電子情報通信学会　電子通信エネルギー技術研究会
広島工業大学 （2014年7月10日(木)ー7月11日(金)）

Transient Response Improvement of DC-DC Buck Converter by Adjustable Triangular Wave Generator

Shu Wu, Yasunori Kobori, Haruo Kobayashi

Gunma University, Japan

Outline

- Research Objective
- Proposed Triangular Wave Generator
  - Duty Cycle Modulation
  - Slope Adjustable Triangular Wave Generator
  - Improvement of Transient Response
- Stability Analysis
- Simulation Results
  - Line Transient Response
  - Load Transient Response
- Conclusion

Outline

- Research Objective
- Proposed Triangular Wave Generator
  - Duty Cycle Modulation
  - Slope Adjustable Triangular Wave Generator
  - Improvement of Transient Response
- Stability Analysis
- Simulation Results
  - Line Transient Response
  - Load Transient Response
- Conclusion

Transient Response

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

Fast dynamic current slew rate presents challenge in load transient response of power supplies

Previous Control Schemes

- Feedback
  - Voltage-Mode Control (VMC)
    - Easy to design and analyze
    - Limited bandwidth: slow response
  - Current-Mode Control (CMC)
    - Inherent line feed-forward control
    - Wide band
    - Slope compensation
    - Current sensor
- Feed-forward

Complicated non-linear calculation

Research Objective

- Design a slope adjustable triangular wave generator to improve transient response of DC-DC buck converter
  - **Based on VMC:**

    compared to CMC

    ---Not require current sensor and slope compensation
  - **The slope is regulated by input and output voltage:**

    compared to conventional VMC

    ---Provide line feed-forward control and higher band-width
  - **Simple:**

    compared to previous feed-forward control

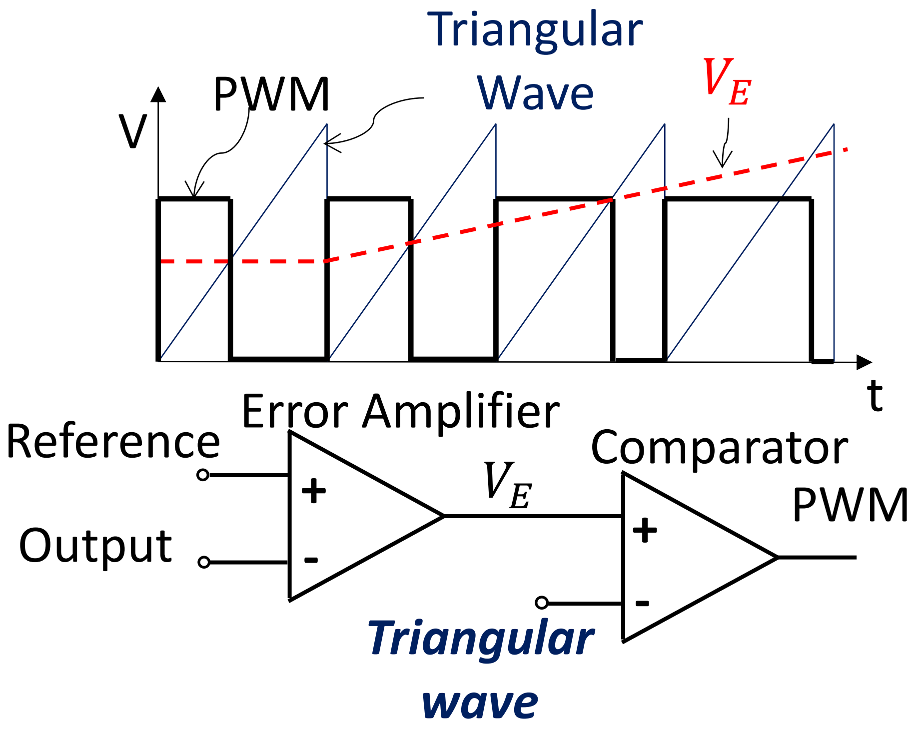
    ---Not require complicated calculation

Outline

- Research Objective
- Proposed Triangular Wave Generator
  - Duty Cycle Modulation
  - Slope Adjustable Triangular Wave Generator
  - Improvement of Transient Response
- Stability Analysis
- Simulation Results
  - Line Transient Response
  - Load Transient Response
- Conclusion

Duty Cycle Modulation (1)

Voltage-Mode Control

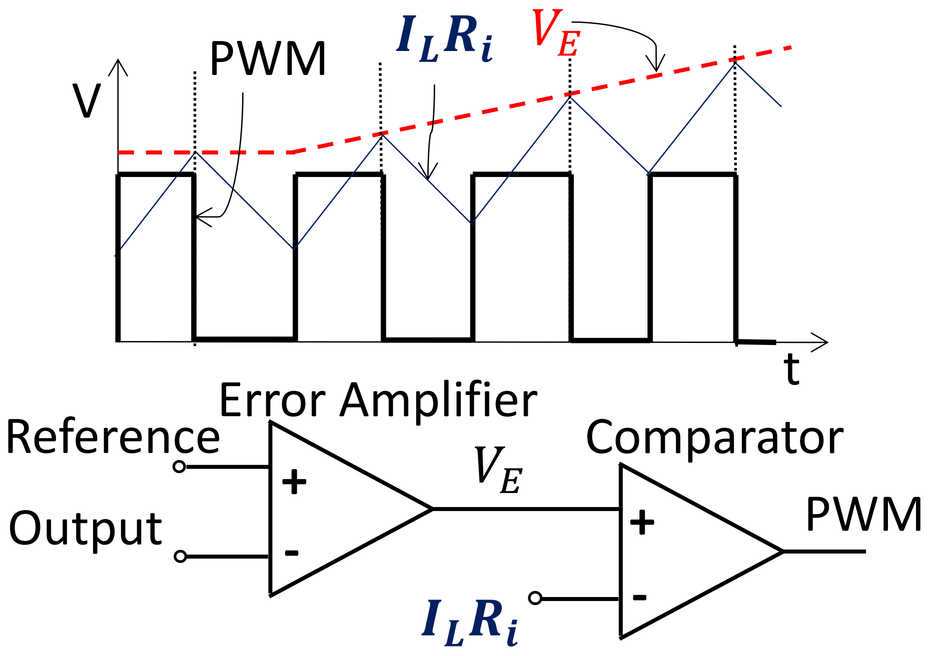


Triangular wave: constant ramp

Duty cycle modulation:

$$\Delta d = \frac{G_c}{V_p}\Delta v$$

Current-Mode Control



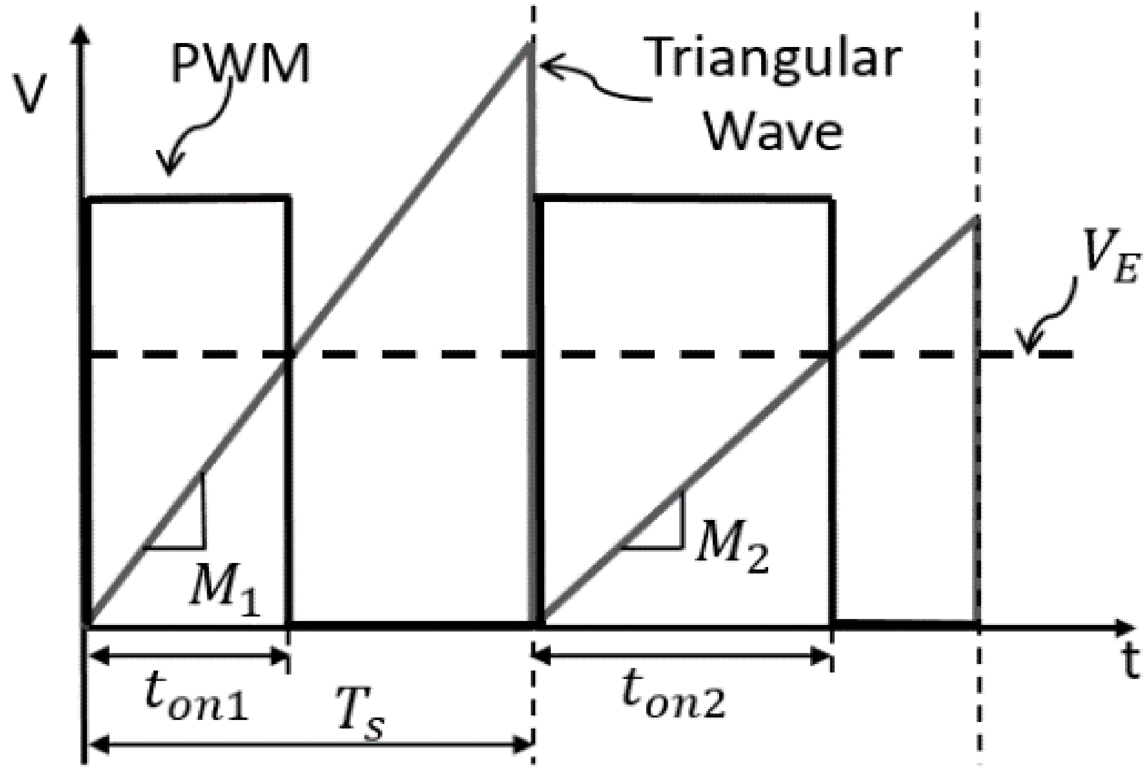
Triangular wave: proportional to inductor current

Duty cycle modulation:

$$\Delta d = \frac{L R_i f_s G_c}{V_{in} - V_{out}}\Delta v$$

Duty Cycle Modulation (2)

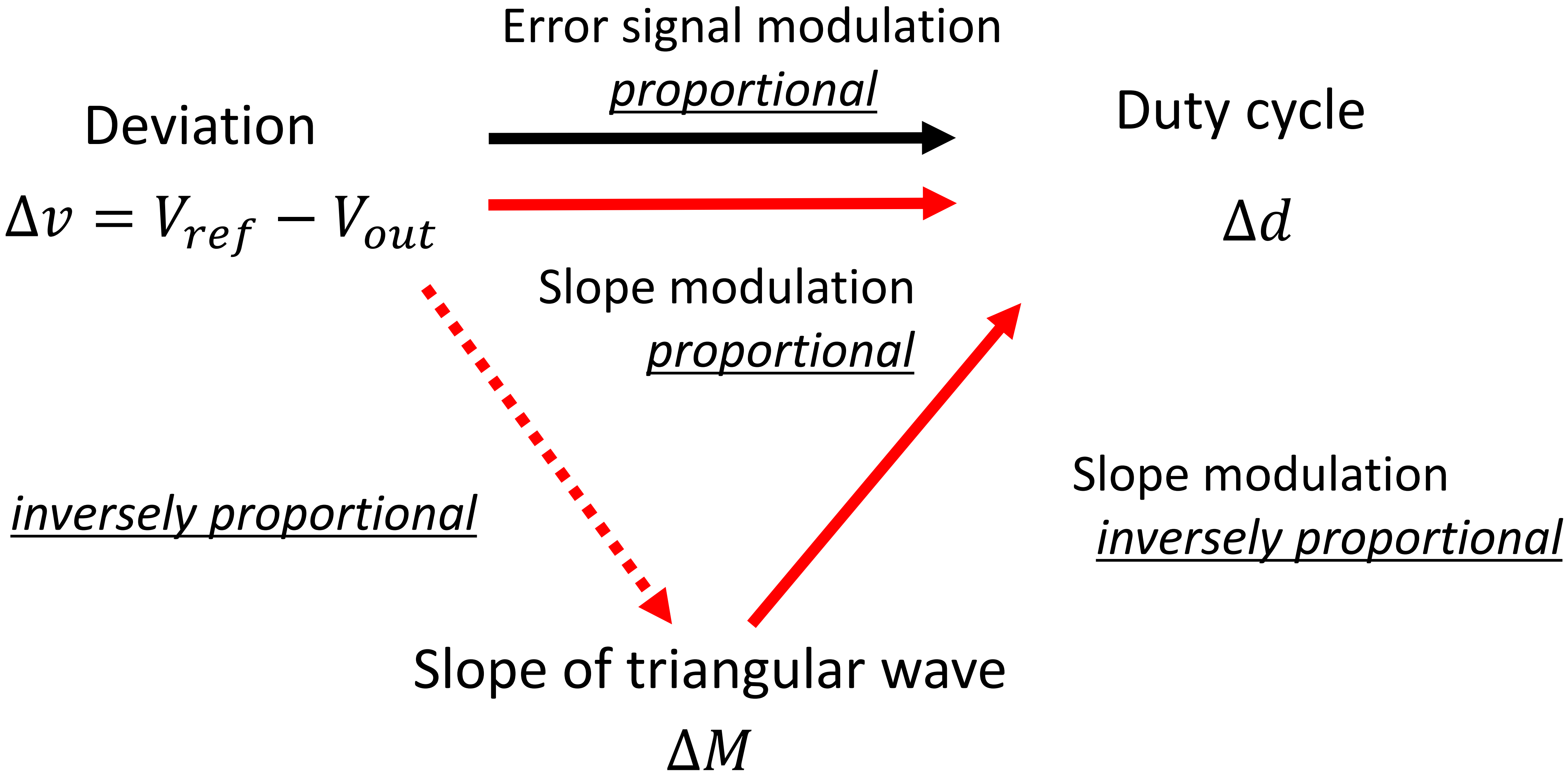
- During <u>load transient response</u>, slope of triangular wave always **keep constant** (conventional VMC and CMC).
- Duty cycle modulation by slope (proposed).



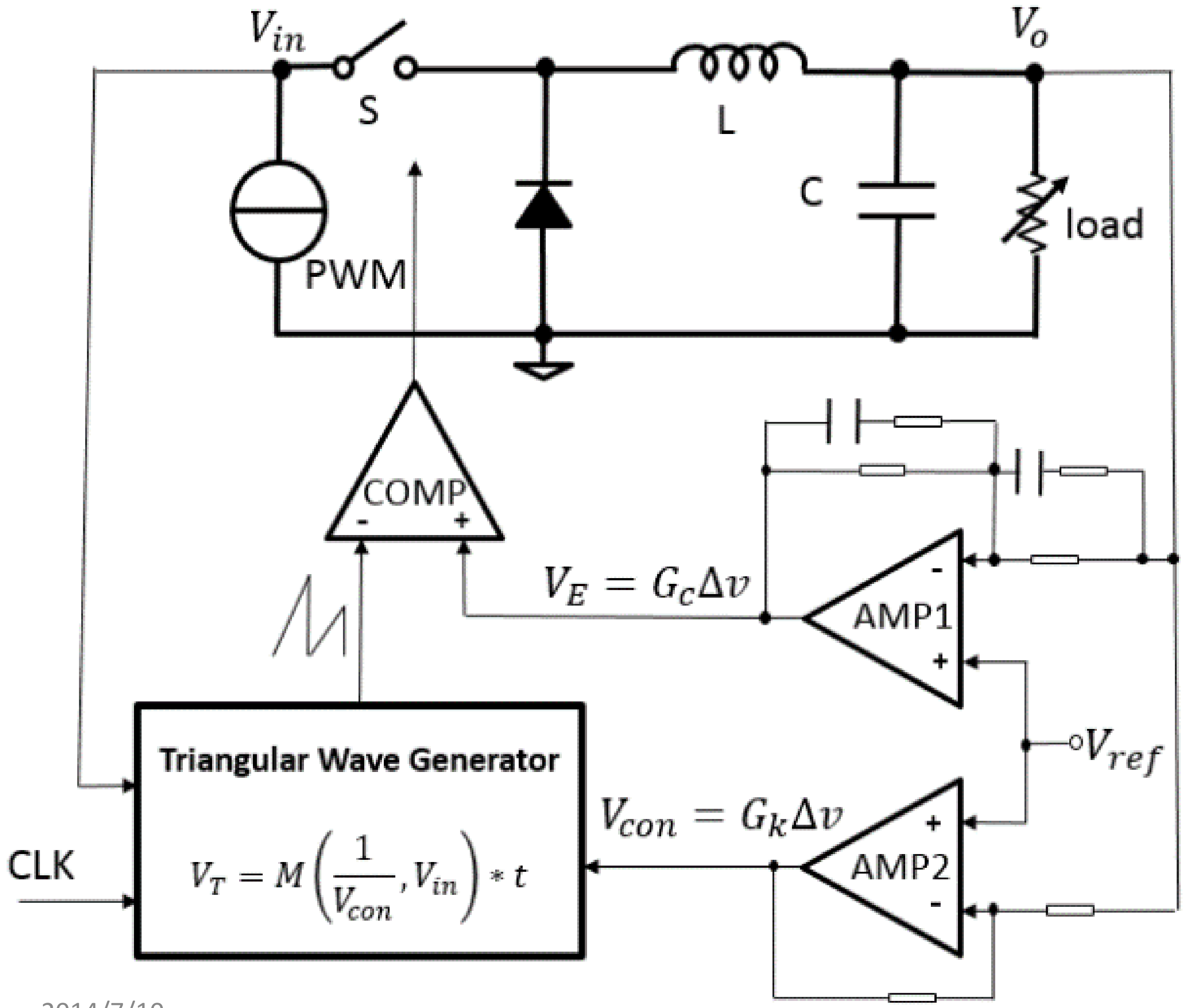
$$\Delta d = \frac{t_{on2} - t_{on1}}{T_S} = \frac{V_E}{T_S}\left(\frac{1}{M_2} - \frac{1}{M_1}\right) = \frac{V_E}{T_S}\Delta\frac{1}{M}$$

Duty cycle variation is inversely proportional to slope.

Duty Cycle Modulation (3)



System Configuration



Op-amp1:

- generate error signal
- Type 3 compensation

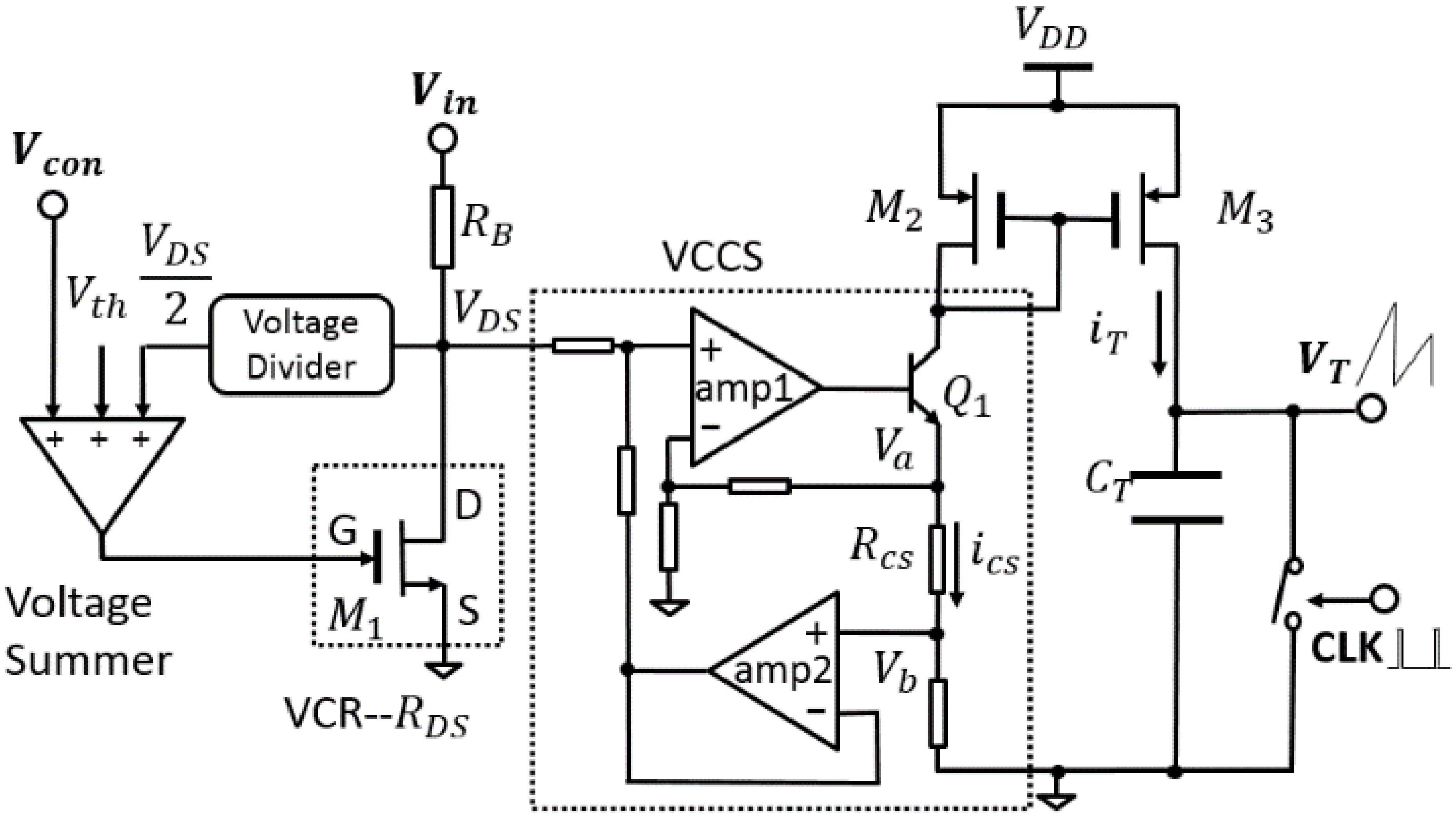
Op-amp2:

- Amplify deviation
- Control variable of TWG

TWG: slope adjustable

- $V_{in} \propto M$
- $G_k\Delta v \propto \frac{1}{M}$

Triangular Wave Generator (1)

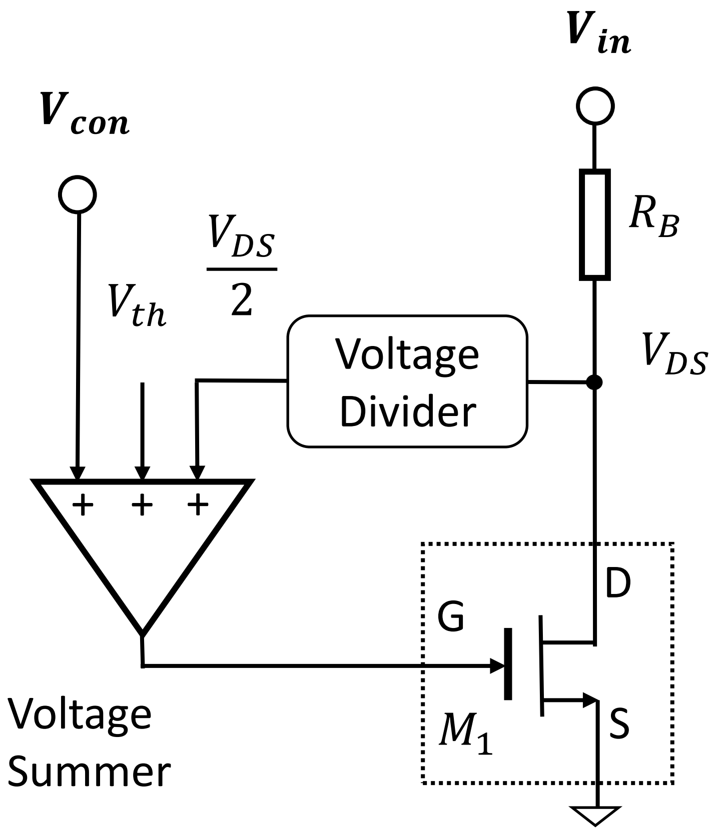


VCR: Voltage Controlled Resistor

VCCS: Voltage Controlled Current Source

Triangular Wave Generator (2)

- VCR



VCR--R_{DS}

Triode region

$$I_D = K_n\left((V_{GS} - V_{th})V_{DS} - \frac{V_{DS}^2}{2}\right) \quad \text{where} \quad K_n = \mu_n C_{ox} W/L$$

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

Set $V_{GS} = V_{th} + \frac{V_{DS}}{2} + V_{con}$ by voltage summer, get a voltage controlled resistor

$$R_{DS} = \frac{1}{K_n V_{con}} \quad \text{......(1)}$$

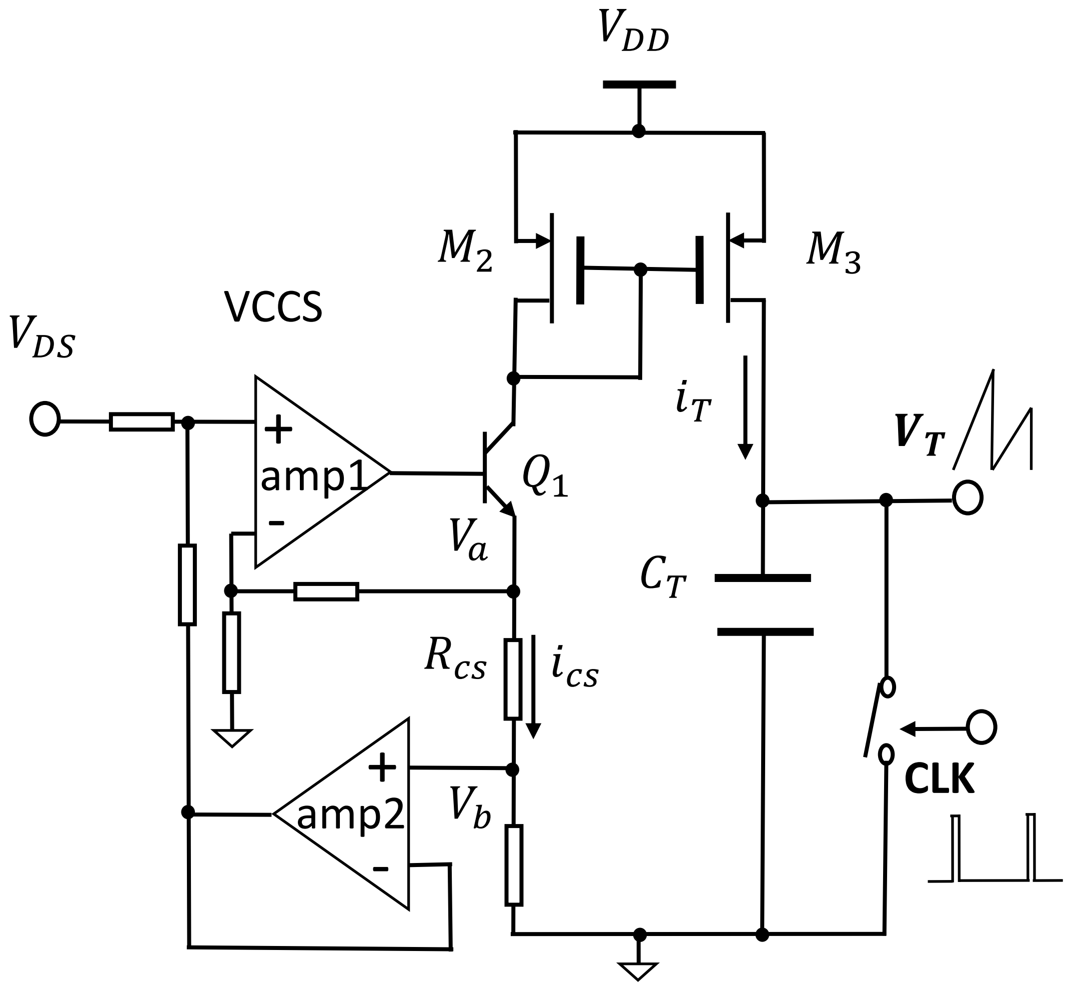
If $R_B \gg R_{DS}$

$$\boldsymbol{V_{DS} = \frac{1}{K_n R_B}\frac{V_{in}}{V_{con}}} \quad \text{......(2)}$$

V_{DS} is controlled by input voltage and control variable

Triangular Wave Generator (3)

- VCCS & TWG



$$i_T = i_{CS} = \frac{V_a - V_b}{R_{CS}} = \frac{V_{DS}}{R_{CS}}$$

$$V_T = \frac{i_T}{C_T} t$$

Substitute Eq. (2)

$$\boldsymbol{V_T = \frac{V_{in}}{K_n R_B R_{CS} C_T V_{con}} t = M\left(\frac{1}{V_{con}}, V_{in}\right) t} \text{ ......(3)}$$

Improve Line Transient Response

------ Line feed-forward Control

Transfer function from error signal to output voltage (VMC buck converter)

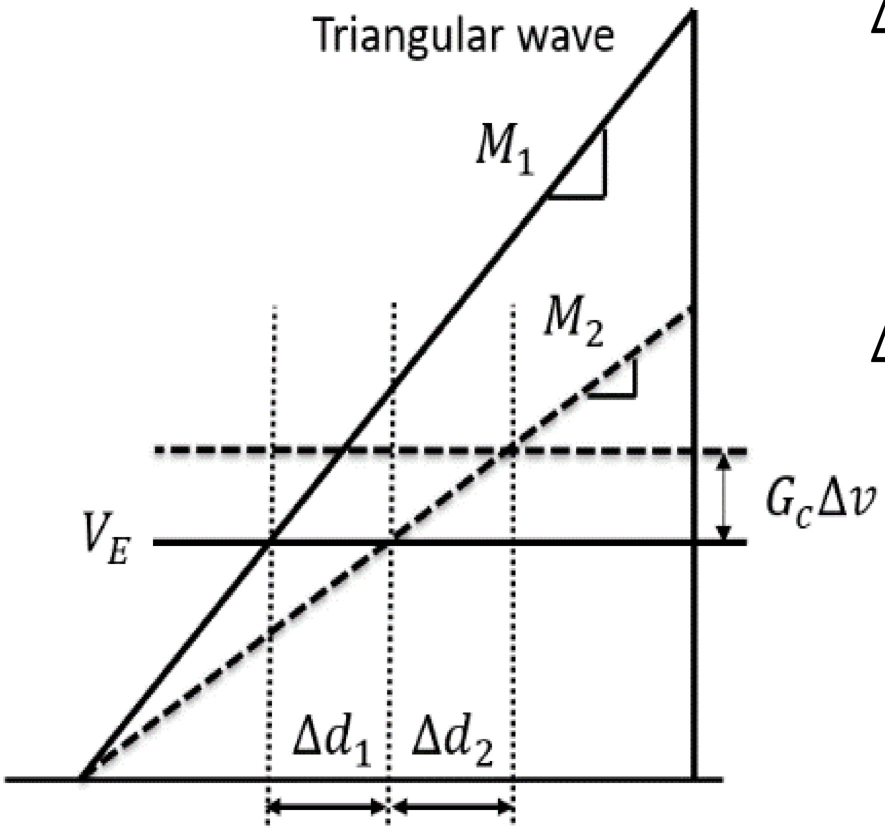
$$V_{out} = \frac{1}{LCs^2 + \frac{L}{R}s + 1} \frac{V_{in}}{V_P} V_E$$

Since $V_p = MT_s$, where M depend on V_{in} (proportional) and V_{con}

Input voltage change effects are reduced.

Improve Load Transient Response

------ Additional duty cycle modulation



Δd_1 is caused by slope modulation

$$\Delta d_1 = \frac{V_E}{T_s}\left(\frac{1}{M_1} - \frac{1}{M_2}\right) = \frac{V_E}{T_s}\Delta\frac{1}{M}$$

Δd_2 is caused by slope modulation and error signal modulation

$$\Delta d_2 = \frac{G_c\Delta v}{T_s}\left(\frac{1}{M_1} - \Delta\frac{1}{M}\right) = \frac{G_c\Delta v}{T_s M_1} - \frac{G_c\Delta v}{T_s}\Delta\frac{1}{M}$$

$$\boldsymbol{\Delta d = \Delta d_1 + \Delta d_2 = \left(\frac{V_E}{T_s} - \frac{G_c\Delta v}{T_s}\right)\Delta\frac{1}{M} + \frac{G_c\Delta v}{T_s M_1}} \quad \text{.....(4)}$$

Additional duty cycle modulation by proposed TWG

Conventional VMC

Outline

- Research Objective
- Proposed Triangular Wave Generator
  - Duty Cycle Modulation
  - Slope Adjustable Triangular Wave Generator
  - Improvement of Transient Response
- Stability Analysis
- Simulation Results
  - Line Transient Response
  - Load Transient Response
- Conclusion

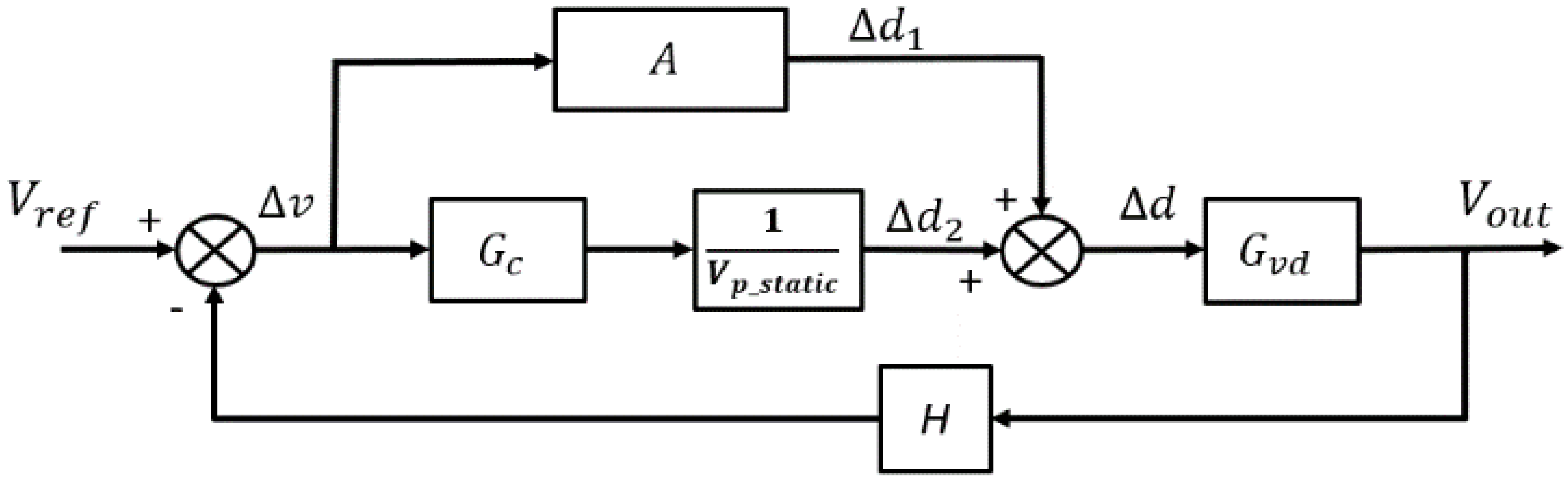
System Block Diagram

Ignore non-linear terms

$$\boldsymbol{\Delta d = \Delta d_1 + \Delta d_2 \approx A\Delta v + \frac{G_c}{V_{p\_static}}\Delta v}$$

$$A = \frac{K_n R_B R_{CS} C_T V_E G_k}{T_S V_{in}}$$

$$V_{p\_static} = T_S M_1$$



Open-loop transfer function: $T = \left(A + \frac{G_c}{V_{p\_static}}\right) G_{vd} H$

Example

Power Stage

- $V_{in} = 5V$
- $V_{out} = 3.5V$
- $V_{p\_static} = 3V$
- $L = 10\mu H\ (ESR = 10m\Omega)$
- $C = 50\mu F(ESR = 10m\Omega)$
- $R = 35\Omega$
- $f_{switch} = 1MH$

Phase Compensation

- Type 3 compensation
- $f_c = \frac{f_{switch}}{20} = 50kHz$
- $\mathrm{PM} = 40°$

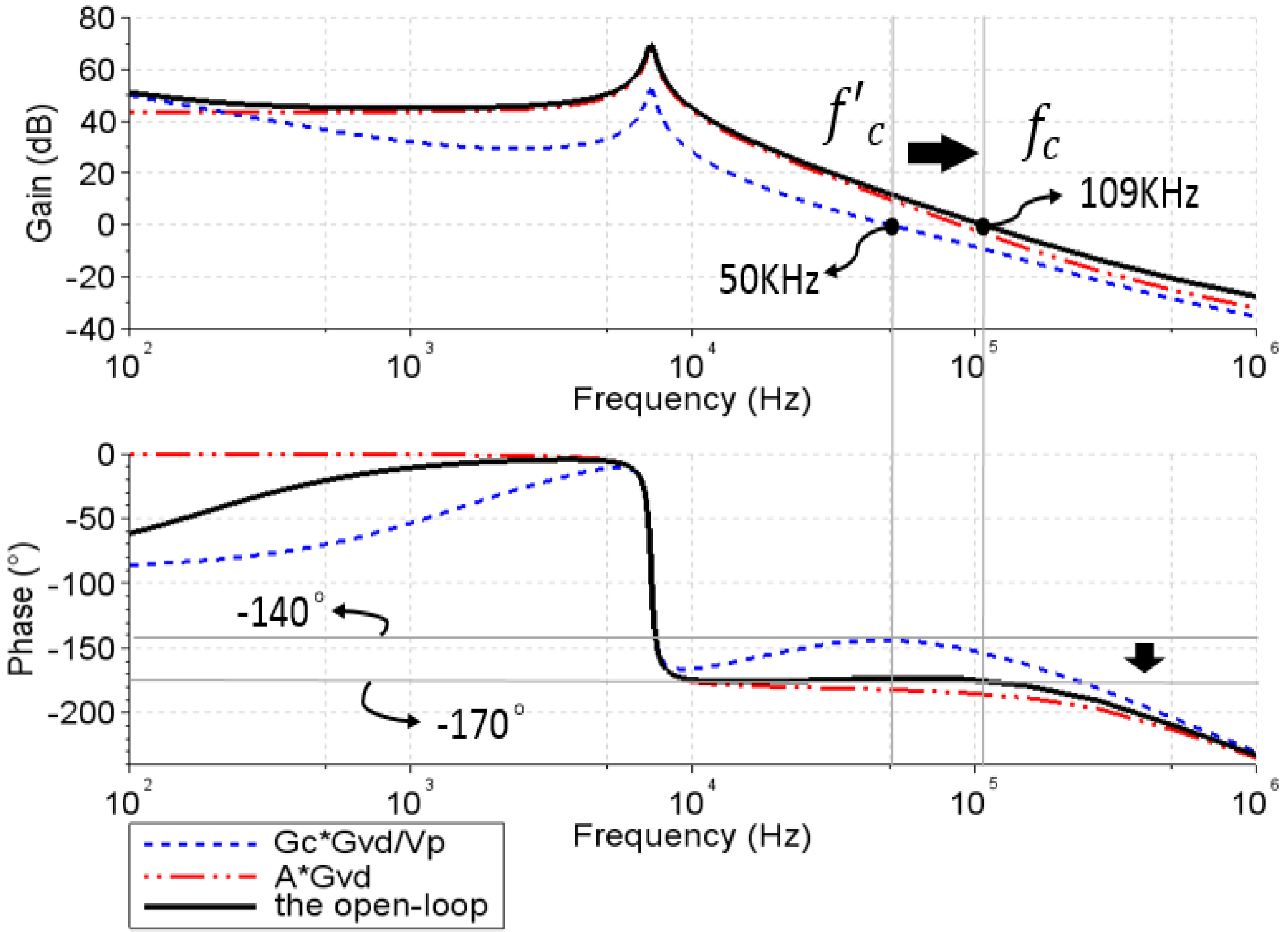
Design for conventional VMC

TWG

- $G_k = 10$
- $R_B = 1k\Omega$
- $K_n \approx 3$
- $R_{cs} = 100\Omega$
- $C_T = 50pF$

$\boldsymbol{A \approx 30}$

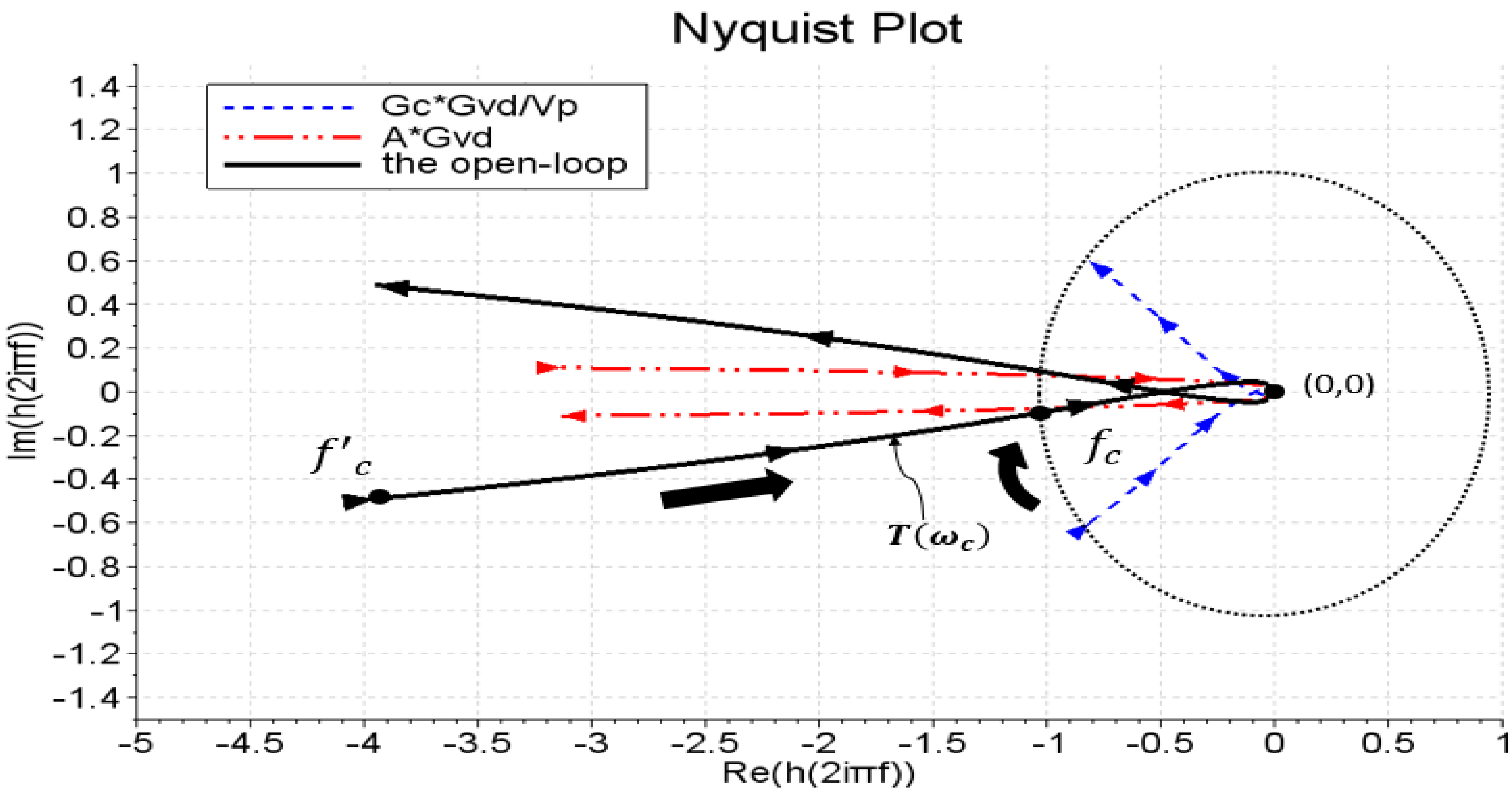
Bode Plot



Compare to conventional VMC --- $(G_c G_{vd}/V_p)$

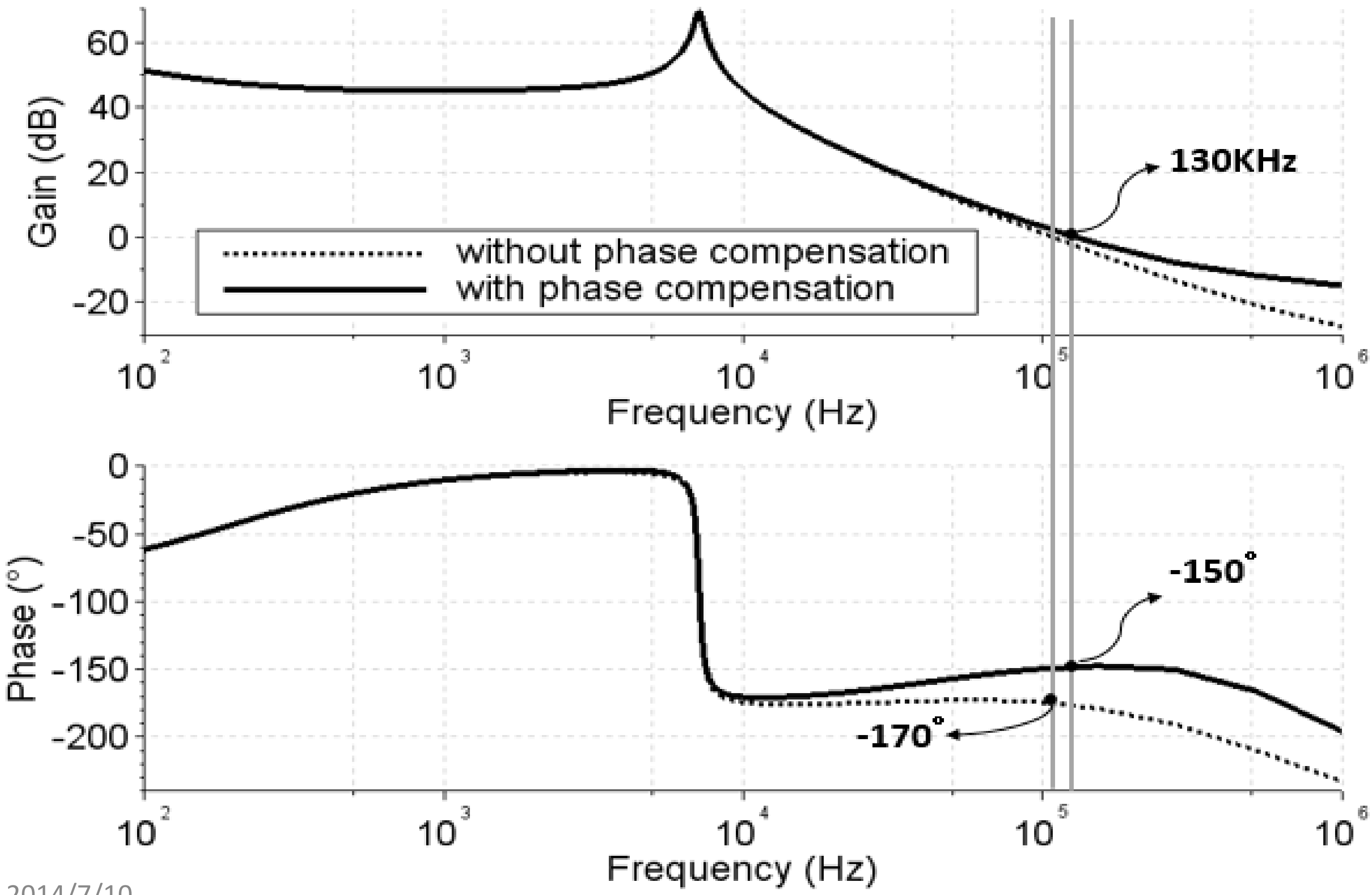
- Bandwidth is increased
  50kHz → 109kHz
- Phase margin is decreased
  40° → 10°

Nyquist Plot



Increase Phase Margin

Add a high frequency zero point to A: A → A∗ $(s + \omega_h)$



- Bandwidth

109kHz → 130kHz

- Phase Margin

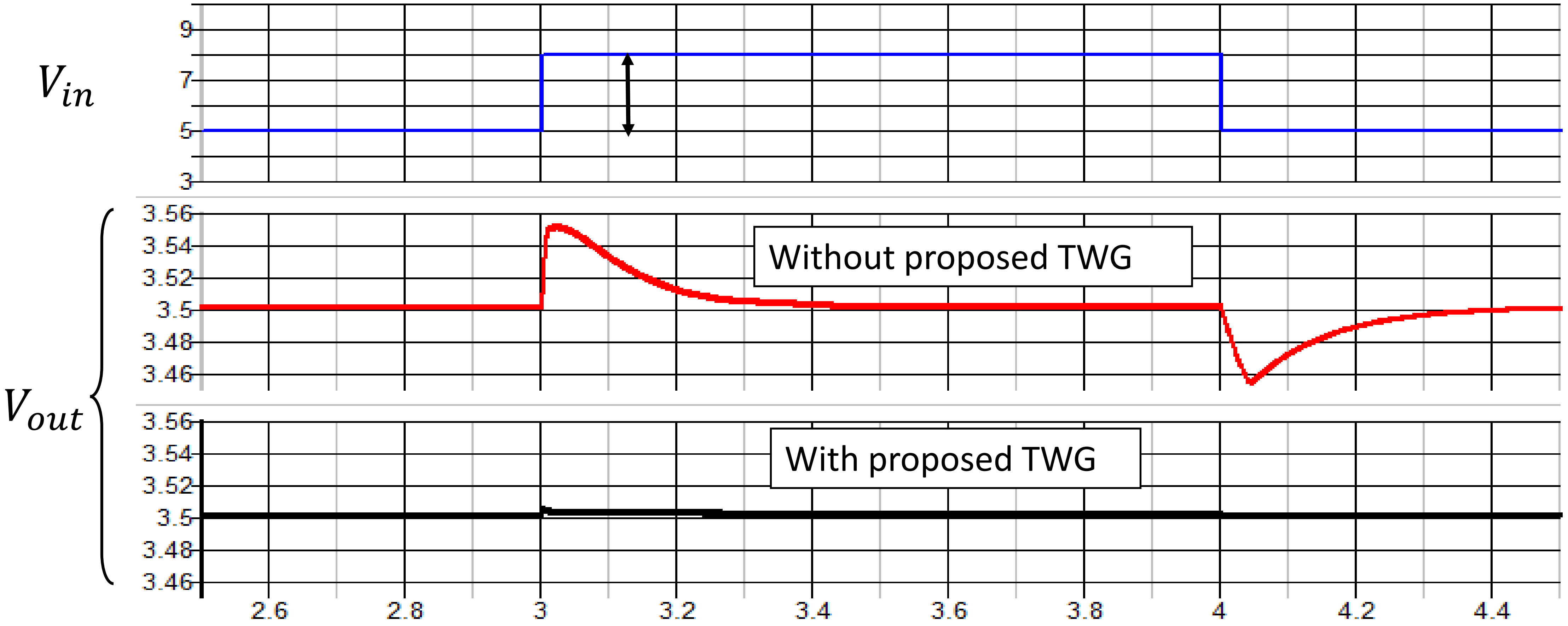
10° → 30 °

Outline

- Research Objective
- Proposed Triangular Wave Generator
  - Duty Cycle Modulation
  - Slope Adjustable Triangular Wave Generator
  - Improvement of Transient Response
- Stability Analysis
- Simulation Results
  - Line Transient Response
  - Load Transient Response
- Conclusion

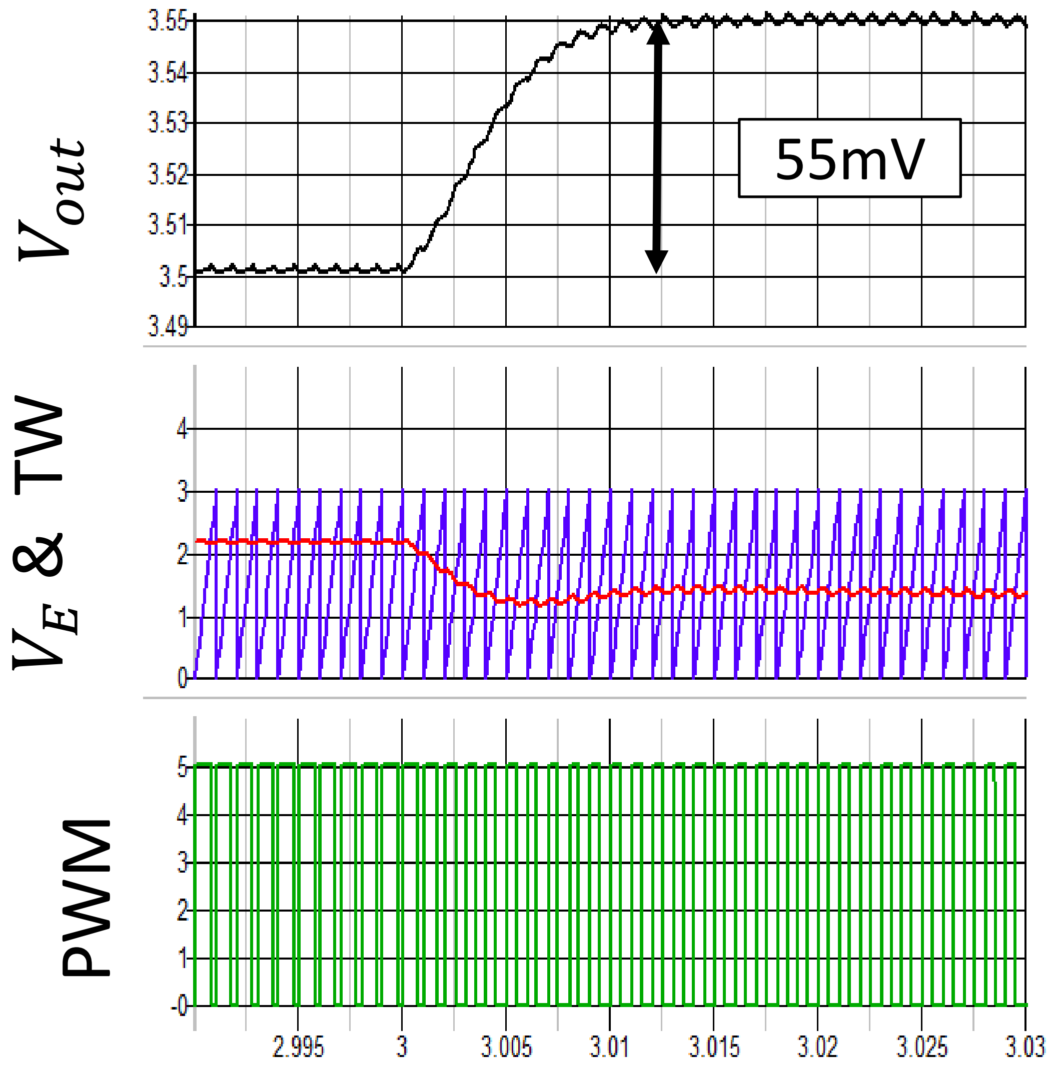
Line Transient Response (1)

V_{in}: 5V ↔ 8V

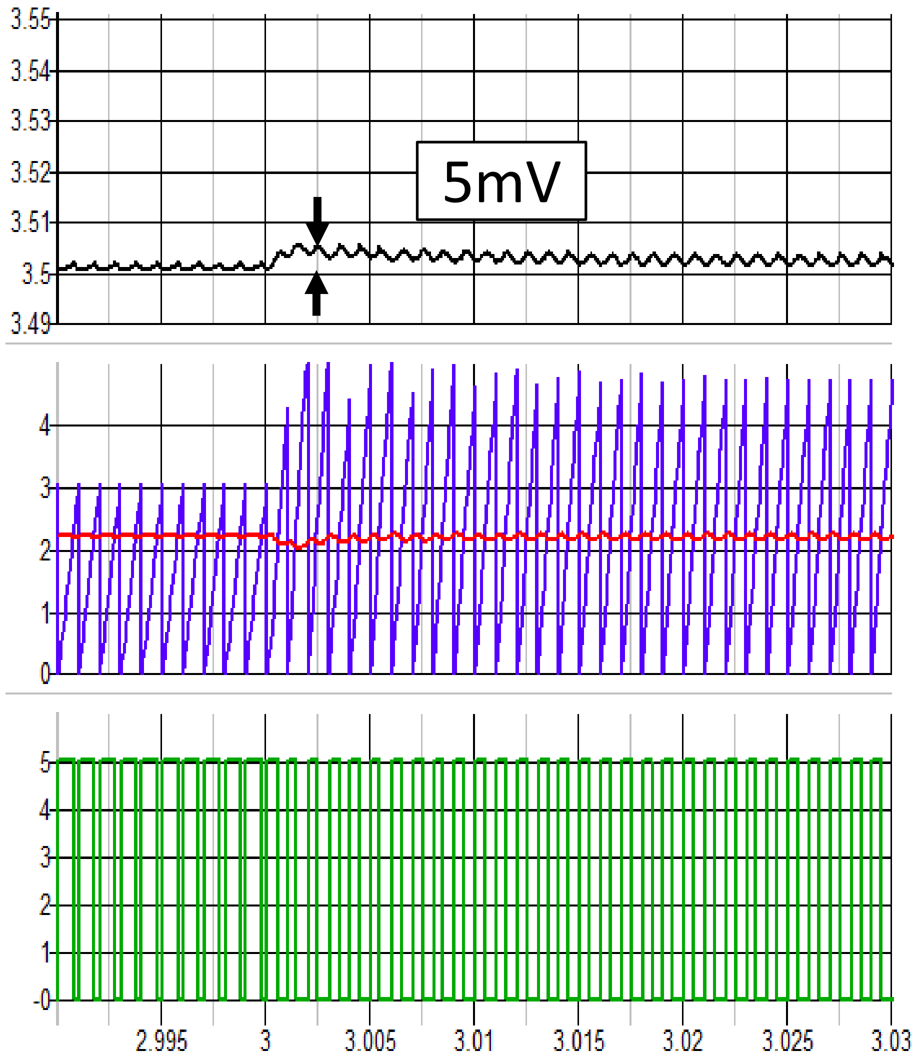


(Simulation conditions is shown in P19)

Line Transient Response (2)



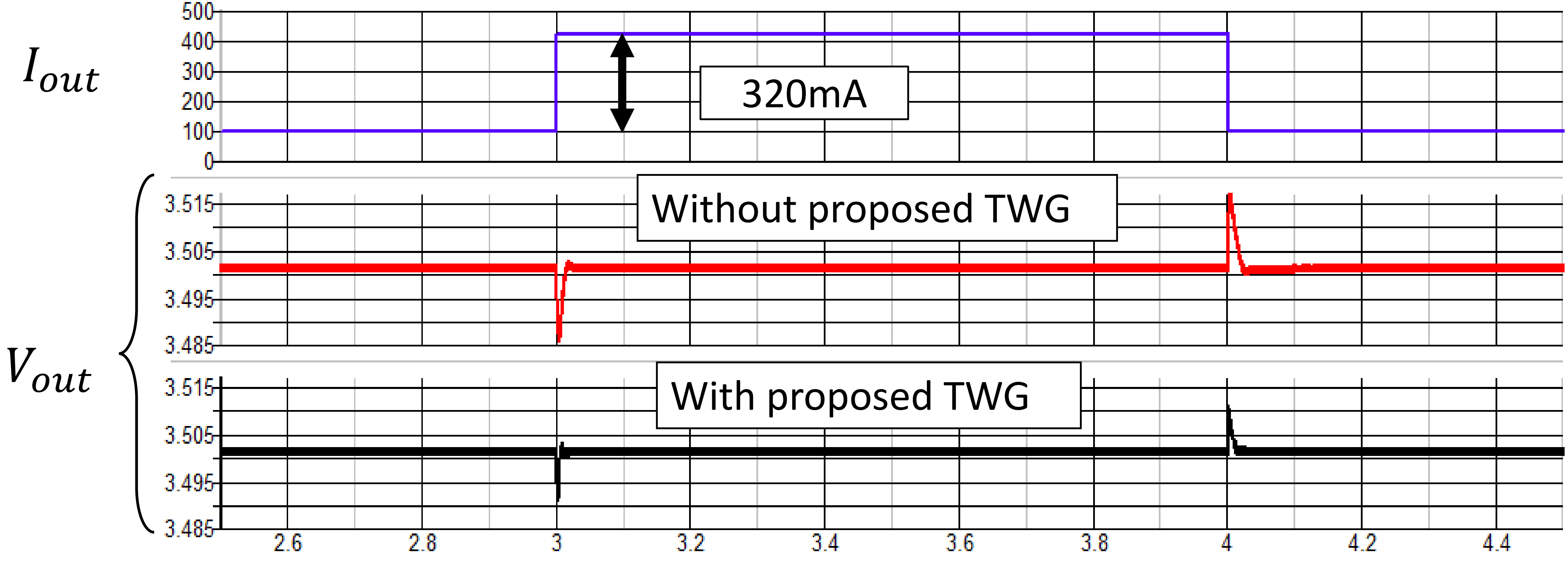
Without proposed TWG



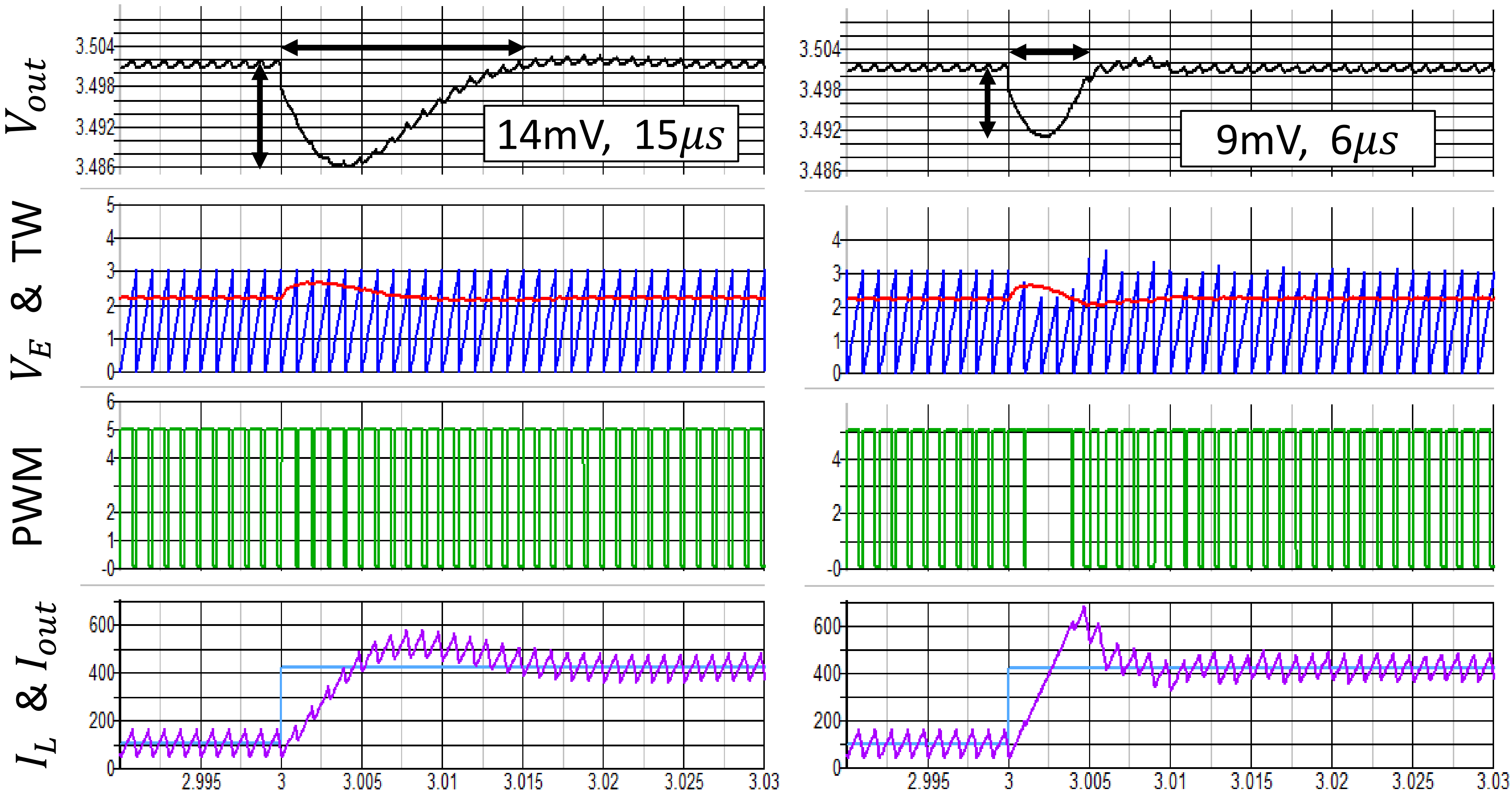
With proposed TWG

Load Transient Response (1)

I_{out}: 100mA ↔ 420mA

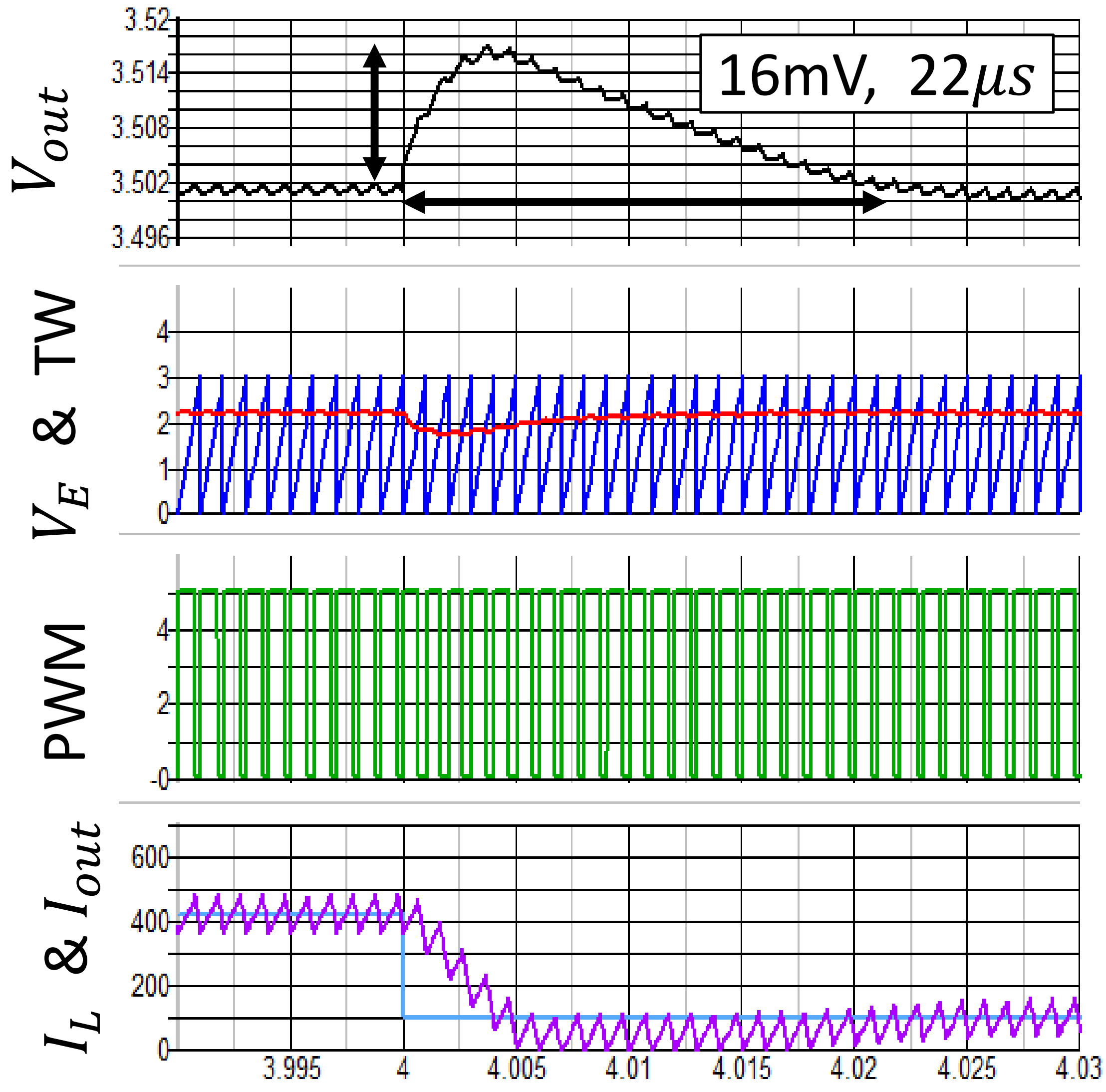


Load Transient Response (2) --- step up

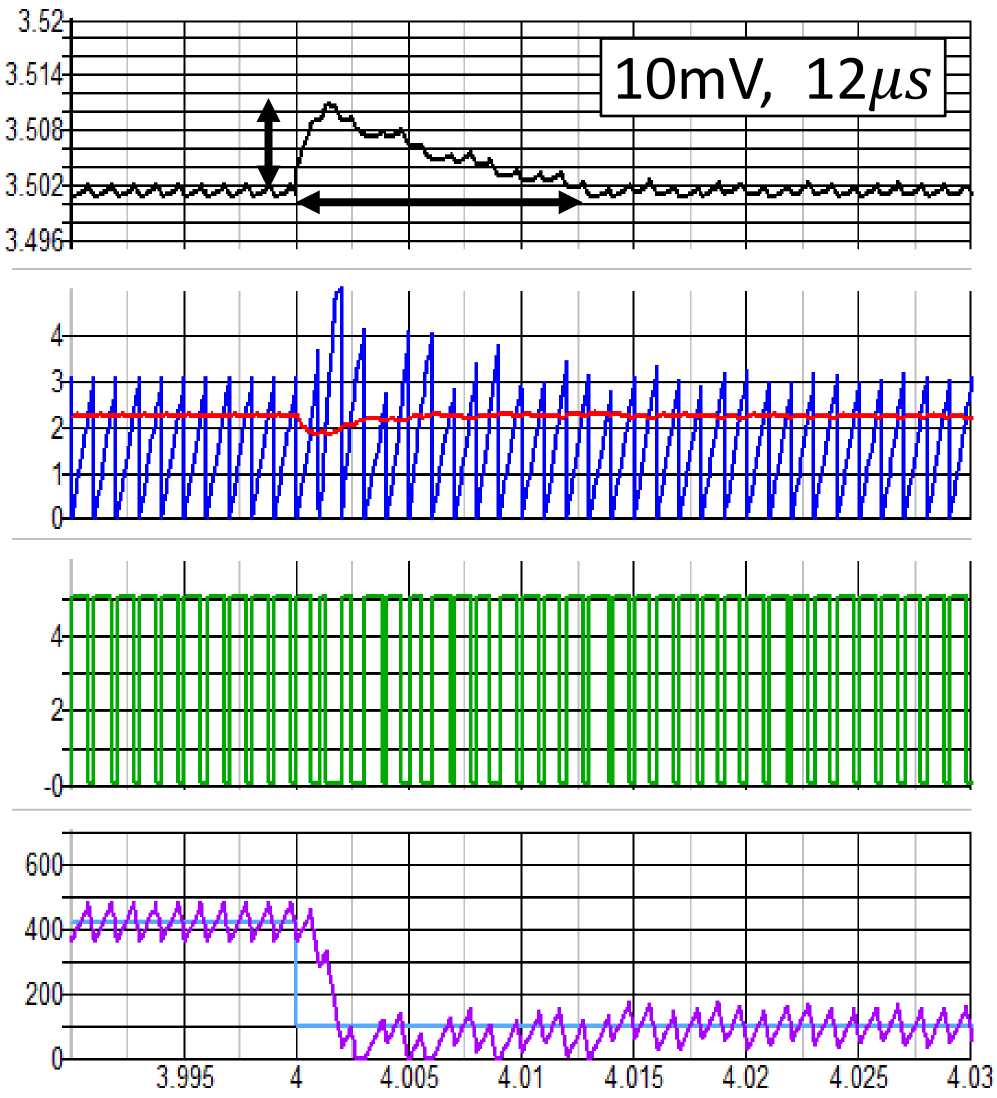


Without proposed TWG **With** proposed TWG

Load Transient Response (3) --- step down



Without proposed TWG



With proposed TWG

Outline

- Research Objective
- Proposed Triangular Wave Generator
  - Duty Cycle Modulation
  - Slope Adjustable Triangular Wave Generator
  - Improvement of Transient Response
- Stability Analysis
- Simulation Results
  - Line Transient Response
  - Load Transient Response
- Conclusion

Conclusion

- Design a slope adjustable triangular wave generator for DC-DC converter.
  - Improve line and load transient response
  - Simple
    - Not require current sensor and slope compensation

- Next Step
  circuit implementation

The End

Thanks for your attention

Q&A

- Normally, we increased the feedback gain to improve transient response. So that, what is the advantage of your method, comparing to the normal method?

A: with a larger feedback gain, we can get higher bandwidth, but it is limited by the gain-bandwidth product of op-amp, especially, VMC need Type 3 compensation. The proposed method increase the open-loop bandwidth by a novel way. Although it also limited by op-amp, but not so much as conventional method.

- During line transient response, which parameter is changed?

A: Since the triangular wave slope is controlled by input voltage, it means the peak value of triangular wave --Vp also be controlled by input. During line transient response, the variation in Vin is eliminated by the changed Vp.