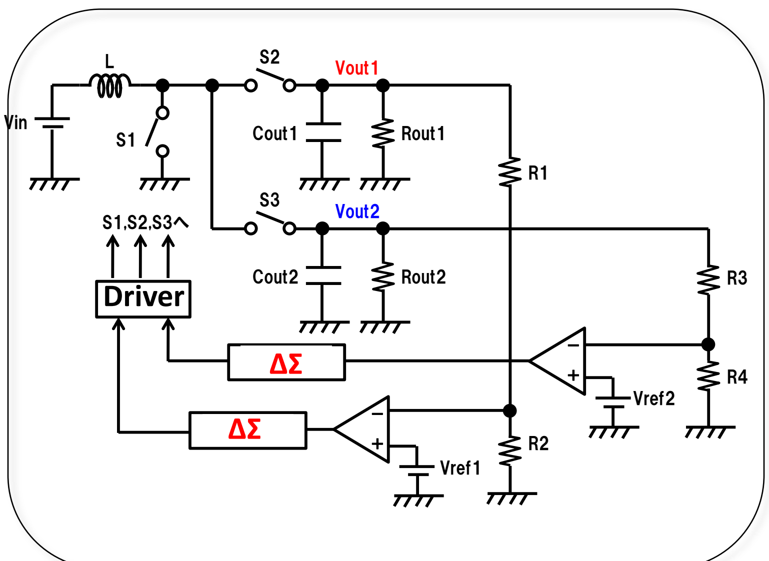
# Simulation Results with Feedforward ΔΣ Controller

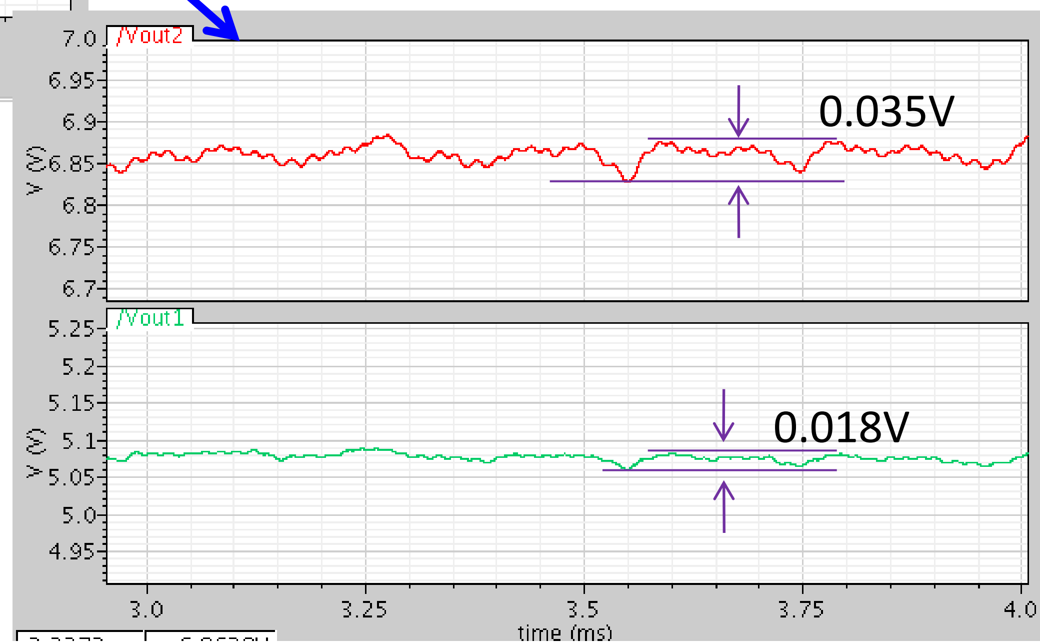



Vout1 (Vref1=7.0V)

Vout2 (Vref2=5.0V)

Smaller ripple voltage



# SIDO & ΔΣ Modulator

- We here showed
  ΔΣ modulator is applicable to SIDO converter

- Zout1 changes ➡ Vout1, Vout2 change

⬇

ΔΣ modulator ➡ high switching freq. operation

⬇

Vout1, Vout2 recover soon
(fast response and good cross-regulation)

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# Conclusion

- As the DC-DC Converter Controller

  ΔΣ Modulator excels PWM

  Merit: Fast transient response

  FeedForward ΔΣ Modulator excels Feedback-type

  Second-Order Modulator excels First-Order

  Merits : Small output voltage ripple

  Fast transient response

- ΔΣ Modulator applicable to SIDO DC-DC Converter

# Future Work

- Efficiency evaluation of DC-DC converter with ΔΣ modulator
- Application of ΔΣ modulator to current-mode control
- Application of ΔΣ modulator to AC-DC converter

# Thank you for your attention!

# Any questions?

# Simulation Results with Feedforward ΔΣ Controller

Vin : 3 [V]
L:1 [uH]
Cout1,2:200 [uF]
Rout1,2:200 [Ω]
R1, 3:9K [Ω]
R2, 4:1K [Ω]
Vref1:500 [mV]
Vref2:700 [mV]
Fs:5 [MHz]