59th System LSI Joint Seminar

# A Novel Triangular Wave Slope Modulation for Improving Dynamic Performance of DC-DC Buck Converter

**Shu Wu**

Division of Electronics and Informatics

School of Science and Technology

Gunma University

# Outline

- Background
- Control schemes of buck converter
- Triangular wave slope modulation
  - Circuit and principle
  - Stability analysis
  - Simulation
- Conclusion

# Outline

- Background
- Control schemes of buck converter
- Triangular wave slope modulation
    - Circuit and principle
    - Stability analysis
    - Simulation
- Conclusion

# Background

- **Switching converter** as a part of **power supplies** system is very impotent for various electronic devices

  (DC-DC converter, AC-DC rectifier, DC-AC inversion, AC-AC cycloconversion )

- **Two concerned issues**
  - **Efficiency**
    - Save energy
    - Control temperature (cost and stability)
  - **Reliability**
    - Stability
    - **Dynamic performance**

# Motivation

- 3 disturbance sources
  - Output reference signal ← ☺ Band-gap reference
  - Input voltage ← ☺ Line feed-forward control
  - Load ☹ Trouble

- Continuous advancement of integrated circuits
  - Faster and faster dynamic current slew rate (120A/us)
  - Lower and lower voltage (0.8V for subthreshold operated circuit)

↓

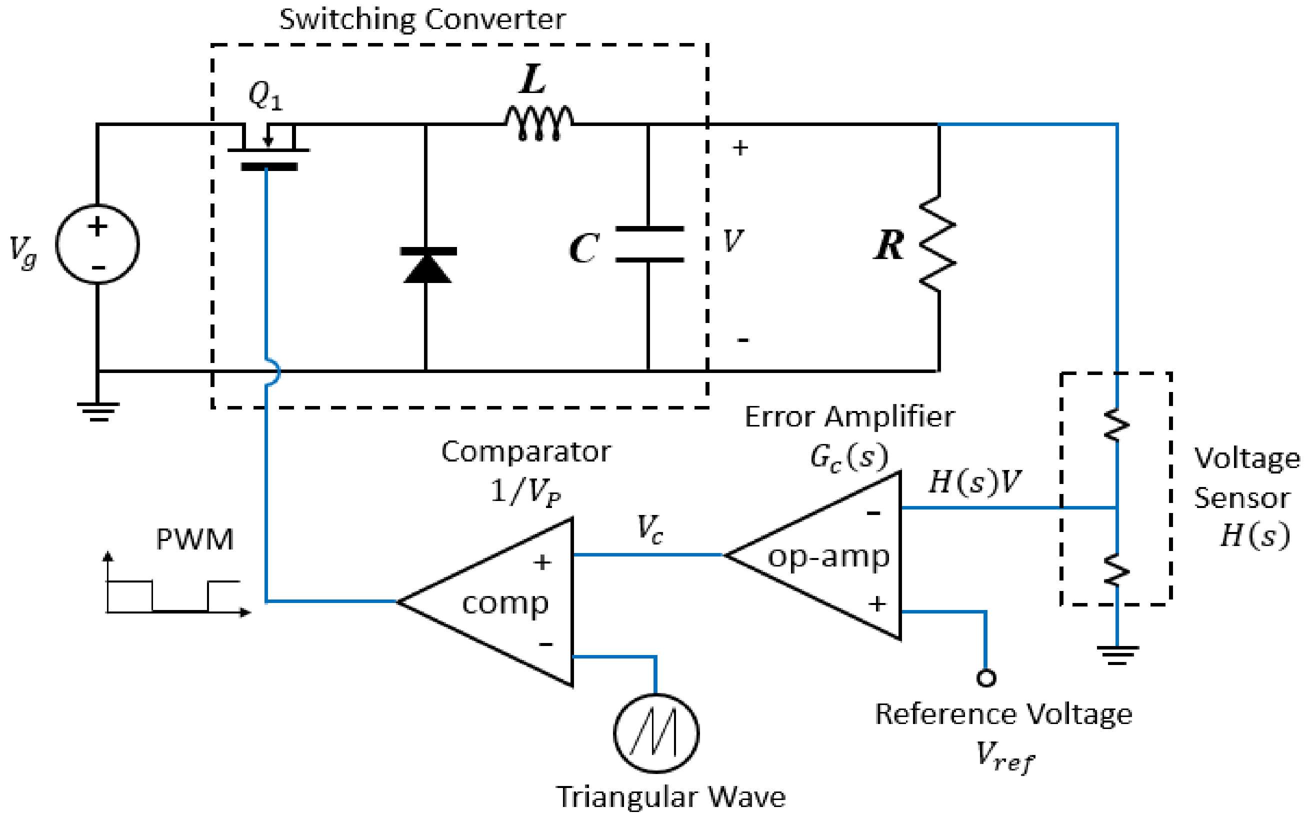
Dynamic performance improvement of power supplies

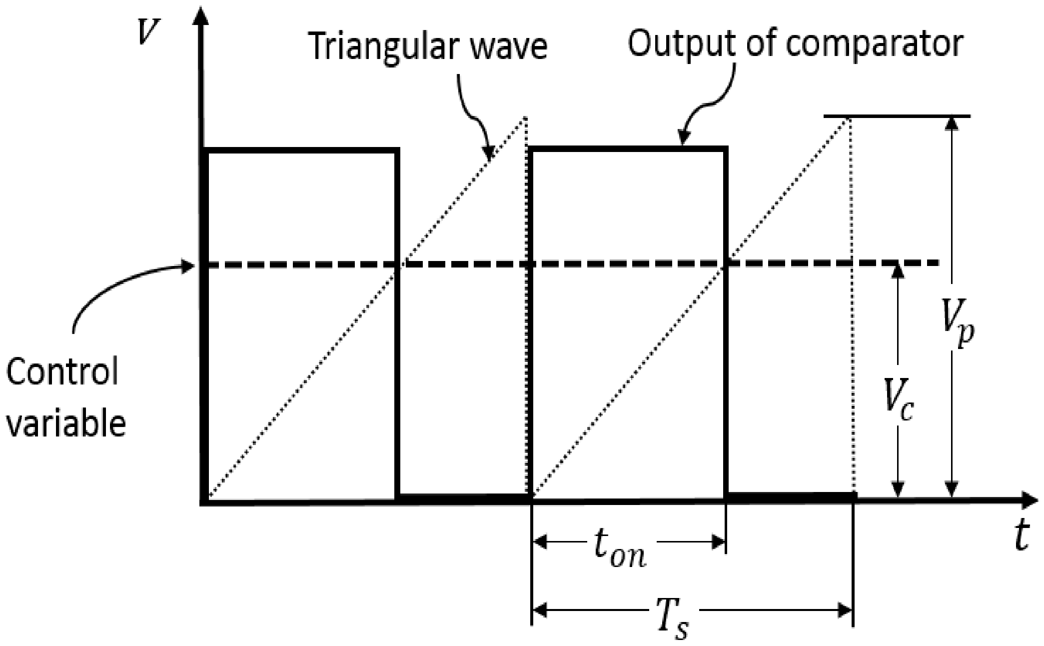
# Outline

- Background
- Control schemes of buck converter
- Triangular wave slope modulation
  - Circuit and principle
  - Stability analysis
  - Simulation
- Conclusion

# Feedback control scheme

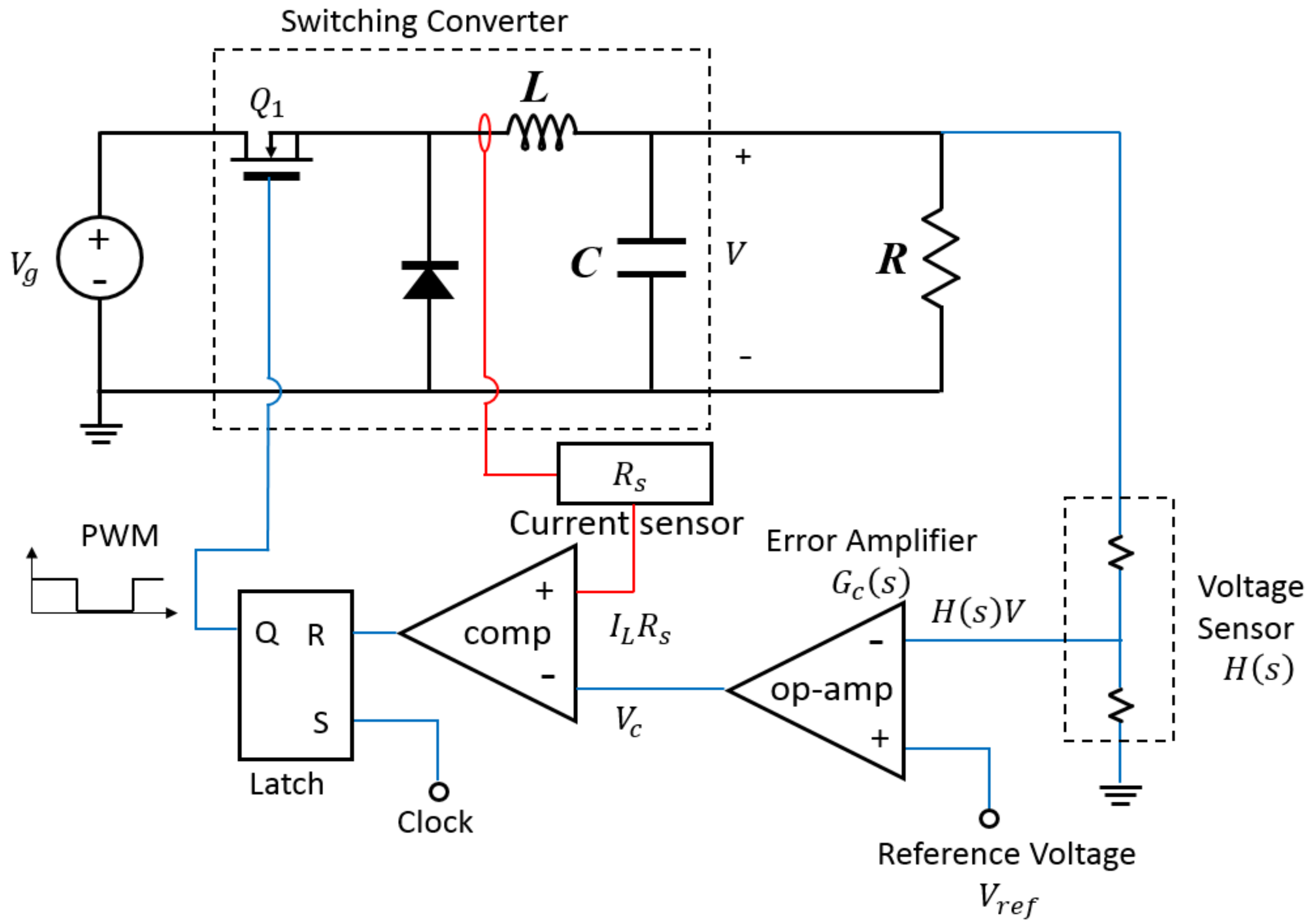
## ------Voltage-Mode Control

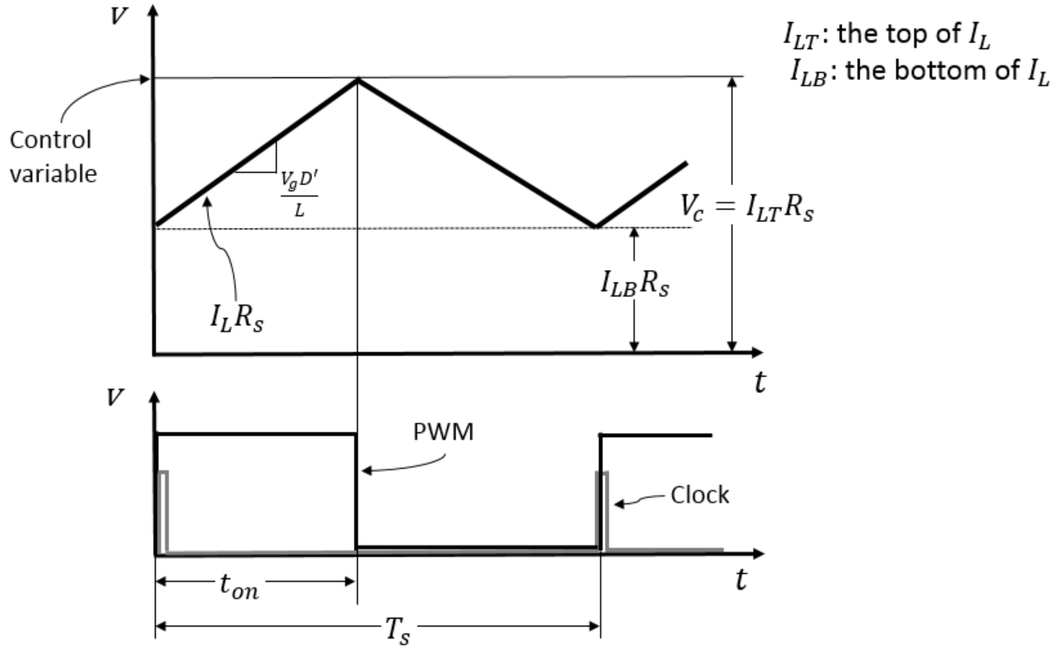




# Feedback control scheme

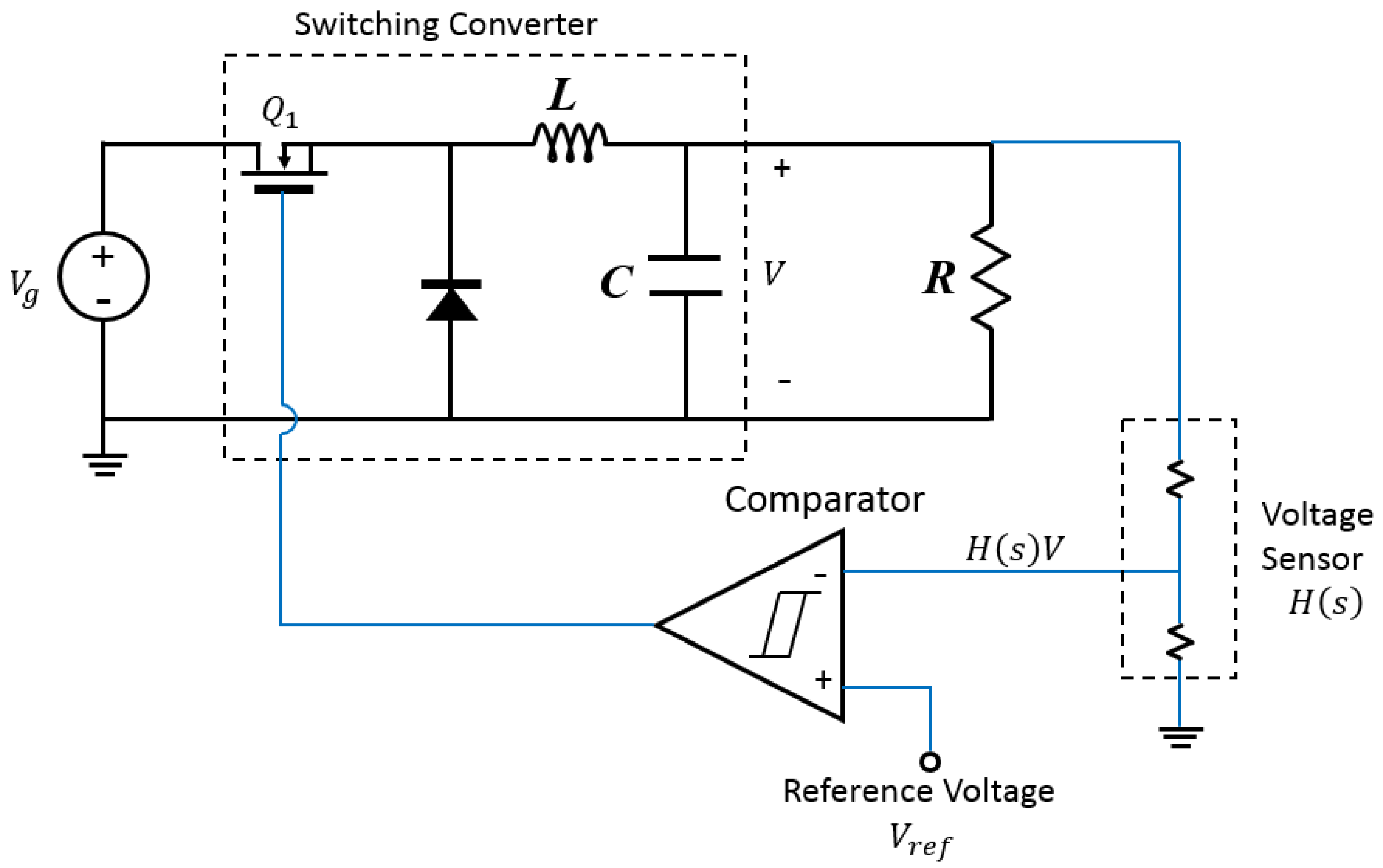
## ------Current-Mode Control

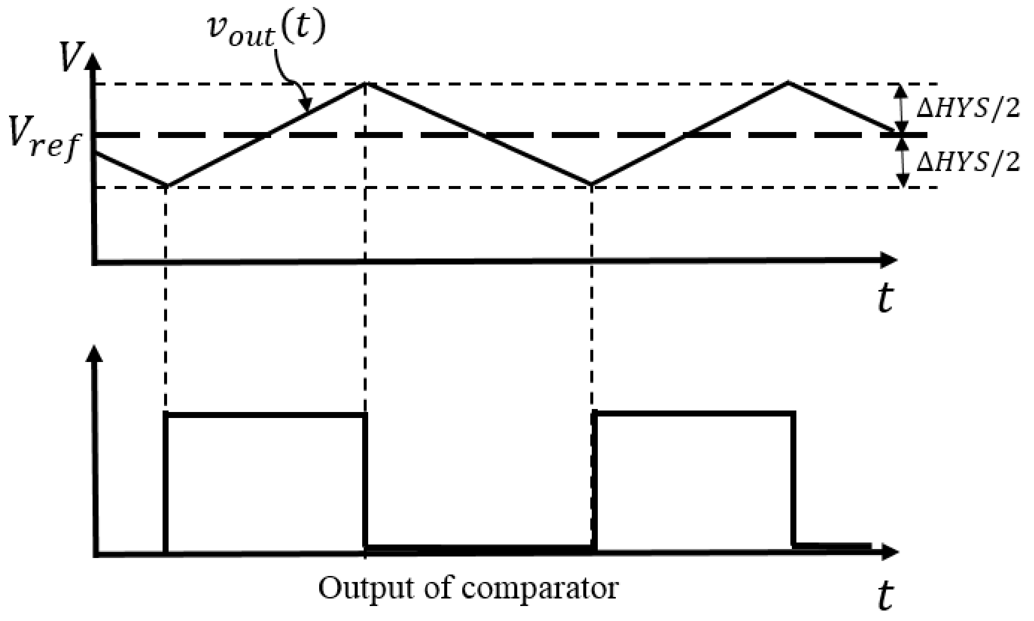




# Feedback control scheme

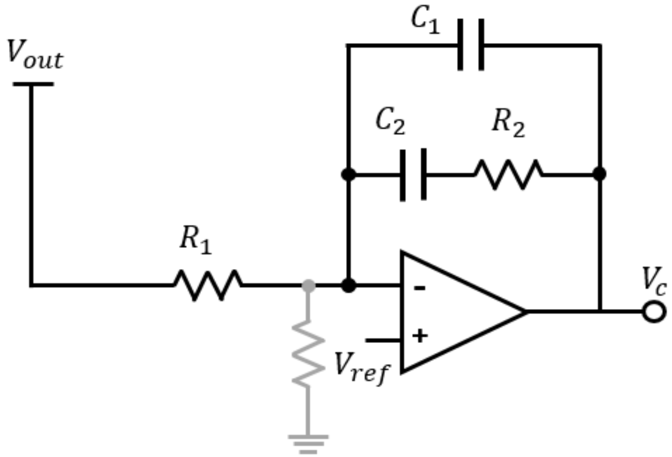
## ------Hysteretic Control

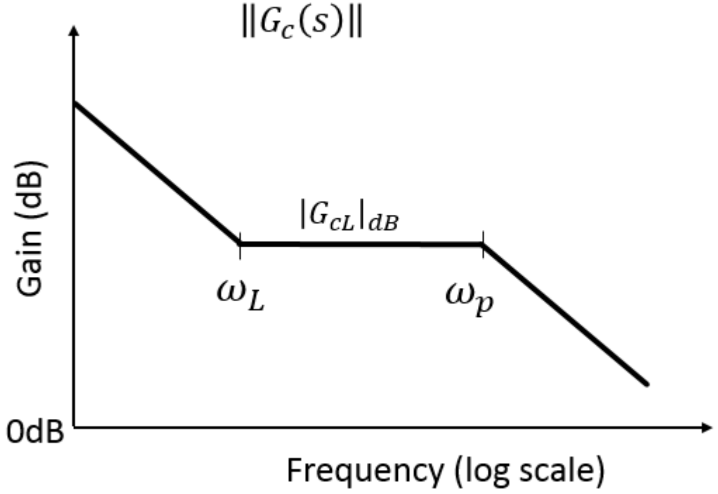




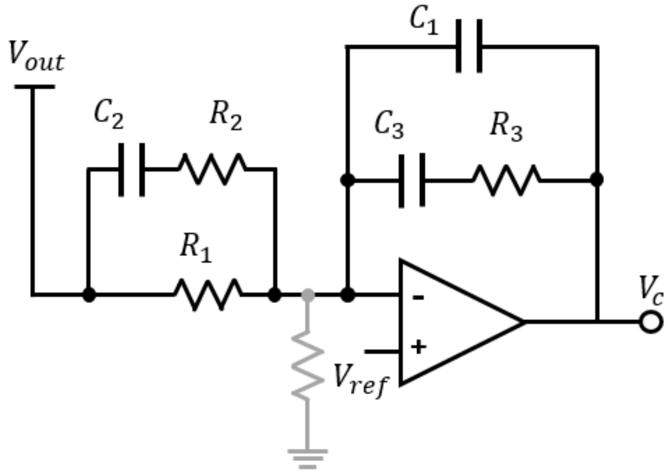
# Phase compensation for VMC and CMC

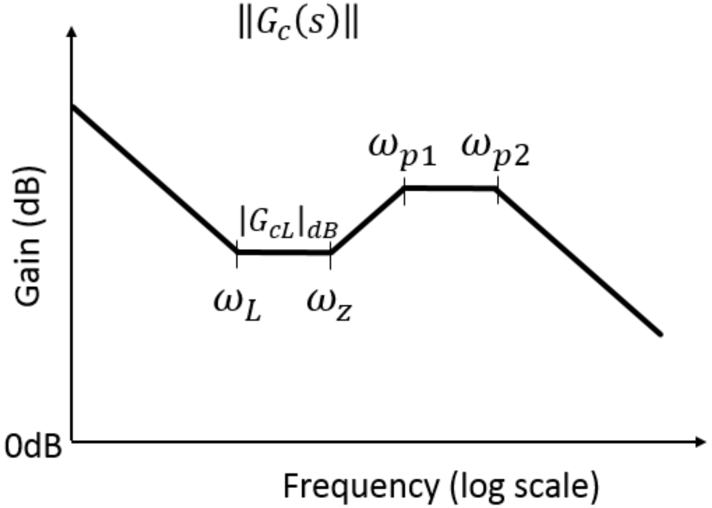
## Type 2 compensator





## Type 3 compensator

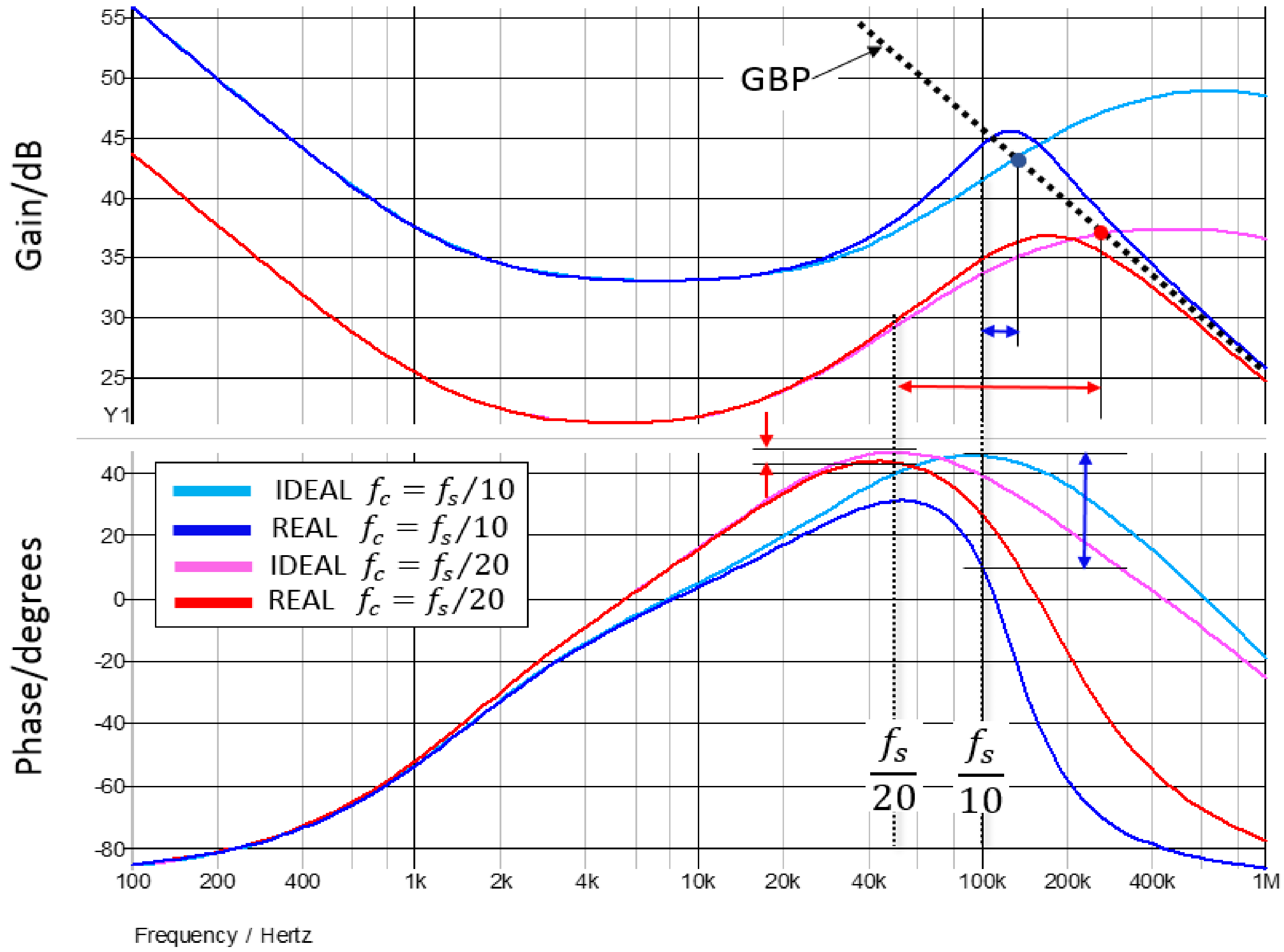




- Not be required in Hysteretic control
- Realize by the error amplifier
- Type 2 for CMC
- Type 3 for VMC

# GBP constraint for Type 3 compensator

(GBP---the Gain Bandwidth Product of op-amp)



Type 3 :

- Large gain at high frequency
- Increase phase margin

**Severe GBP constraint**

**VMC cannot has wider band**

# Advantages and Disadvantages

## VMC

- Easy loop analysis
- Fixed switching frequency

- No line feed-forward
- Low bandwidth (GBP of op-amp)

**The slowest**

## CMC

- Inherent line feed-forward
- Wider band
- Fixed switching frequency

- Current sensor
- Slope compensation
- Blanking time

## Hysteretic control

- Simple
- Fast transient

- Variable switching frequency
- Large output ripple

**The fastest**

This research is based on VMC

# Objective of this research

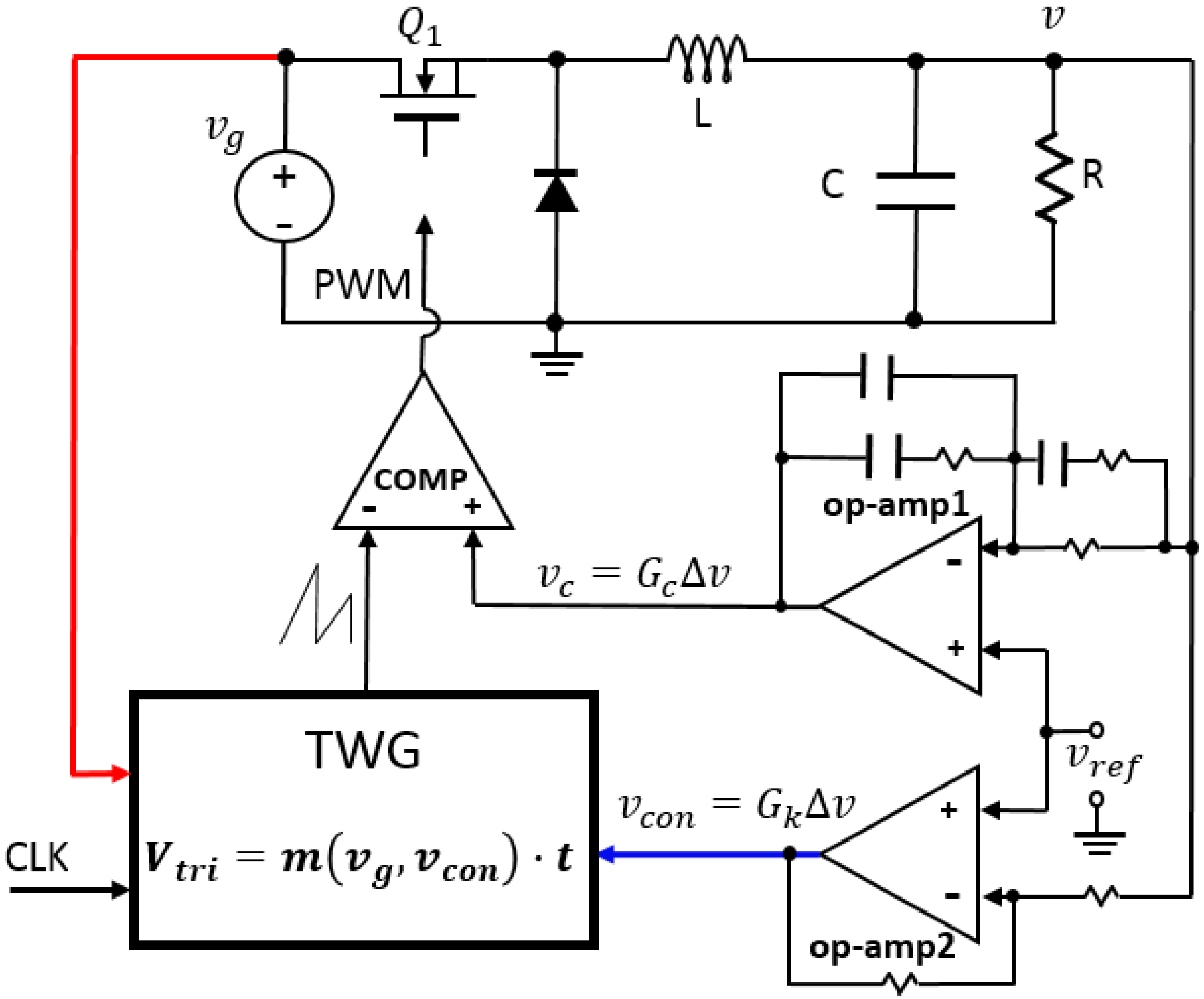
- Triangular wave slope modulation
  - ➢Based on VMC
    - Fixed switching frequency
    - No require current sensor, slope compensation, and blanking time
  - ➢The slope depends on input and output voltage
    - Line feed-forward control
    - Wider band
    - Non-linearly changed loop gain

The **line** and **load** transient response both are improved

# Outline

- Background
- Control schemes of buck converter
- Triangular wave slope modulation
  - Circuit and principle
  - Stability analysis
  - Simulation
- Conclusion

# System configuration



**Op-amp1**:

- Generate control variable $V_c$
- Type 3 compensation

**Op-amp2**:

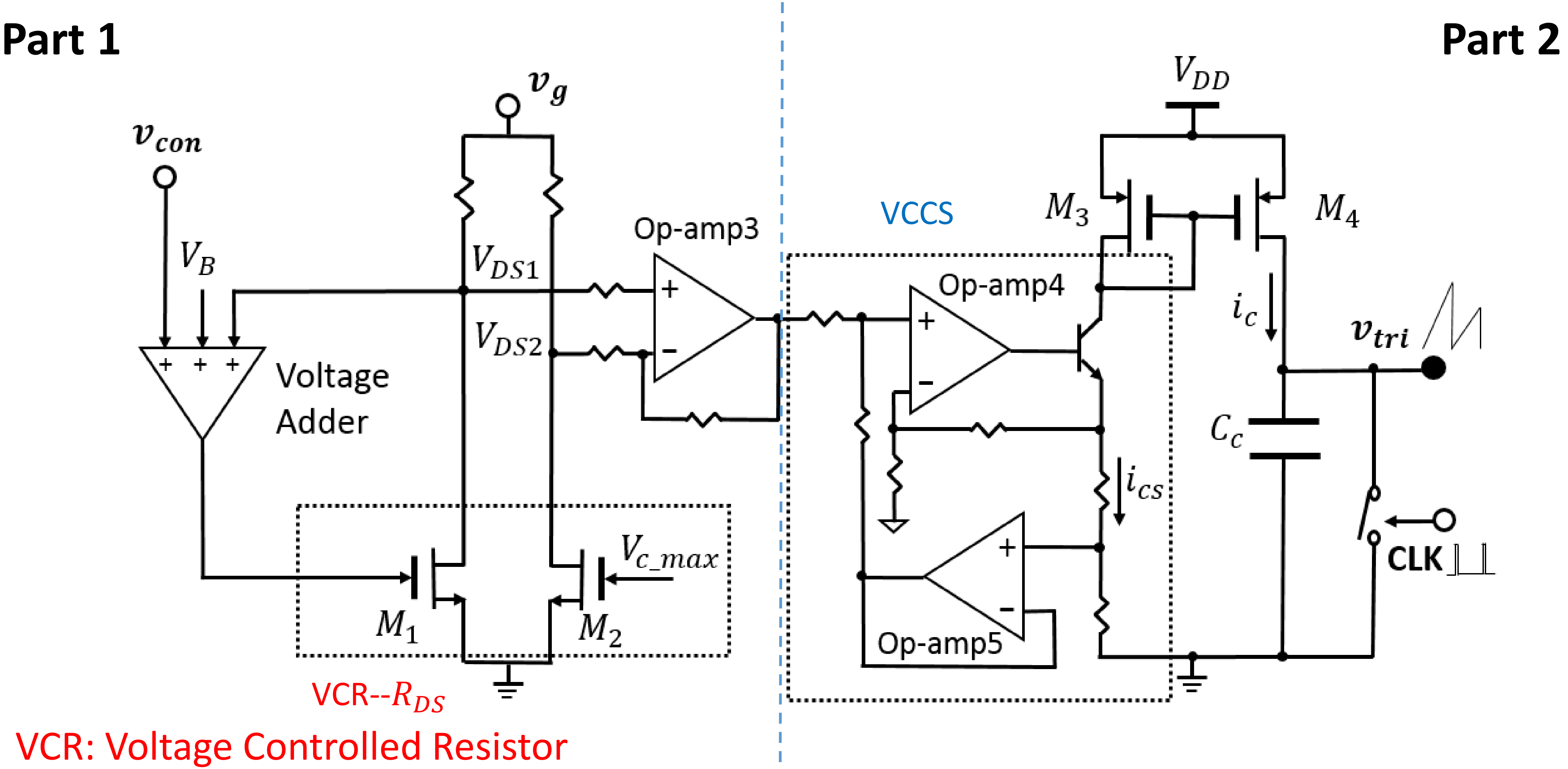
- Amplify deviation
- Control variable of TWG

**TWG (Triangular Wave Generator)**:

Slope adjustable

- Controlled by $V_g$ and $V_{con}$

# Triangular Wave Generator (1)

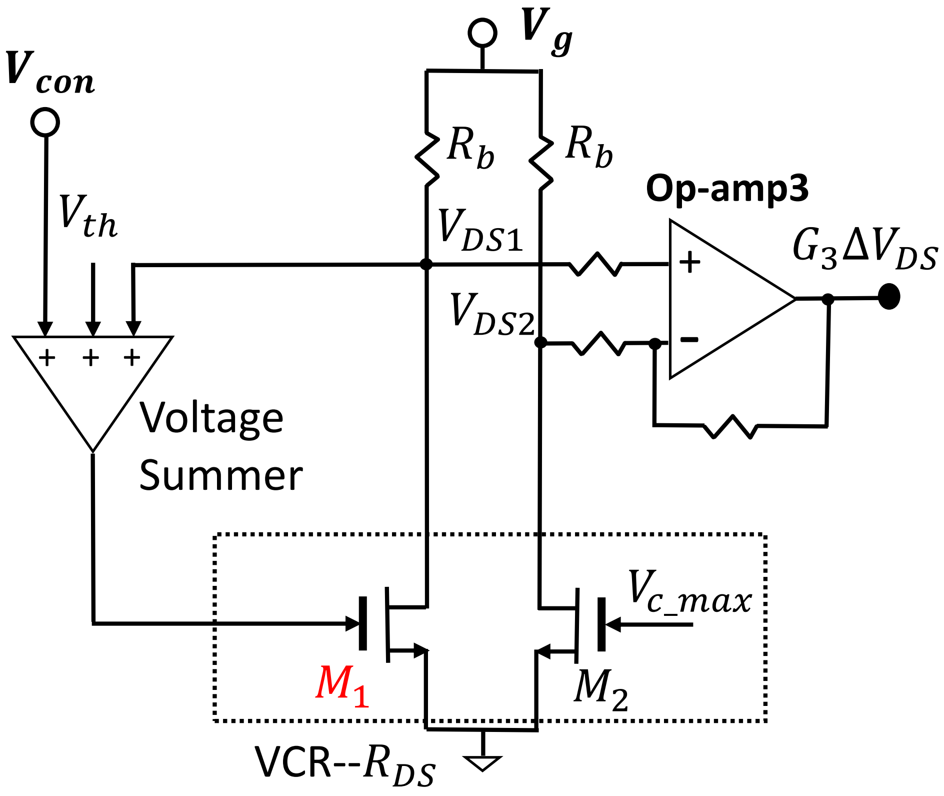


VCR: Voltage Controlled Resistor

VCCS: Voltage Controlled Current Source

# Triangular Wave Generator (2)---Part 1

- VCR



NMOS $M_1$ operates in **triode** region

Equivalent resistor:

$$\frac{1}{R_{DS}} = \frac{I_D}{V_{DS}} = K_n\left(V_{GS} - V_{th} - \frac{V_{DS}}{2}\right)$$

Set $V_{GS} = V_{th} + \frac{V_{DS}}{2} + V_{con}$

$$\boldsymbol{R_{DS} = \frac{1}{K_n V_{con}}}$$

If $R_b \gg R_{DS}$

$$V_{DS} \approx \frac{1}{K_n R_b}\frac{V_g}{V_{con}}$$

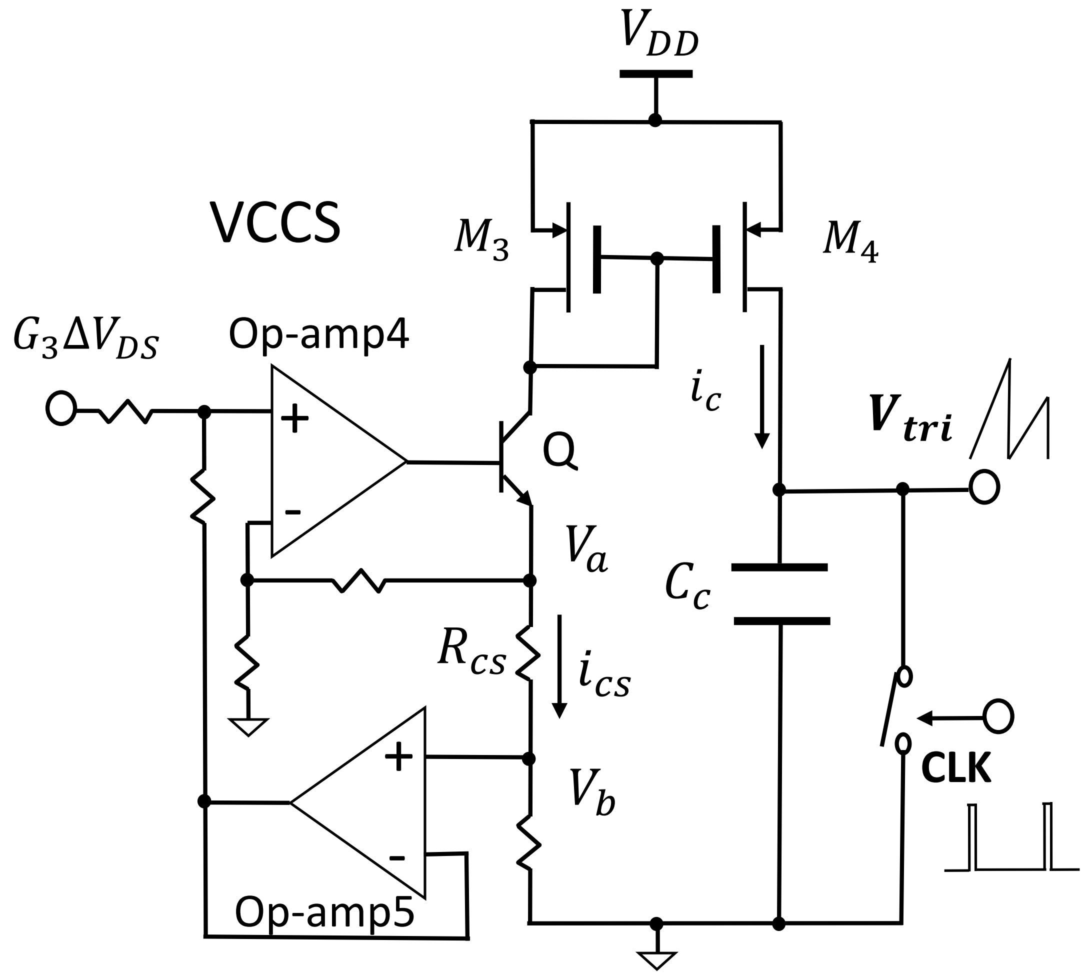
$$\boldsymbol{G_3\Delta V_{DS} = \frac{G_3 V_g}{K_n R_b}\left(\frac{1}{V_{con}} - \frac{1}{V_{con\_max}}\right)}$$

※ $\boldsymbol{K_n = \mu_n C_{ox} W/L}$

$\boldsymbol{V_{c\_max} = V_{th} + \frac{V_{DS}}{2} + V_{con\_max}}$

# Triangular Wave Generator (3)---Part 2

- VCCS & TWG



$$i_C = i_{CS} = \frac{V_a - V_b}{R_{CS}} = \frac{G_3 \Delta V_{DS}}{R_{CS}}$$

$$V_{tri} = \frac{i_c}{C_c} t$$

$$V_{tri} = a \cdot V_g \cdot \left(\frac{1}{V_{con}} - b\right) t = M\left(V_g, V_{con}\right) \cdot t$$

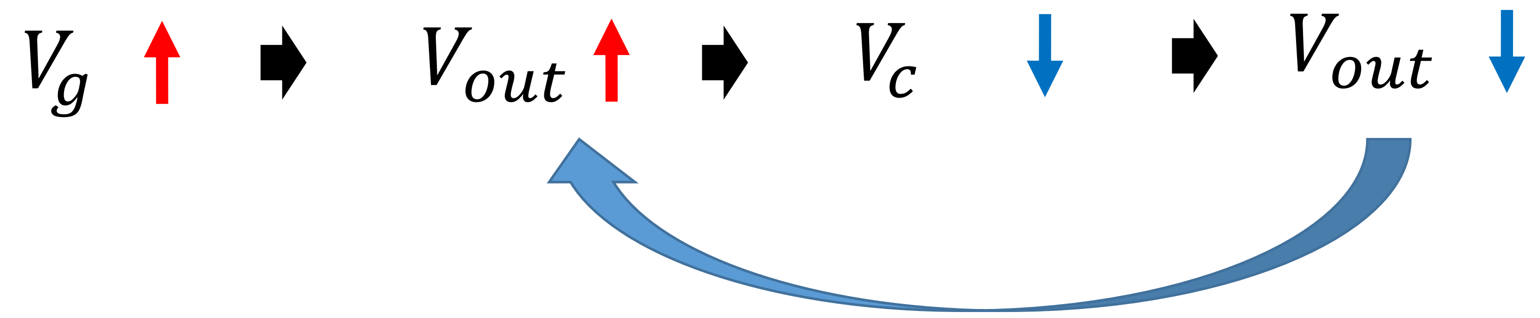
Where $a = \dfrac{G_3}{K_n R_B R_{CS} C_c}$ $\quad b = \dfrac{1}{V_{con\_max}}$

$$M \propto V_g \,,\; M \propto \frac{1}{V_{con}}$$

# Line feed-forward control (1)

Transfer function from control variable to output voltage (VMC buck converter)

$$V_{out} = \frac{1}{LCs^2 + \frac{L}{R}s + 1}\frac{V_g}{V_P}V_c$$



Conventional VMC: $V_g$ ↑ ➡ $V_{out}$ ↑ ➡ $V_c$ ↓ ➡ $V_{out}$ ↓

Output voltage return to the reference

$V_P$ --- the peak of triangular wave

# Line feed-forward control (2)

Line feed-forward: $V_g$ ↑ ➡ $V_P$ ↑

$$V_p = M\left(V_g, V_{con}\right) \cdot T_s = \frac{\left(\frac{1}{V_{con}} - \frac{1}{V_{con\_max}}\right) G_3 T_s}{C_C R_{CS} R_b K_n} \cdot V_g$$

The input variation is eliminated by the proportional variation in $V_P$

Nothing to do with $V_{out}$ and $V_c$

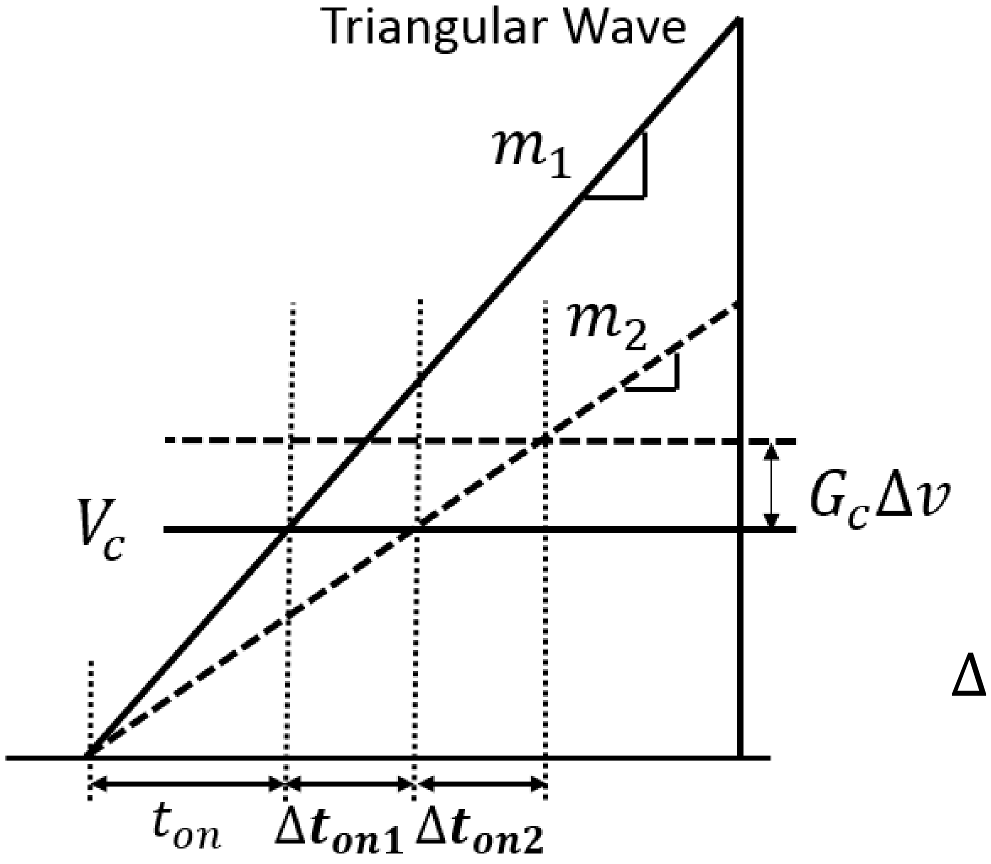
*The changed $V_g$ cause the ripple of inductor current is changed

During line transient response, $\boldsymbol{I_L \neq I_{out}}$. Similar to **load transient response**

Line feed-forward only consider the input voltage variation

# Non-linear duty cycle modulation(1)

Once output voltage deviate from the reference, **whatever the reason**



$\Delta d_1$ is caused by slope modulation

$$\Delta d_1 = \frac{V_C}{T_s} \cdot \left(\frac{1}{m_2} - \frac{1}{m_1}\right) = \frac{V_C}{T_s} \cdot \Delta\frac{1}{m}$$

$\Delta d_2$ is caused by slope and $\boldsymbol{V_c}$ modulations

$$\Delta d_2 = \frac{G_c\Delta v}{T_s} \cdot \frac{1}{m_2} = \frac{G_c\Delta v}{T_s} \cdot \left(\frac{1}{m_1} + \Delta\frac{1}{m}\right)$$

$$\boldsymbol{\Delta d = \Delta d_1 + \Delta d_2 = \boxed{\frac{V_C + G_c\Delta v}{T_s} \cdot \Delta\frac{1}{m}} + \boxed{\frac{G_c\Delta v}{V_{p\_ss}}}}$$

Additional duty cycle modulation by proposed TWG

Conventional VMC

$$\boxed{V_{p\_ss} = m_1 T_s}$$

# Non-linear duty cycle modulation(2)

$$\Delta d(\Delta v) = \mathrm{A}(\Delta v)\cdot\Delta v + \frac{G_c\Delta v}{V_{p\_ss}}$$

$$\mathrm{A}(\Delta v) = \frac{(V_C + G_c\Delta v)G_k}{T_s\cdot a\cdot V_g\left(b\left(V_{ref} - G_k\Delta v\right) - 1\right)\cdot\left(bV_{ref} - 1\right)}$$

Large | Large → Enable fast transient response

$\Delta v$ $\updownarrow$ ➡ $\mathrm{A}(\Delta v)$ $\updownarrow$ Non-linearly change

approach to 0 | approach to a constant → To ensure the loop stability

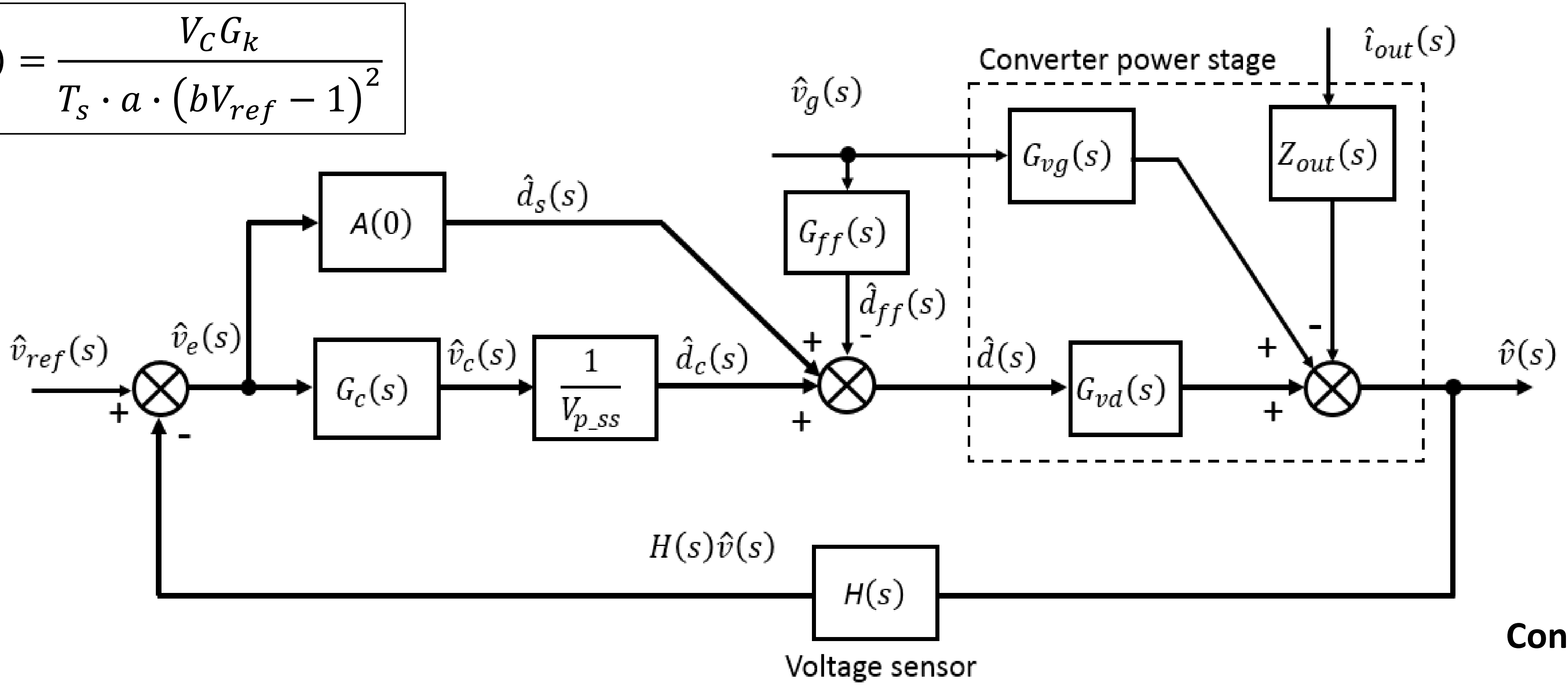
$$\mathrm{A}(0) = \frac{V_C G_k}{T_s\cdot a\cdot\left(bV_{ref} - 1\right)^2}$$

# Outline

- Background
- Control schemes of buck converter
- Triangular wave slope modulation
  - Circuit and principle
  - Stability analysis
  - Simulation
- Conclusion

# System block diagram

$$\mathrm{A}(0) = \frac{V_C G_k}{T_s \cdot a \cdot \left(bV_{ref} - 1\right)^2}$$



**Conventional VMC**

$$T(s) = \left(A(0) + \frac{G_c(s)}{V_{p\_ss}}\right) \cdot H(s) \cdot G_{vd}(s) \Rightarrow T(s) = A(0) \cdot H(s) \cdot G_{vd}(s) + \frac{H(s)G_c(s)G_{vd}(s)}{V_{p\_ss}}$$

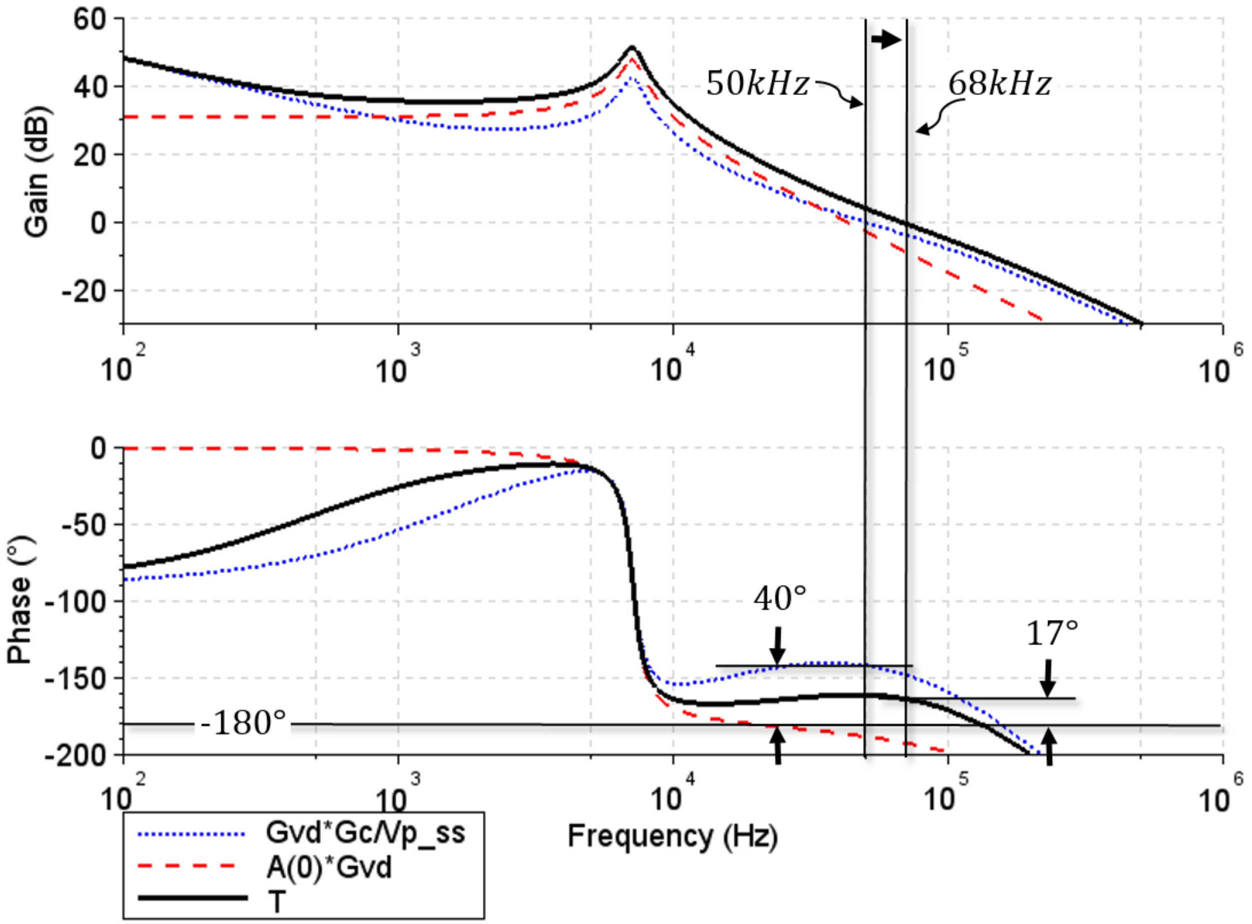
# Bode plot

Buck converter with conventional VMC:

$f_c = f_s/20 = 50kHz, \varphi_m = 40°$

TWG:

$A(0) \approx 6.65$



Compared to conventional VMC

--- $(G_c G_{vd}/V_p)$

- Bandwidth increase

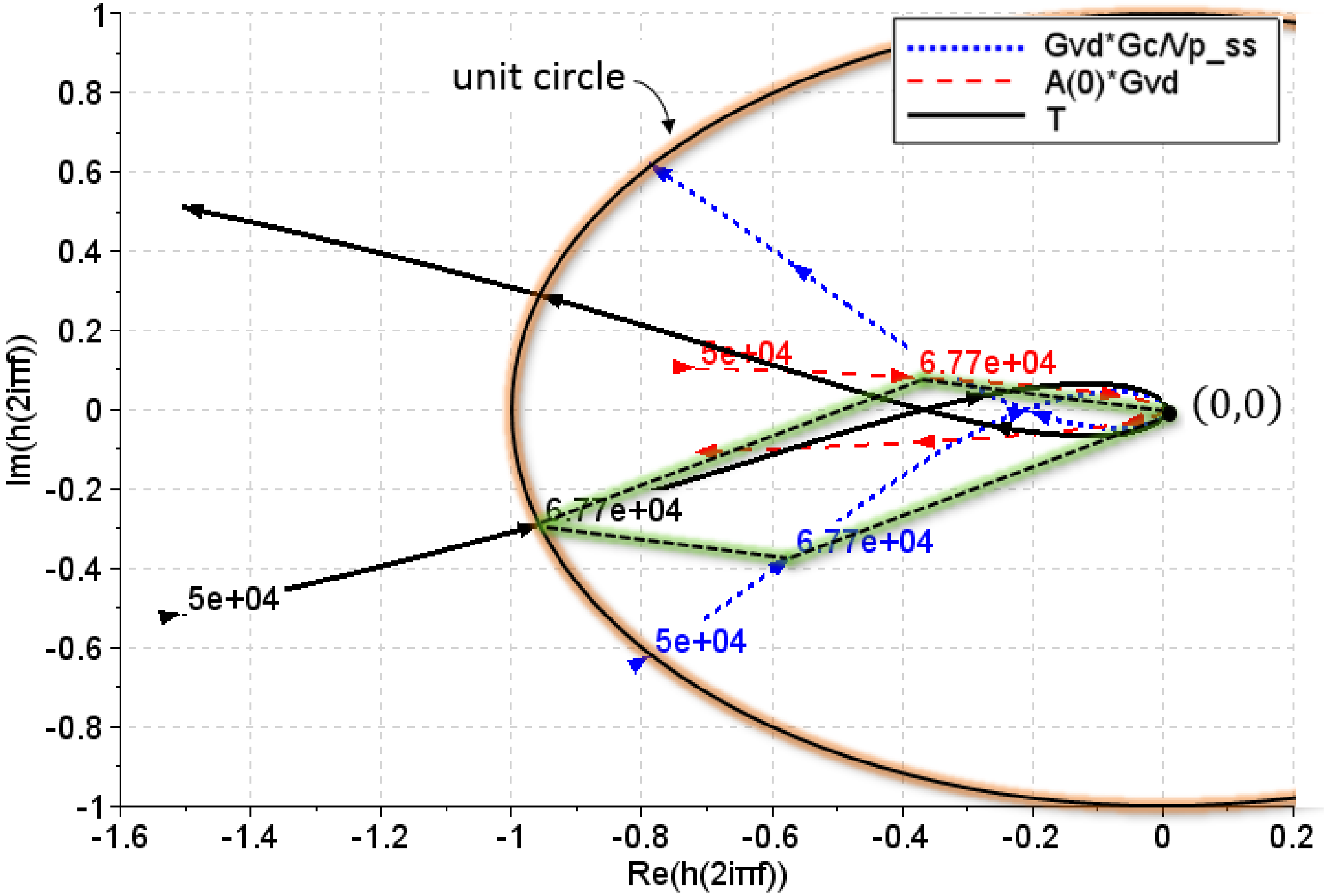
  50kHz → 68kHz

- Phase margin decrease

  40° → 17°

**Oscillation, even unstable**

# Nyquist plot



In order to get enough phase margin

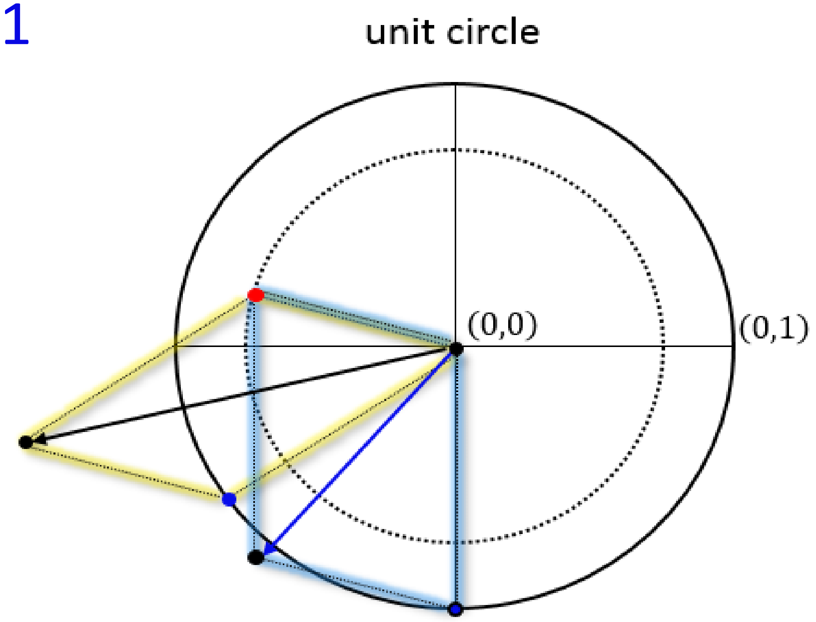
Method 1:
Increase the high-frequency phase of $G_c(s)G_{vd}(s)/V_{p\_ss}$

Method 2:
Increase the high-frequency phase of $A(0)G_{vd}(s)$

# Two methods for enough phase margin

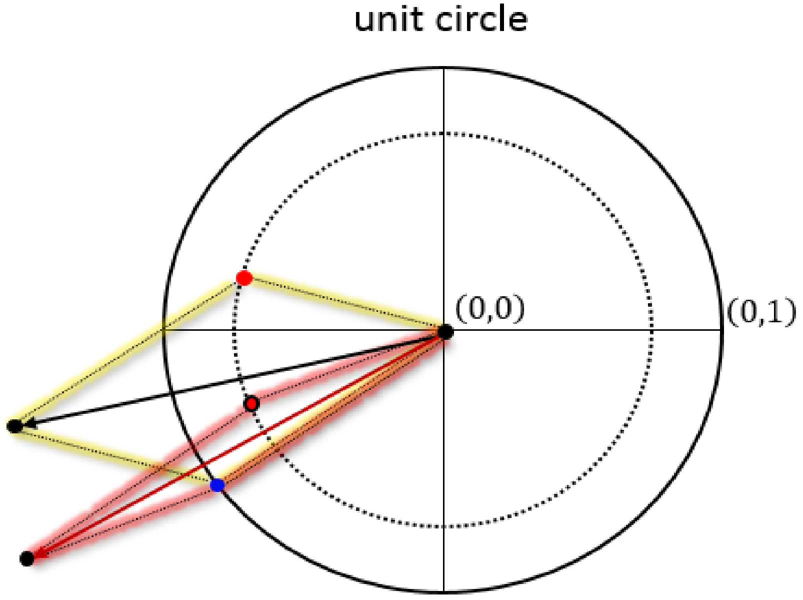
| | | | |
|---|---|---|---|
| ● | $A(0)G_{vd}(s)$ | @ 50kHz | |
| ● | $G_c(s)G_{vd}(s)/V_{p\_ss}$ | @ 50kHz | |
| ● | $A(0)G_{vd}(s)$ | @ 50kHz | phase increased |
| ● | $G_c(s)G_{vd}(s)/V_{p\_ss}$ | @ 50kHz | phase increased |

Method 1



- Crossover frequency decrease ☹
- Impossible (GBP of op-amp1) ☹

Method 2

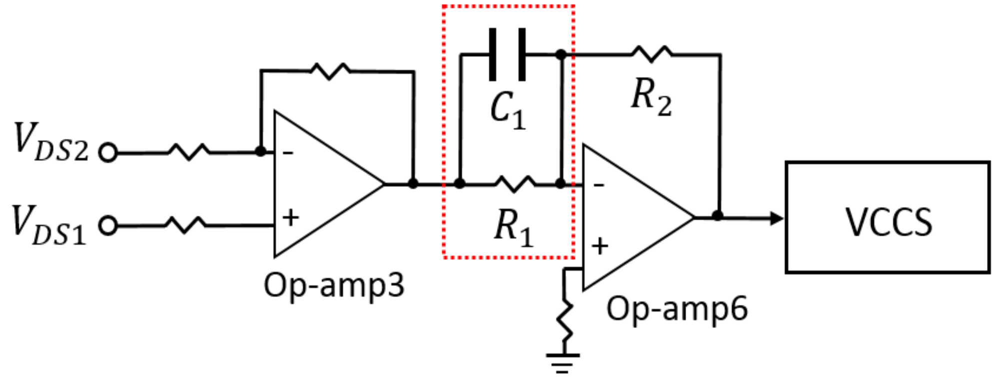


TWG phase compensation

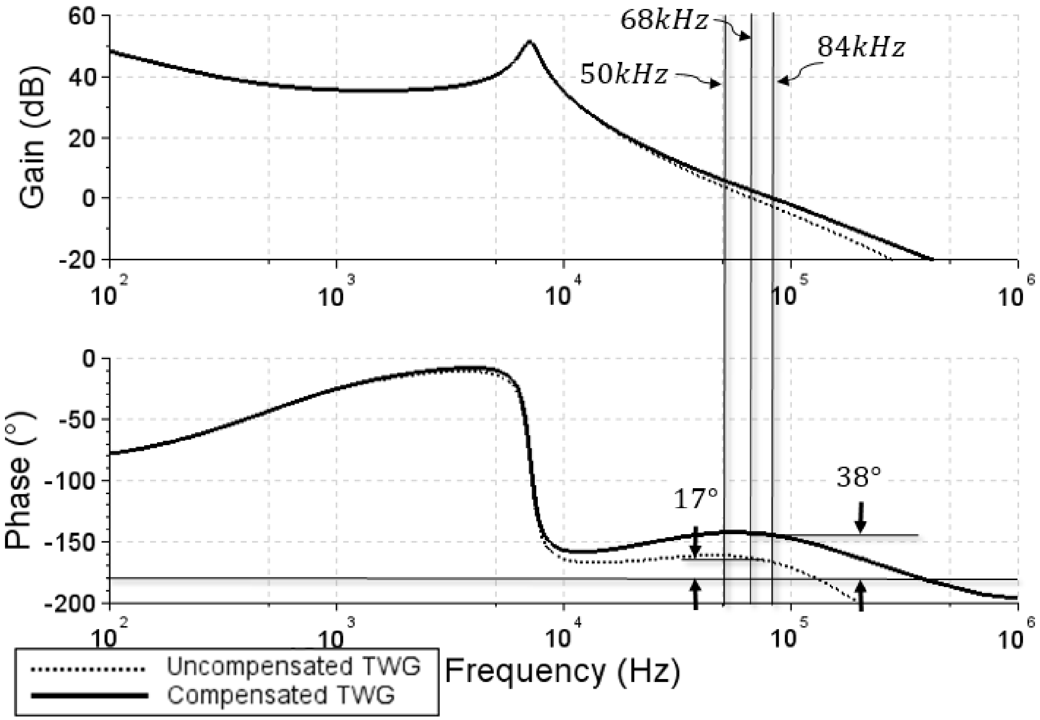
- Crossover frequency increase ☺
- Easy ☺

**Add a high-frequency zero in TWG**

# TWG phase compensation

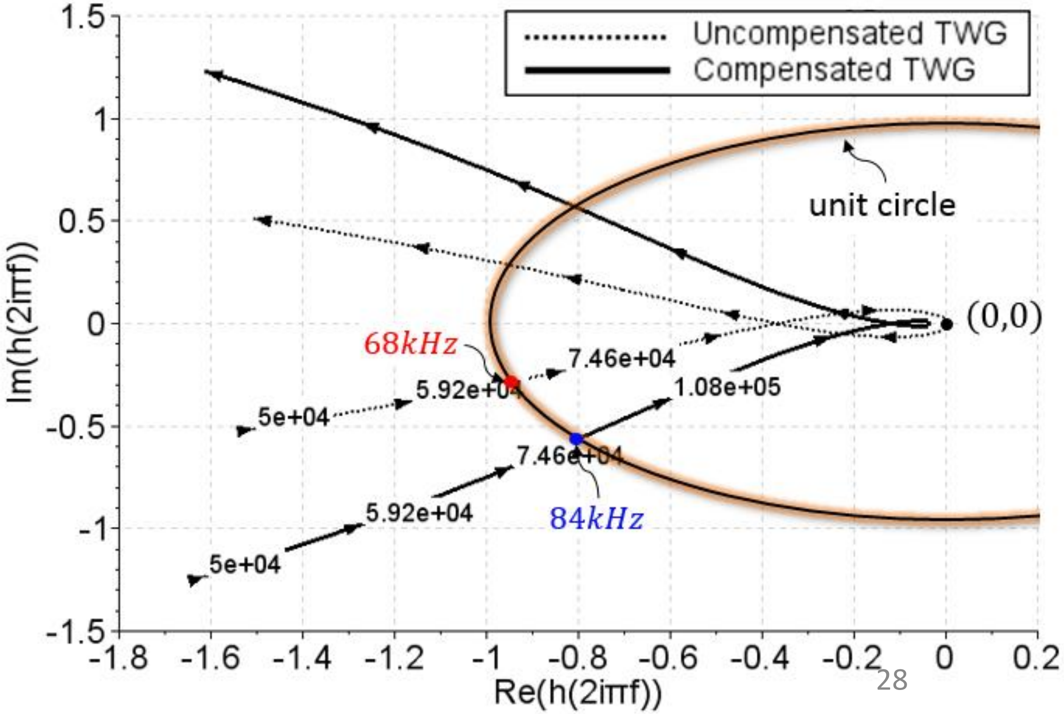


$$G_6(s) = \frac{R_2}{R_1}(C_1 R_1 s + 1)$$



$$\boldsymbol{f_c = 84kHz}$$

$$\boldsymbol{\varphi_m = 38°}$$



# Outline

- Background
- Control schemes of buck converter
- Triangular wave slope modulation
  - Circuit and principle
  - Stability analysis
  - Simulation
- Conclusion

# Simulation condition

Simulator: SIMetrix 6.2

## Buck converter

$V_g = 5V$
$V_{out} = 3.5V$
$V_{p\_ss} = 3V$
$L = 10\mu H$
$C = 50\mu F$
$R = 35\Omega$
$R_{ESR} = 2m\Omega$
$R' = 50m\Omega$
$f_s = 1MHz$

Power loss elements:
$R' = R_L + DR_{on} + D'R_D$

## Type 3 compensator

**Compensation Goal**
$f_c = f_s/20 = 50kHz$
$\varphi_m = 40°$

**Error Amplifier**
$G_{open-loop} = 100k$
$GBP = 20MHz$

**Realization**
$R_1 = 10k\Omega$
$R_2 = 9\Omega$
$R_3 = 10.6k\Omega$
$C_1 = 180pF$
$C_2 = 11.2nF$
$C_3 = 647pF$

## TWG

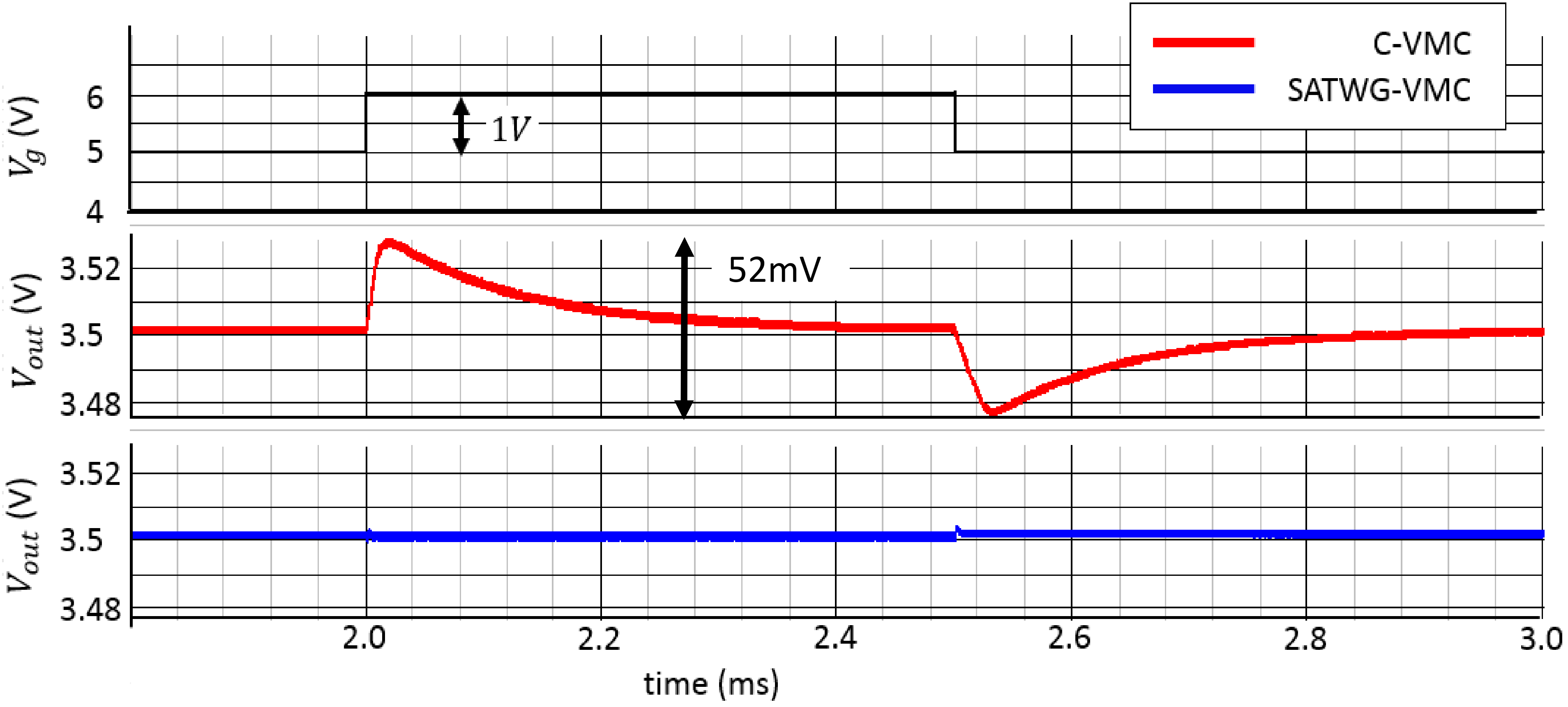
$G_{\mathrm{k}} = 100$
$G_3 = 200$
$K_n \approx 2$
$R_b = 1k\Omega$
$R_{CS} = 330\Omega$
$C_C = 300pF$
$V_{th} = 0.9V$
$V_{con\_max} = 1V$
$\omega_{hz} = 2\pi \cdot 100kHz$

$A(0) \approx 6.65$
$\omega_{hz}$: high frequency zero

# Line transient response (1-1)

Stepwise Change $V_g$: $5\text{V} \leftrightarrow 6V$

**C-VMC**: conventional voltage-mode control
**SATWG-VMC**: voltage-mode control with
slope adjustable triangular wave generator

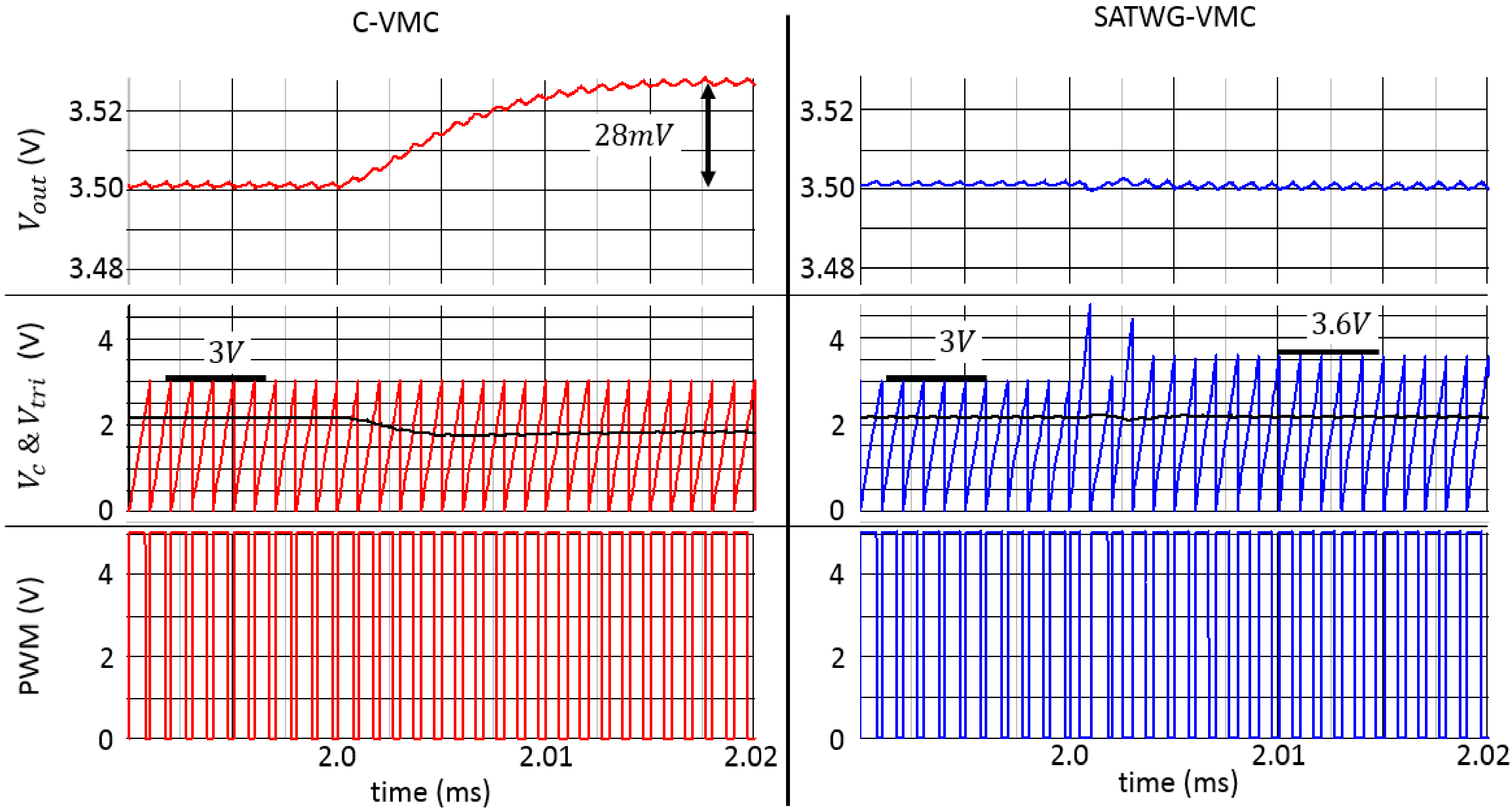


C-VMC:
$V_{pp} = 52mV$
Step-up: $400\mu s$
Step-down: $300\mu s$

SATWG-VMC:
No distinct change

# Line transient response (1-2)

$V_g: 5\text{V} \rightarrow 6\text{V}$



C-VMC:

$V_{out}$ increase

$V_c$ decrease

$$\frac{\textit{Decreased } V_c}{\textit{Fixed } V_p} = \frac{V_{out}}{\textit{Increased } V_g}$$

SATWG-VMC:

$V_P$ increase

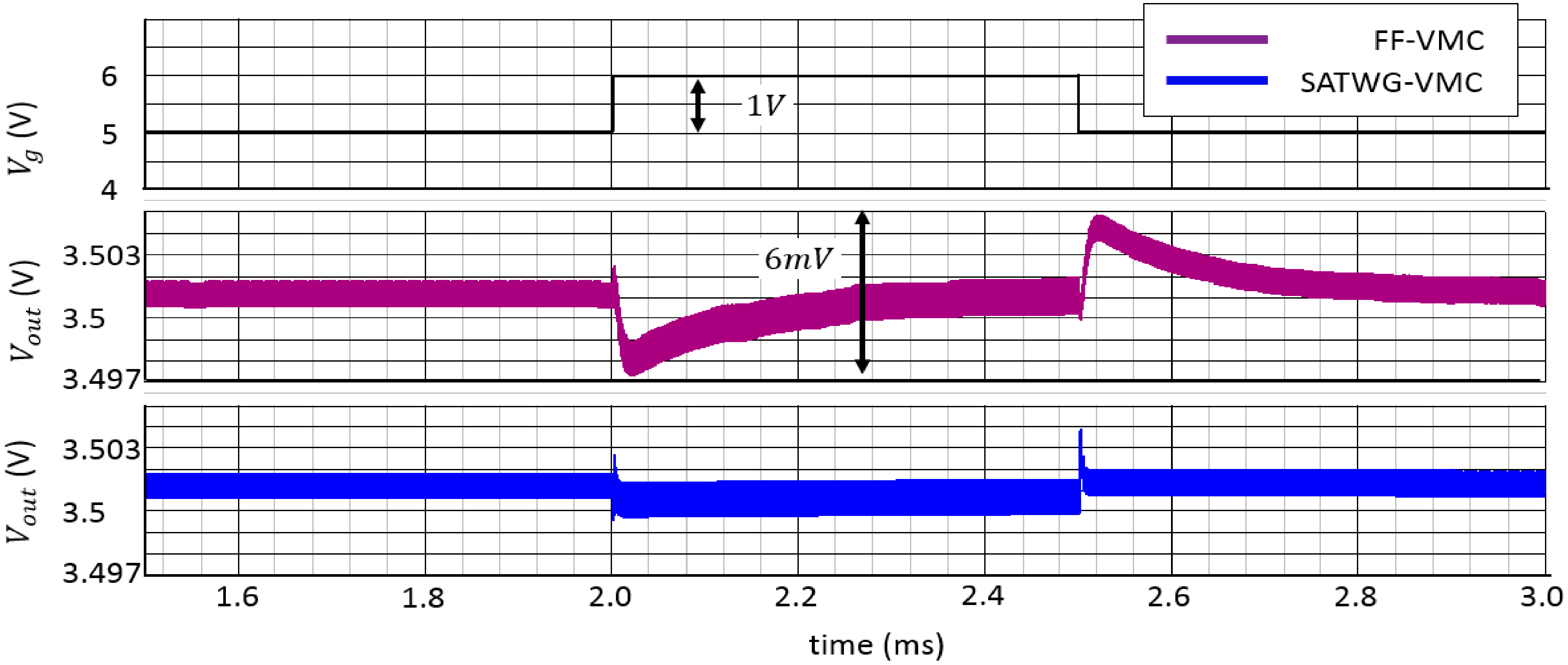
$$\frac{\textit{Unchanged } V_c}{\textit{Increased } V_p} = \frac{V_{out}}{\textit{Increased } V_g}$$

# Line transient response (2-1)

Stepwise Change $V_g$: $5\text{V} \leftrightarrow 6V$

**FF-VMC**: Voltage-mode control with conventional line feed-forward control

**SATWG-VMC**: voltage-mode control with slope adjustable triangular wave generator



FF-VMC:

$V_{pp} = 6mV$

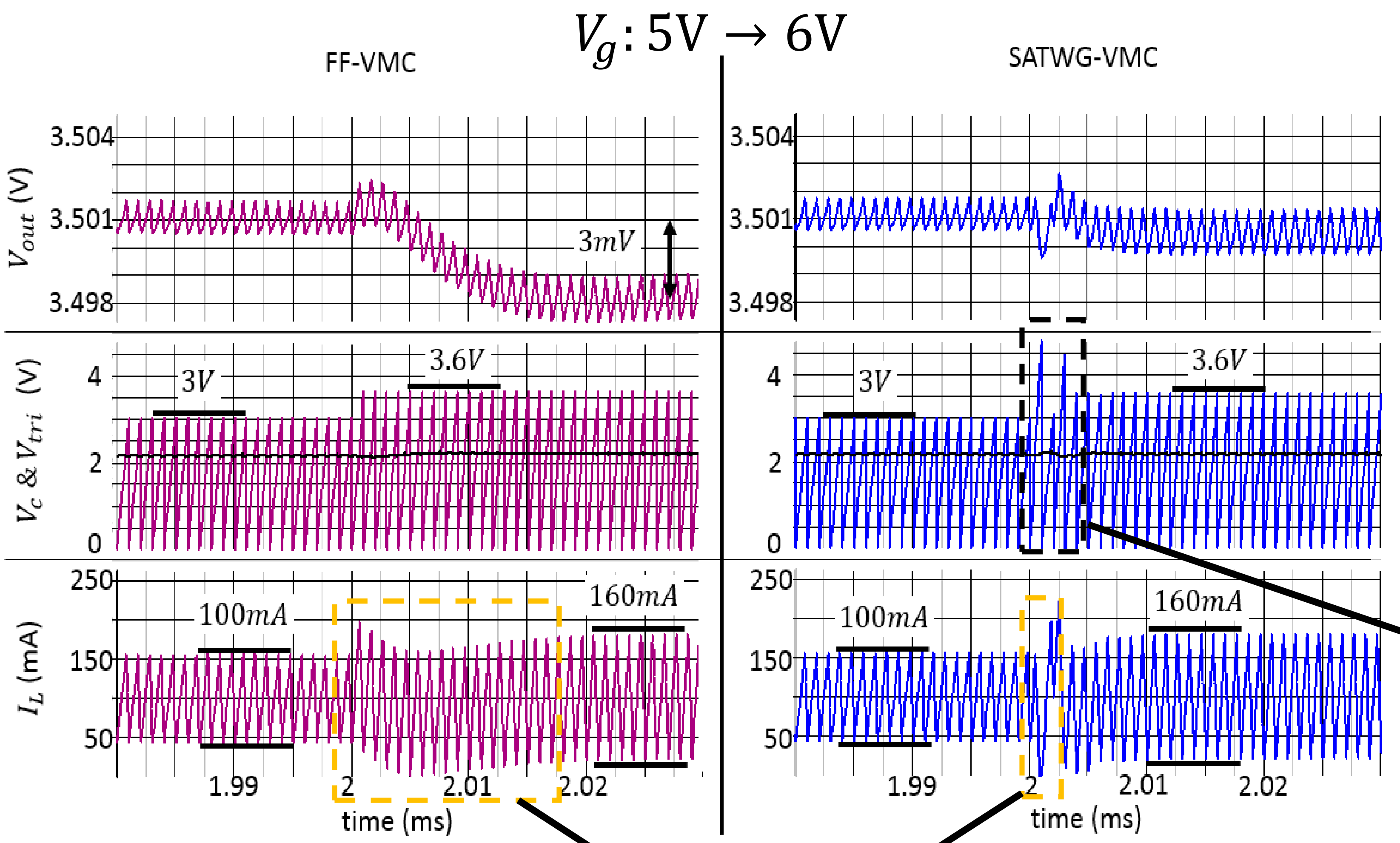
Step-up: $300\mu s$

Step-down: $200\mu s$

SATWG-VMC:

No distinct change

# Line transient response (2-2)



FF-VMC:

- Only consider the variation in $V_g$
- Cannot detect the variation in $V_{out}$

SATWG-VMC:

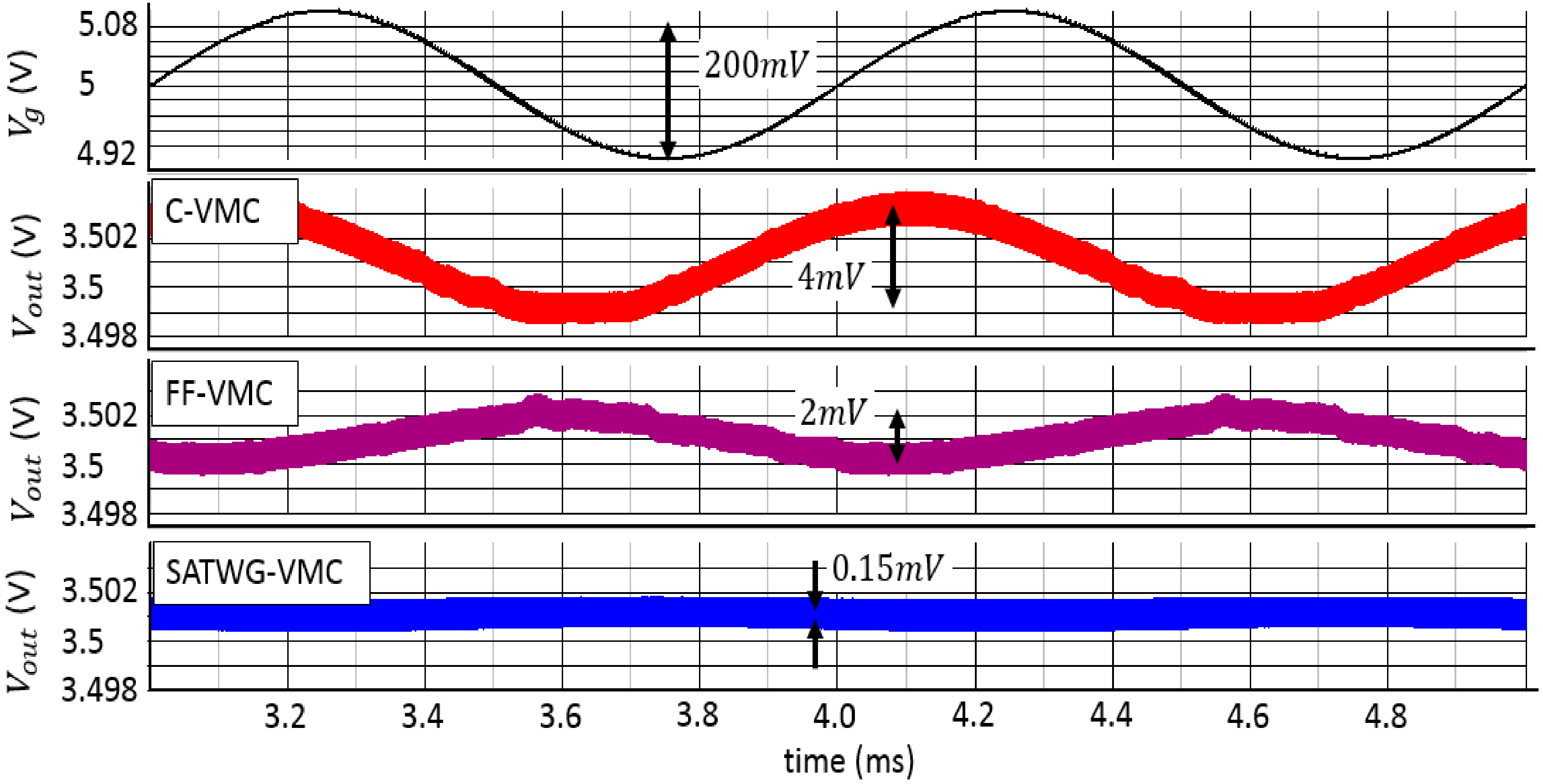
$V_g$ and $V_{out}$ are both considered.

The slope get further regulation by the variation in $V_{out}$

$\boldsymbol{I_L \neq I_{out}}$ Cause variation in output voltage

# Line transient response (3-1)

Periodic Change $V_g$: $5\text{V} + 0.1\sin(2\pi \cdot 1kHz \cdot t)$



Input:
$V_{pp} = 200mV$

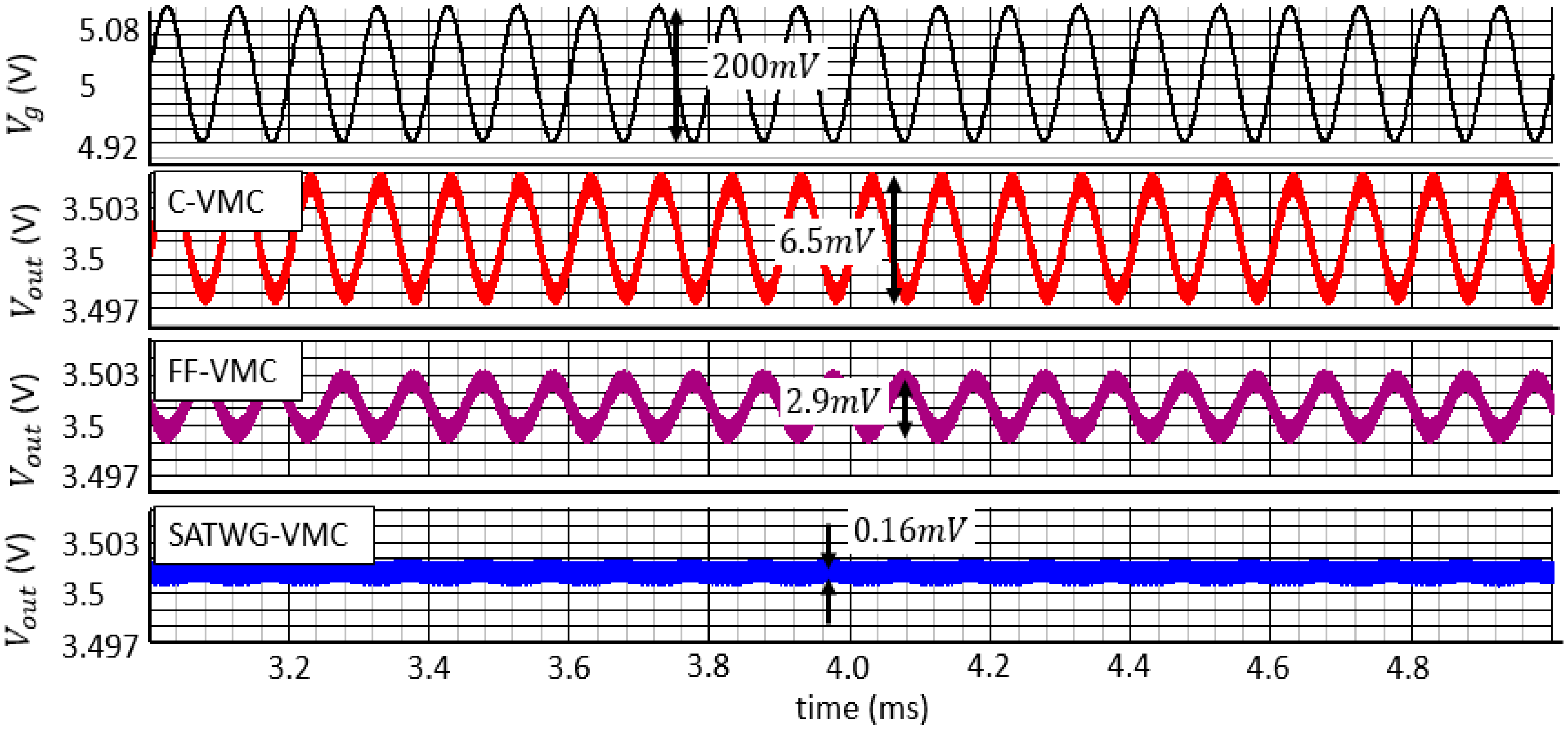
C-VMC:
$V_{pp} = 4mV$

FF-VMC:
$V_{pp} = 2mV$

SATWG-VMC:
$V_{pp} = 0.15mV$

# Line transient response (3-2)

Periodic Change $V_g$: $5\mathrm{V} + 0.1\sin(2\pi \cdot 10kHz \cdot t)$



Input:
$V_{pp} = 200mV$

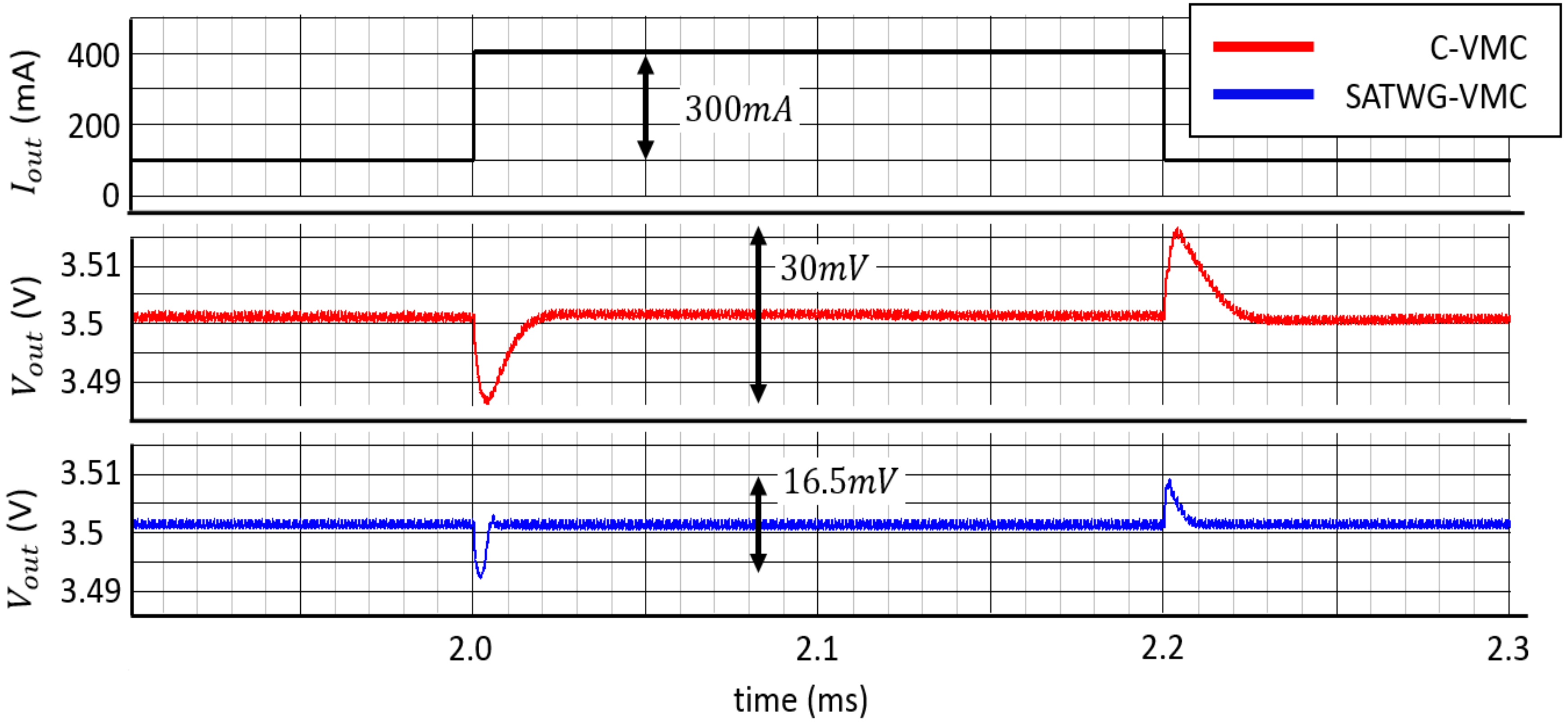
C-VMC:
$V_{pp} = 6.5mV$

FF-VMC:
$V_{pp} = 2.9mV$

SATWG-VMC:
$V_{pp} = 0.16mV$

# Load transient response (1-1)

Stepwise Change $I_{out}$: $100\mathrm{m}A \leftrightarrow 400mA$

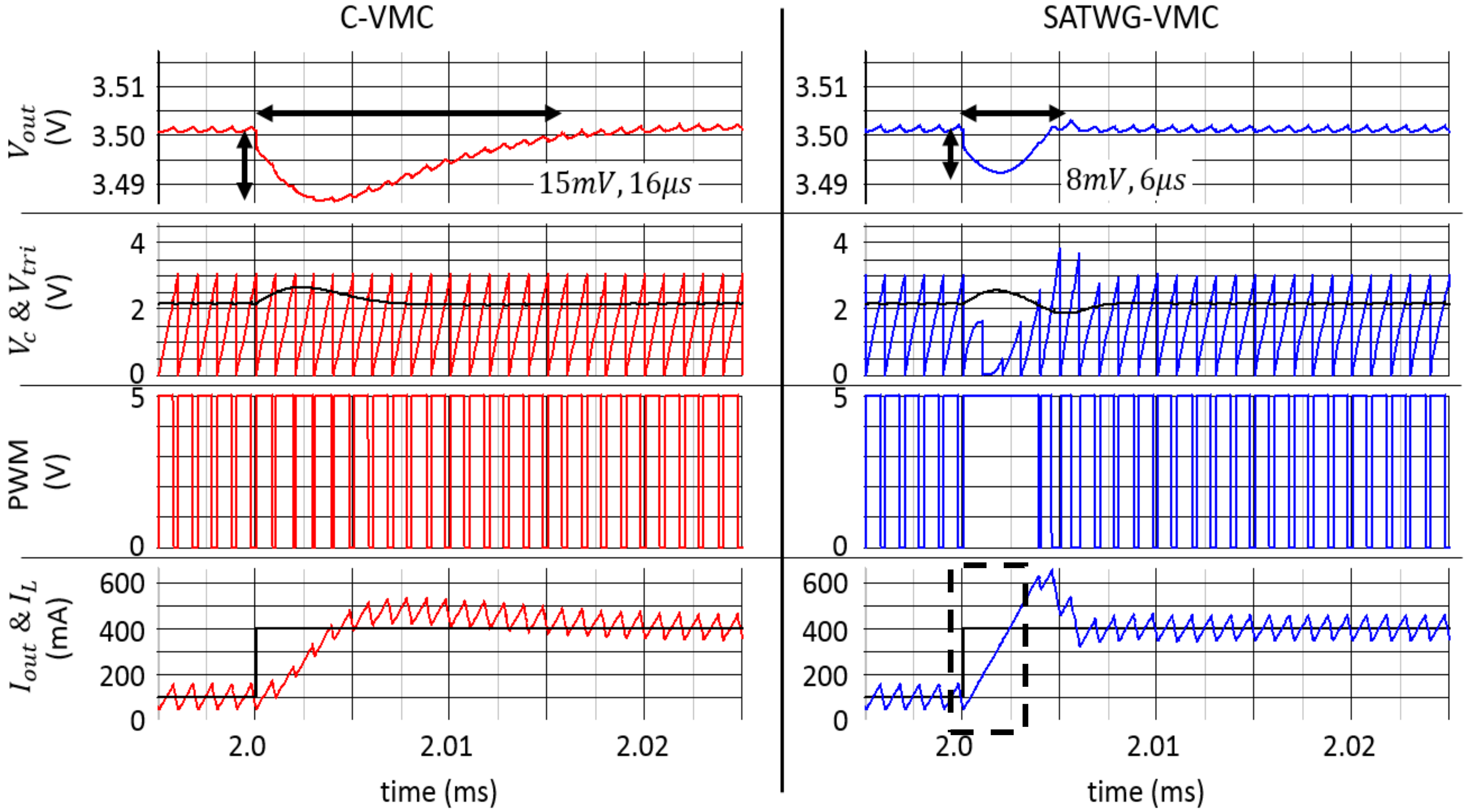


C-VMC:
$V_{pp} = 30mV$
Step-up: $16\mu s$
Step-down: $22\mu s$

SATWG-VMC:
$V_{pp} = 16.5mV$
Step-up: $6\mu s$
Step-down: $8\mu s$

# Load transient response (1-2)

$I_{out}: 100\text{mA} \rightarrow 400\text{mA}$



**C-VMC**:
Only $V_c$ modulates the duty cycle

**SATWG-VMC**:
$V_c$ and triangular wave regulate the duty cycle

Inductor current rise straight

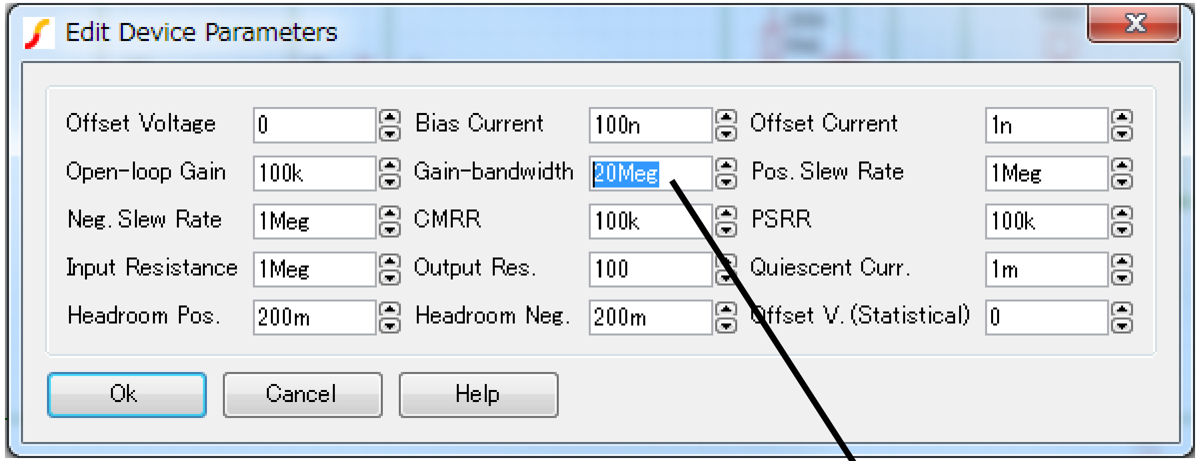
⬇

8mV is the minimum undershoot

# Load transient response (2-1)

Using a wideband op-amp to design type 3 compensator for **conventional VMC**, Set crossover frequency at $f_s/20$, $f_s/10$ and $f_s/5$; phase margin $\varphi_m = 50°$

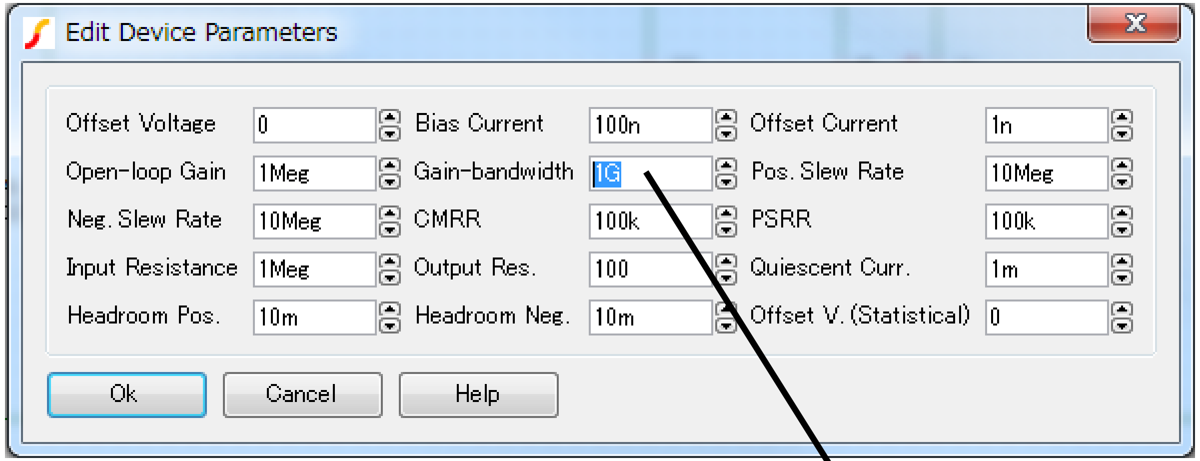
Normal op-amp


Edit Device Parameters

| | | | | | |
|---|---|---|---|---|---|
| Offset Voltage | 0 | Bias Current | 100n | Offset Current | 1n |
| Open-loop Gain | 100k | Gain-bandwidth | 20Meg | Pos. Slew Rate | 1Meg |
| Neg. Slew Rate | 1Meg | CMRR | 100k | PSRR | 100k |
| Input Resistance | 1Meg | Output Res. | 100 | Quiescent Curr. | 1m |
| Headroom Pos. | 200m | Headroom Neg. | 200m | Offset V. (Statistical) | 0 |

GBP=20MHz

Wideband op-amp

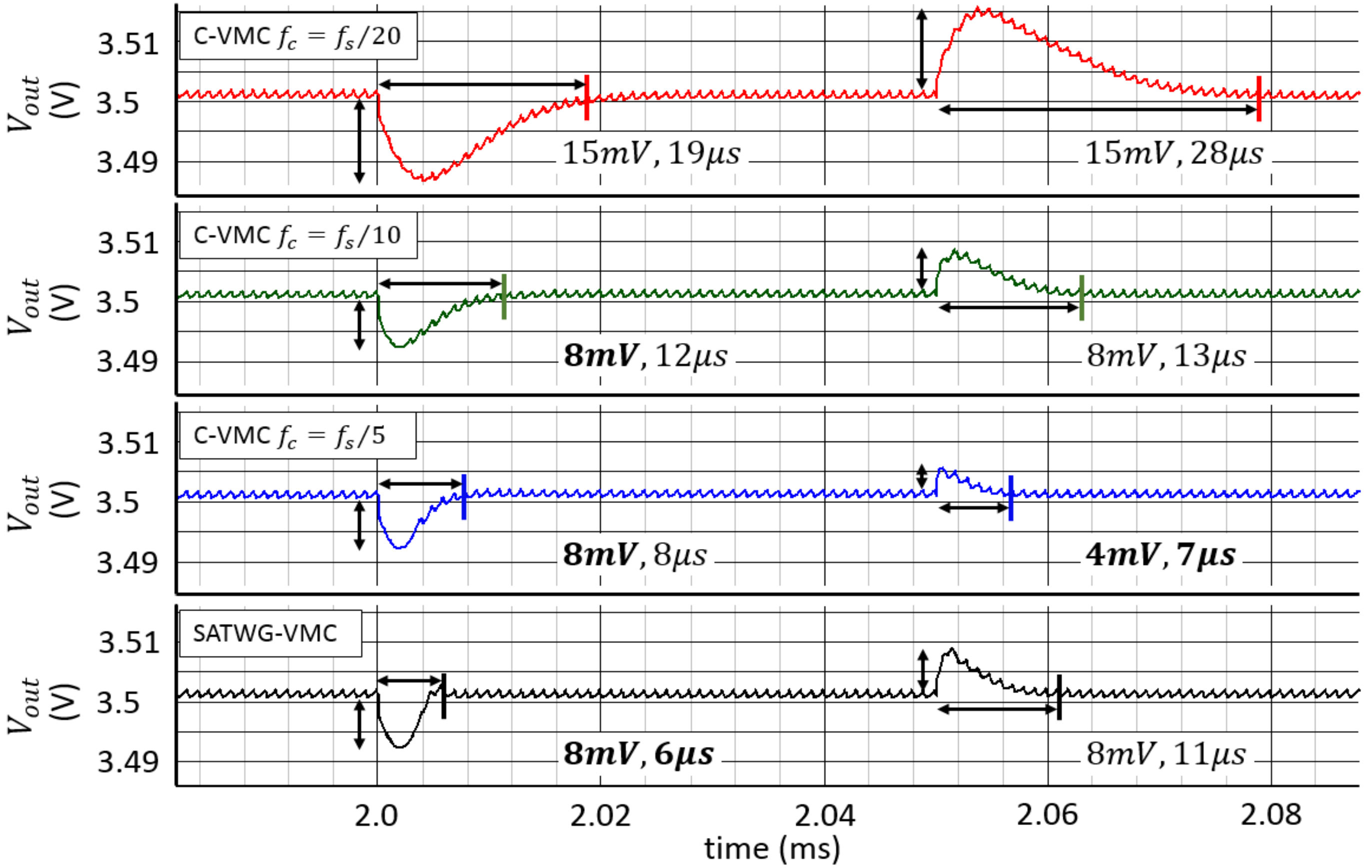

Edit Device Parameters

| | | | | | |
|---|---|---|---|---|---|
| Offset Voltage | 0 | Bias Current | 100n | Offset Current | 1n |
| Open-loop Gain | 1Meg | Gain-bandwidth | 1G | Pos. Slew Rate | 10Meg |
| Neg. Slew Rate | 10Meg | CMRR | 100k | PSRR | 100k |
| Input Resistance | 1Meg | Output Res. | 100 | Quiescent Curr. | 1m |
| Headroom Pos. | 10m | Headroom Neg. | 10m | Offset V. (Statistical) | 0 |

GBP=1GHz

# Load transient response (2-2)

Stepwise Change $I_{out}$: $100\text{mA} \leftrightarrow 400mA$



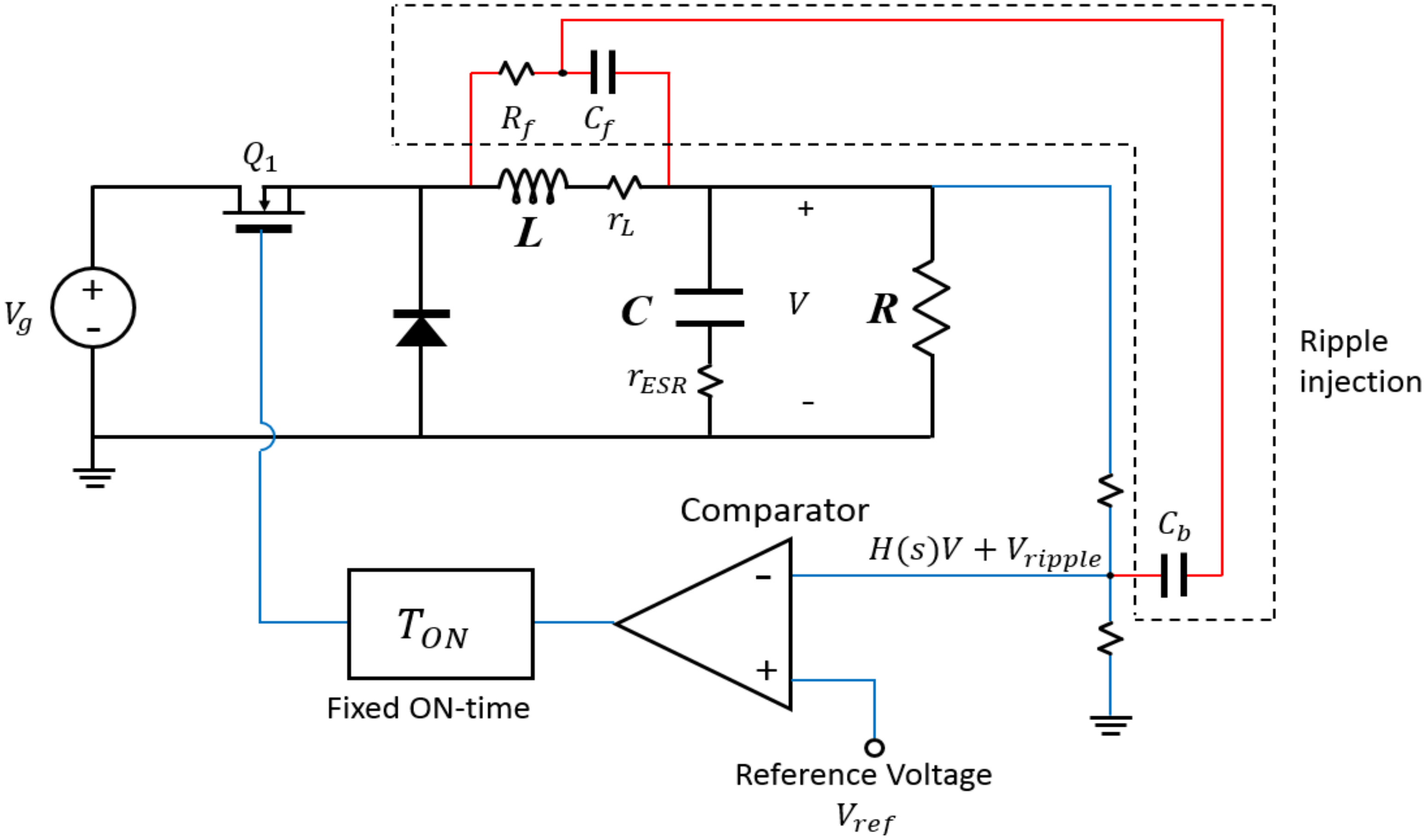
## Dynamic performance ranking

| $100\text{mA} \rightarrow 400mA$ | | $400\text{mA} \rightarrow 100mA$ | |
|---|---|---|---|
| Under shoot | Time | over shoot | Time |
| **SATWG** | **SATWG** | $f_s/5$ | $f_s/5$ |
| $f_s/5$ | $f_s/5$ | **SATWG** | **SATWG** |
| $f_s/10$ | $f_s/10$ | $f_s/10$ | $f_s/10$ |
| $f_s/20$ | $f_s/20$ | $f_s/20$ | $f_s/20$ |

**SATWG is comparable with $f_s/5$ VMC, but only require a normal op-amp**

# Load transient response (3-1)

Improved Hysteretic control in [1]



- Fixed On-time:
  almost constant switching frequency
- Ripple injection:
  small output voltage ripple

Simulation conditions

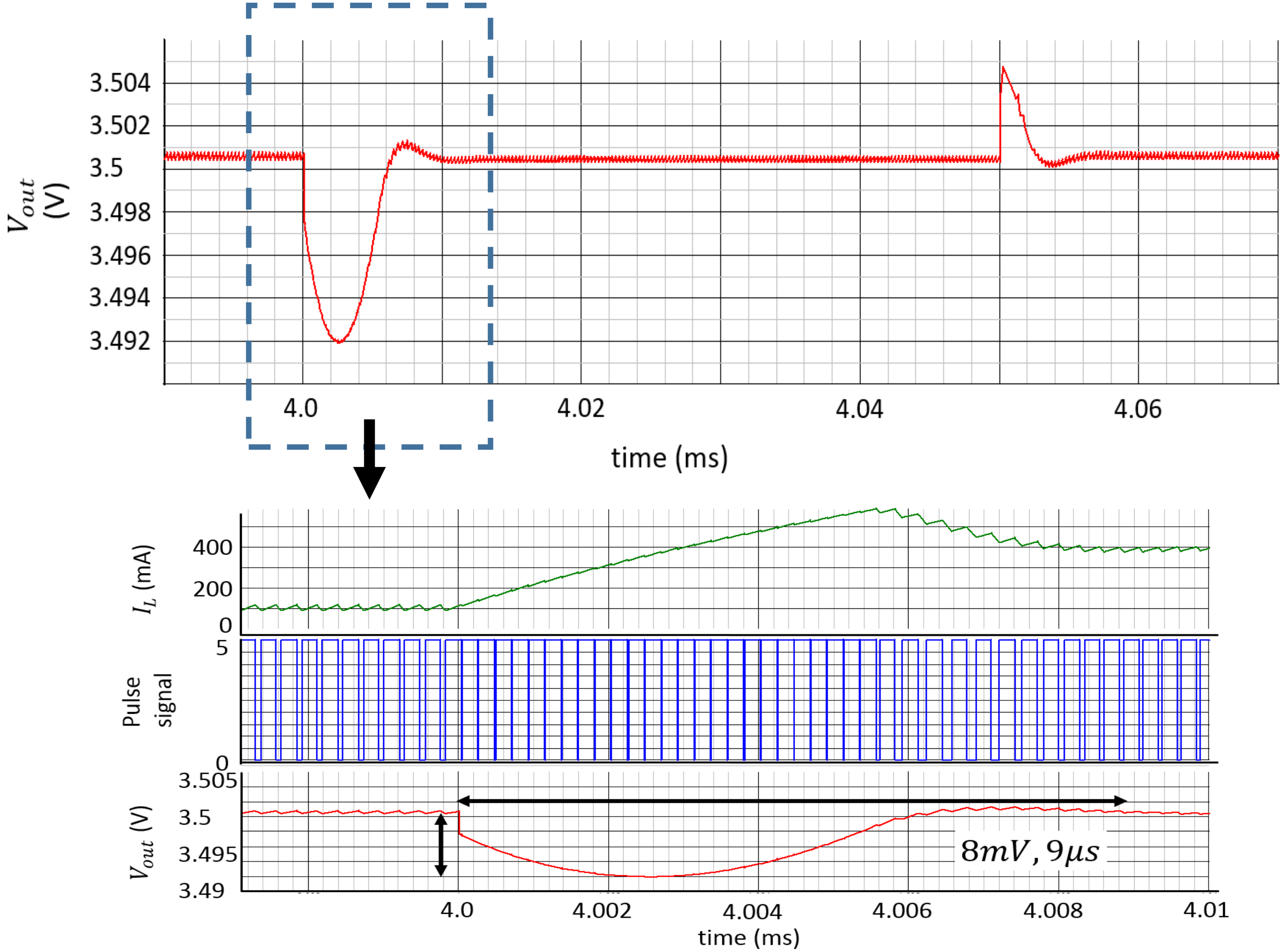
$$R_f = 500k\Omega$$
$$C_f = 2nF$$
$$C_b = 1nF$$
$$T_{on} = 200ns$$
$$T_{off\_min} = 1ns$$
$$f_s \approx 3.5MHz\ (steady\ state)$$

[1] M. Lin, T. Zaitsu, T. Sato and T. Nabeshima, “Frequency Domain Analysis of Fixed On-Time with Bottom Detection Control for Buck Converter”, IEEE IECON2010, pp. 475-479.

※ **$V_g$, $V_{out}$, L, C and R are the same as P30**

# Load transient response (3-2)

Stepwise Change $I_{out}$: $100\mathrm{m}A \leftrightarrow 400mA$



## Simulation comparison

Hysteretic control (SATWG-VMC)

$I_{out}: 100mA \rightarrow 400mA$

Under-shoot: 8mV (8mV)

Response time: 9µs (6µs)

Frequency: 3.1M~5MHz (Fixed 1MHz)

$I_{out}: 400mA \rightarrow 100mA$

Over-shoot: 4mV (8mV)

Response time: 6µs (11µs)

Frequency: 1M~3.8MHz (Fixed 1MHz)

# Outline

- Background
- Control schemes of buck converter
- Triangular wave slope modulation
    - Circuit and principle
    - Stability analysis
    - Simulation
- Conclusion

# Conclusion

- Slope adjustable triangular wave
  - ➢ Slope is regulated by input voltage and output voltage
  - ➢ Provide line feed-forward control and non-linear duty cycle modulation for VMC
  - ➢ Simulation prove the effectiveness
    - – Line transient response is improved, and better than conventional line feed-forward control
    - – Load transient response is improved. Result is comparable with wide band VMC buck converter ($f_c = f_s/5$) and hysteretic control, but only require a normal op-amp and has fixed switching frequency.

# The End

Thanks for you attention and comments !

# Q&A

- Q1: Compare to the other method, how about the efficiency of the proposed method

A: In my research, I do not consider the efficiency problem. Normally, CMC control requires current sensor which will cause more power loss than VMC. However, in the proposed method, we add some op-amp, it is hard to say whose power loss is larger. In different application and conditions, I think the comparison result is also different. Even if compare to the simplest control scheme---Hysteretic control which only need a comparator. The switching frequency is unfixed and high, it can save the energy which is dissipated on current sensor and op-amp. But it maybe cause more switching loss.

- Q2: The triangular wave slope is constant in one period?

A: Under the steady state, the slope is constant, and the voltage Vtri linear increase. But during the transient response, since the current which is used the capacitor Cc has a large change, the slope should change during one period.

- VMC and CMC, you think which one is better?

A: CMC use Type 2 compensator, and always has enough phase margin, so that its bandwidth can be designed as wider than VMC. And CMC has a inherent line feed-forward control. Therefore, considering the dynamic performance, the CMC is better.

But CMC require current sensor, slope compensation, and so on. And the double feedback loop configuration is hard to analyze. It is why I try to improve the dynamic performance of VMC, VMC is simpler than CMC (except that the Type 3 compensator is more complicated than Type 2)