第57回 自動制御連合講演会
10^{th} ~11^{th} November, Gunma

群馬大学
GUNMA UNIVERSITY

Voltage Mode Control Using Triangular Wave Slope Modulation for DC-DC Buck Converter

Shu WU, Yasunori KOBORI, Nobukazu Tsukiji , Haruo KOBAYASHI
Division of Electronics and Informatics
Gunma University

November 10, 2014

OUTLINE

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

Transient Response

- 3 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

Conventional Control Schemes

- Feedback
  - Voltage-Mode Control (VMC)
    - Easy to design and analyze
    - Without line feed-forward control
    - Limited bandwidth: slow response
  - Current-Mode Control (CMC)
    - Inherent line feed-forward control (for BUCK)
    - Wide band
    - Slope compensation
    - Current sensor
- Feed-forward

Complicated non-linear calculation

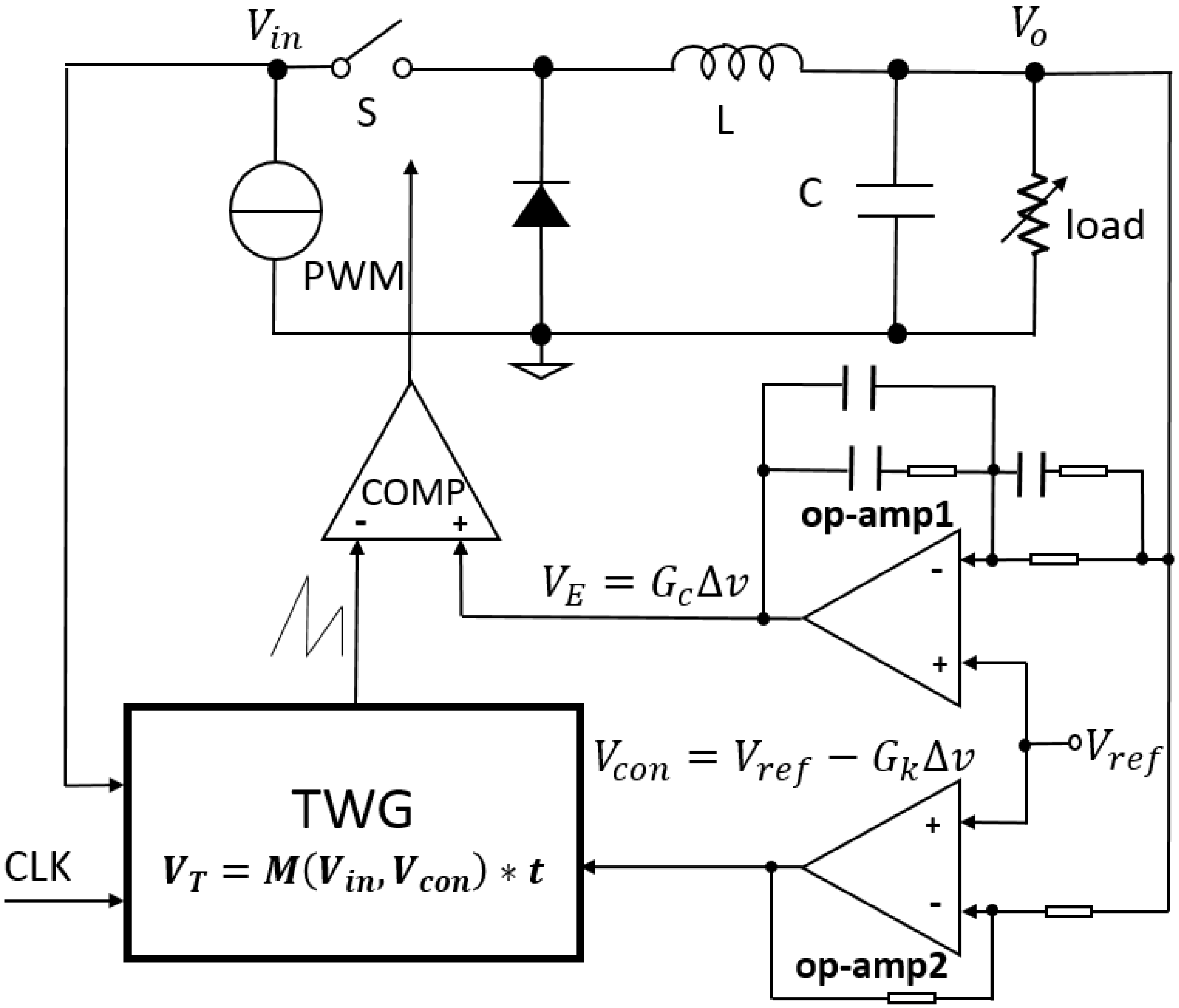
Research Objective

- 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 or slope compensation
  - **Slope is regulated by input and output voltages:**
    compared to conventional VMC
    ---Provide line feed-forward control and wideband
  - **Simple:**
    compared to previous feed-forward control
    ---Not require complicated calculation

OUTLINE

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

System Configuration



Op-amp1:

- Generate error signal
- Type 3 compensation

Op-amp2:

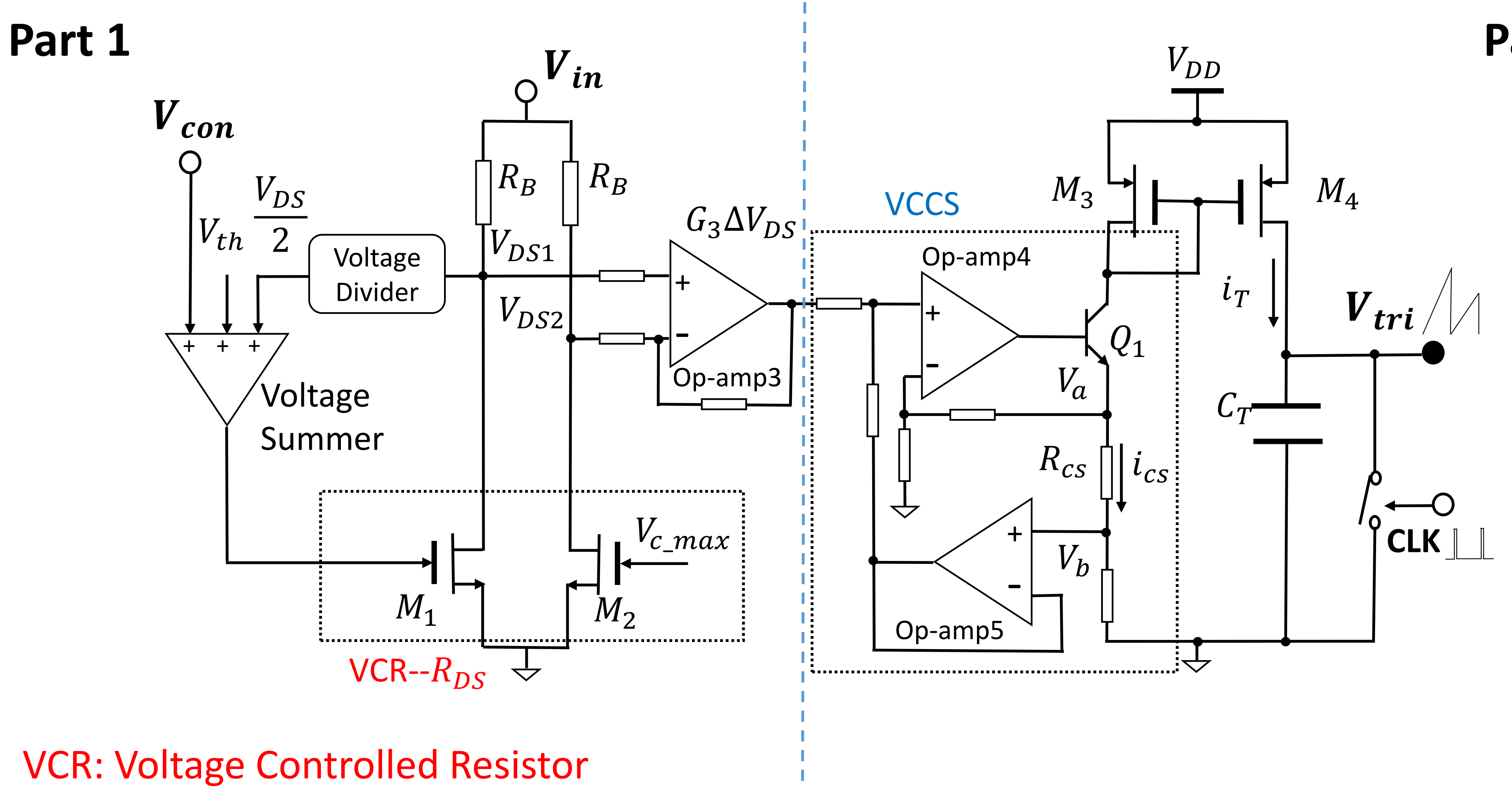
- Amplify deviation
- Control variable of TWG

TWG (Triangular Wave Generator):

Slope adjustable

- Controlled by V_{in} and V_{con}

Triangular Wave Generator (1)

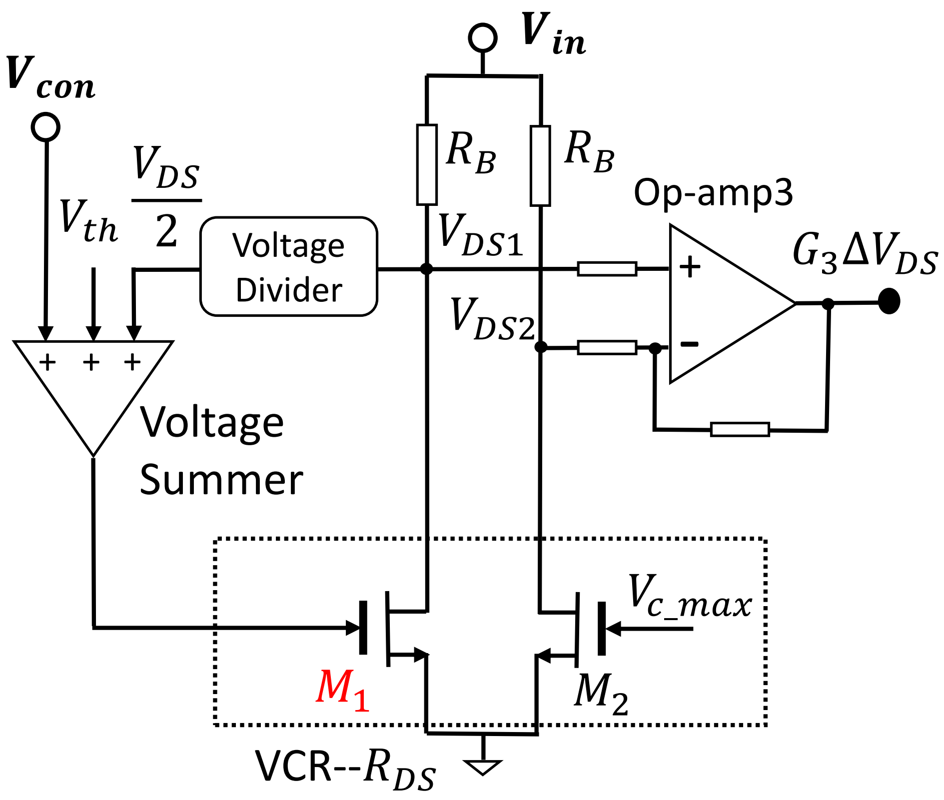


VCR: Voltage Controlled Resistor

VCCS: Voltage Controlled Current Source

Triangular Wave Generator (2)---Part 1

- VCR



※ $K_n = \mu_n C_{ox} W/L$

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

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

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

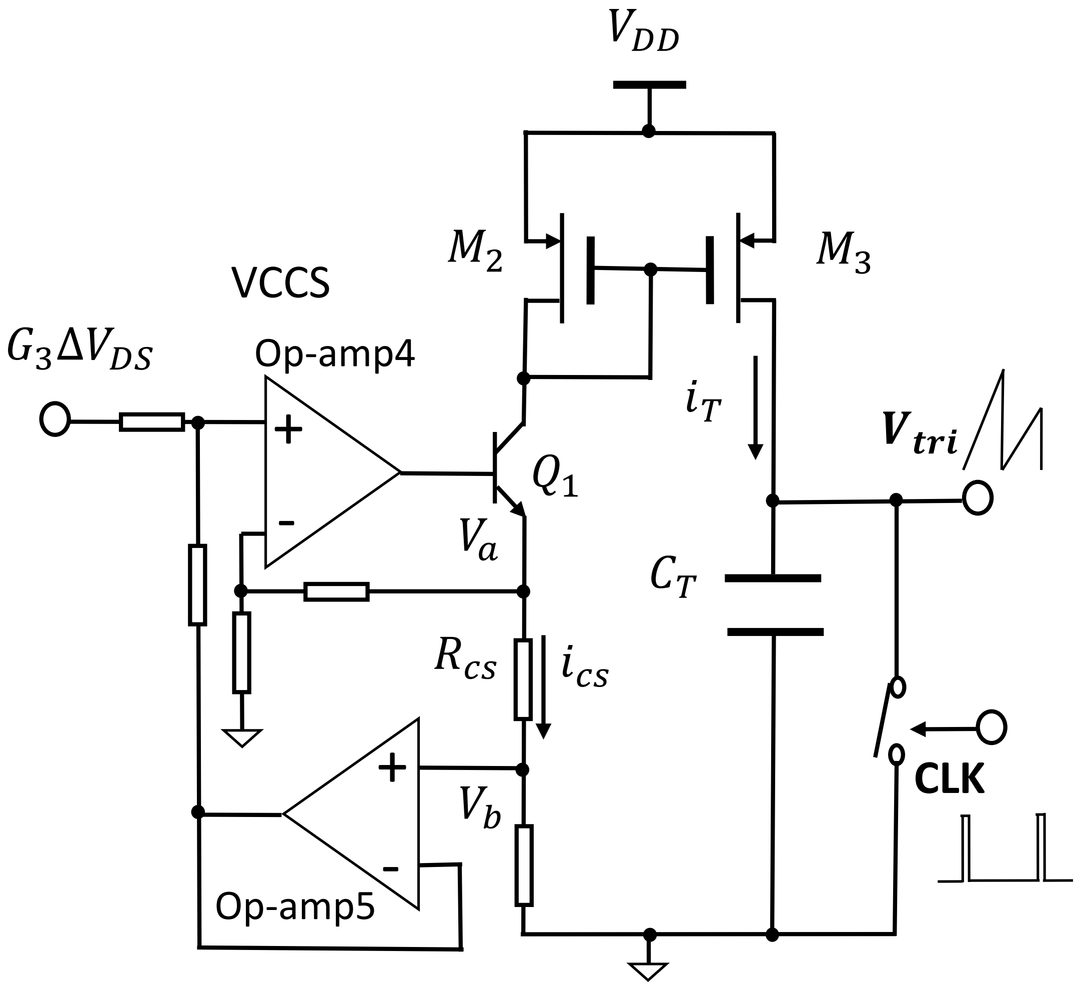
If $R_B \gg R_{DS}$

$$V_{DS} \approx \frac{1}{K_n R_B}\frac{V_{in}}{V_{con}}$$

$$G_3\Delta V_{DS} = \frac{G_3 V_{in}}{K_n R_B}\left(\frac{1}{V_{con}} - \frac{1}{V_{con\_max}}\right)$$

Triangular Wave Generator (3)---Part 2

- VCCS & TWG



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

$$V_{tri} = \frac{i_T}{C_T} t$$

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

Where $a = \frac{G_3}{K_n R_B R_{CS} C_T}$, $b = \frac{a}{V_{con\_max}}$

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

Line Transient Response Improvement

------ 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 $V_p = MT_s$, and M depends on V_{in} (proportional) and V_{con}

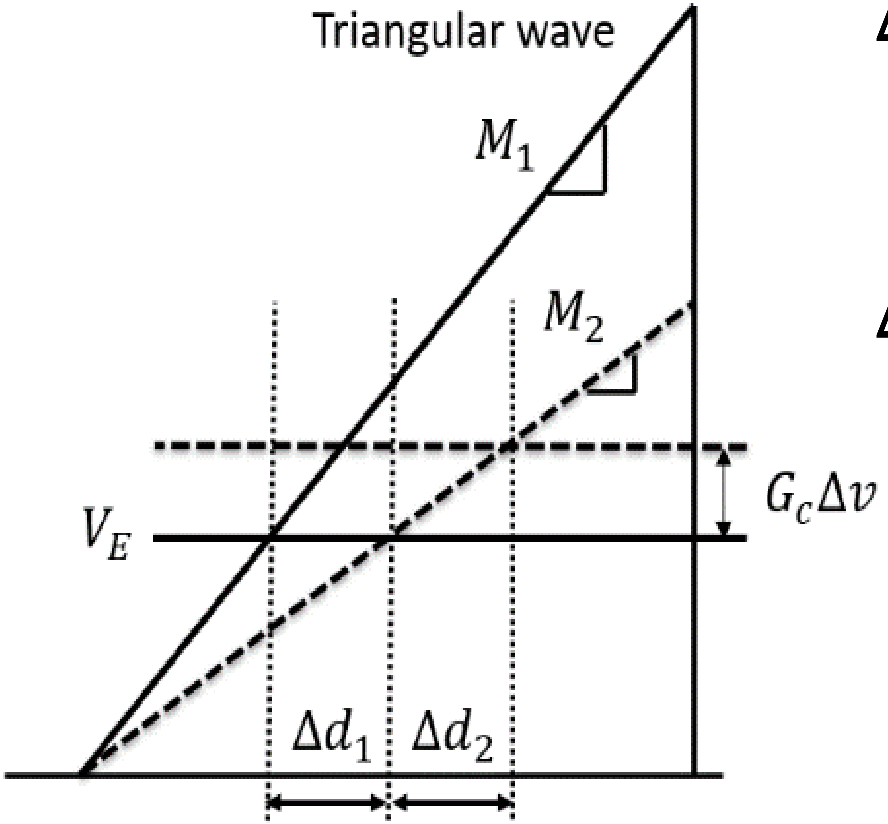
⇩

Input voltage change effects are reduced.

V_P --- the peak of triangular wave

Load Transient Response Improvement (1)

------ Additional duty cycle modulation



Δd_1 is caused by slope modulation

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

Δd_2 is caused by slope and error modulations

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

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

Additional duty cycle modulation by proposed TWG--Δd_s

Conventional VMC--Δd_e

$$\boldsymbol{V_{p\_static} = T_s M_1}$$

Load Transient Response Improvement (2)

------ Non-linear control features

$$\Delta d = \left(\frac{V_E}{T_s} + \frac{G_c \Delta v}{T_s}\right)\left(\frac{\left(V_{ref} + G_k \Delta v\right)}{V_{in}\left(a - b\left(V_{ref} + G_k \Delta v\right)\right)} - \frac{V_{ref}}{V_{in}\left(a - bV_{ref}\right)}\right) + \frac{G_c \Delta v}{V_{p\_static}}$$

$$\Delta d = A\Delta v + \frac{G_c \Delta v}{V_{p\_static}}$$

$$A(\Delta v) = \frac{aG_k\left(V_E + G_c \Delta v\right)}{T_s V_{in}\left(a - bV_{ref}\right)\left(a - bV_{ref} - bG_k \Delta v\right)}$$

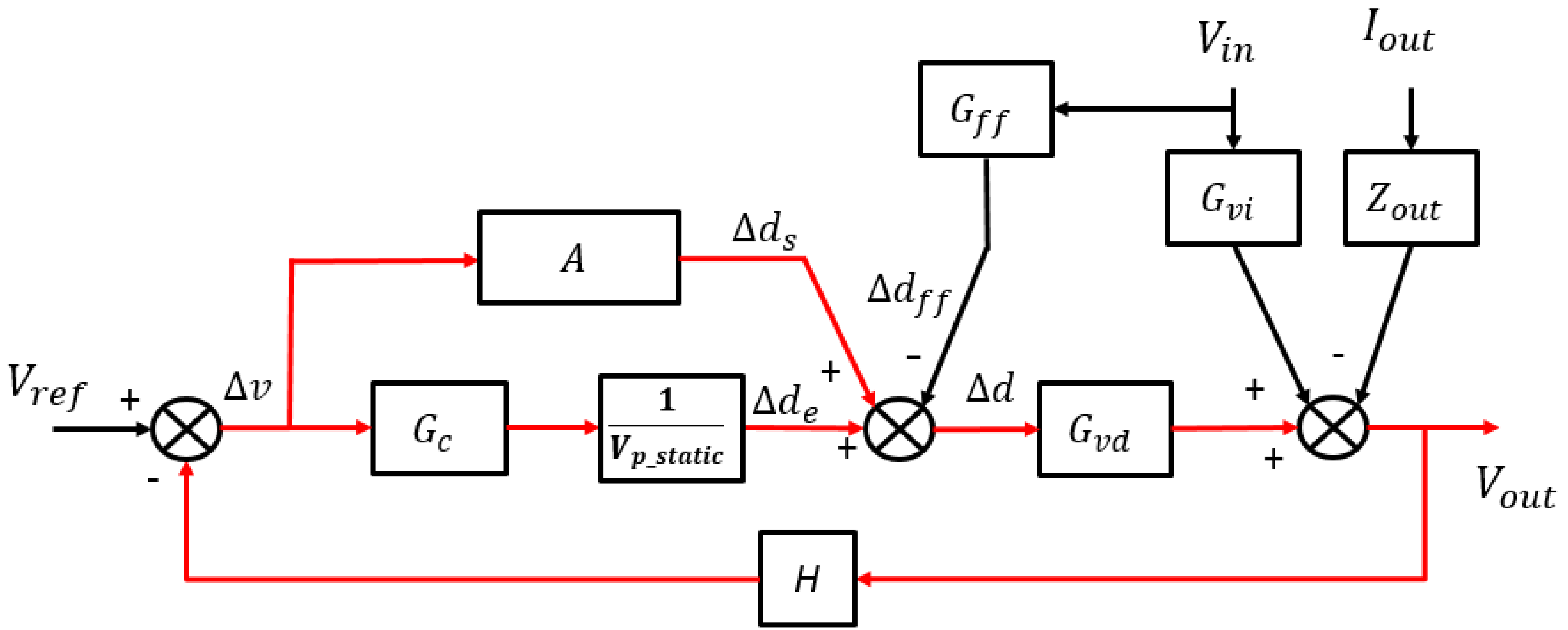
Δv: Large → A: Large → Enable fast transient response

Δv → A: Non-linearly change

Δv: approach to 0 → A: approach to a constant → To ensure the loop stability

System Block Diagram

Supposing Δv is enough small, and A is approximated as constant



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

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

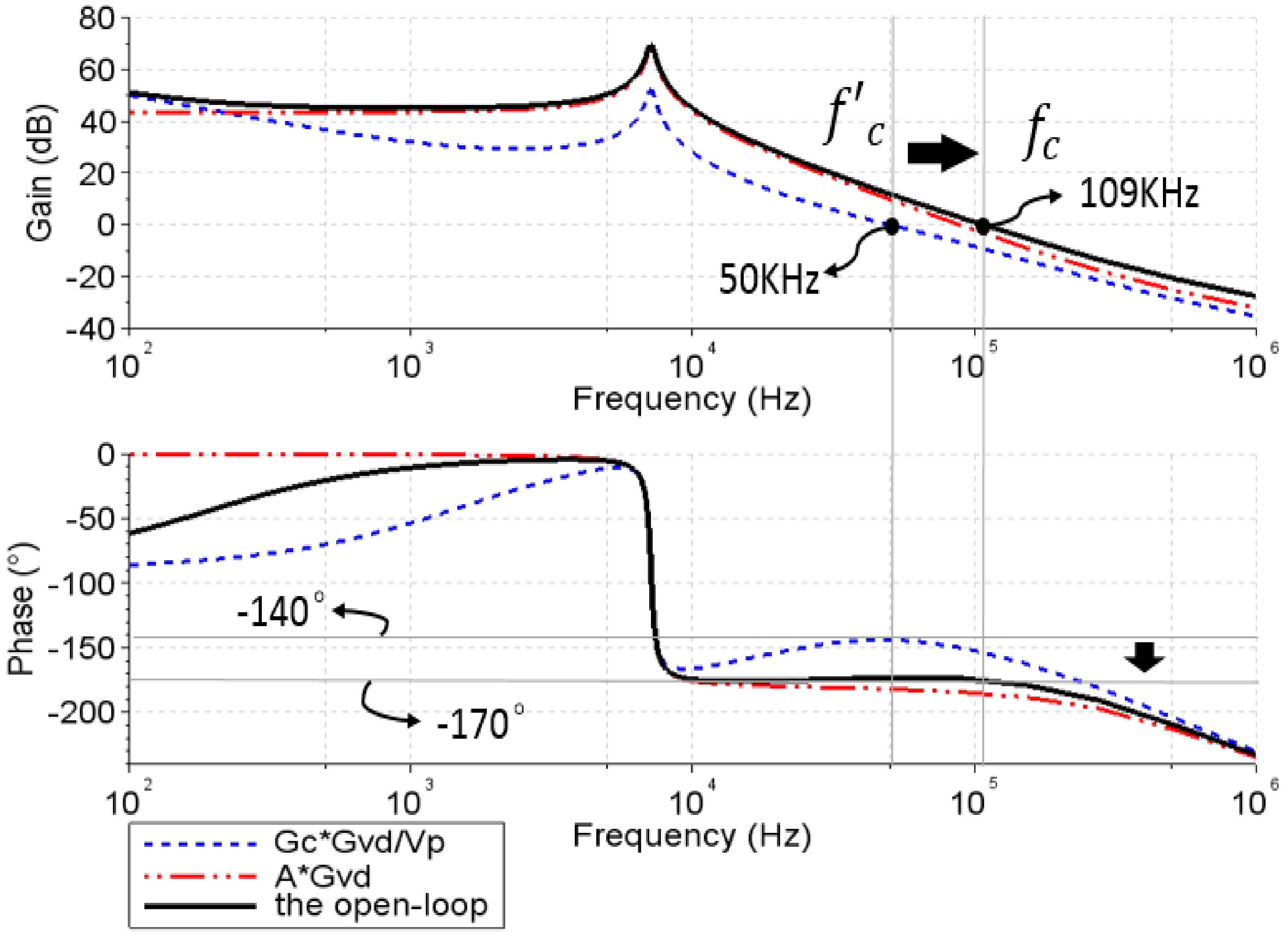
Design for conventional VMC

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

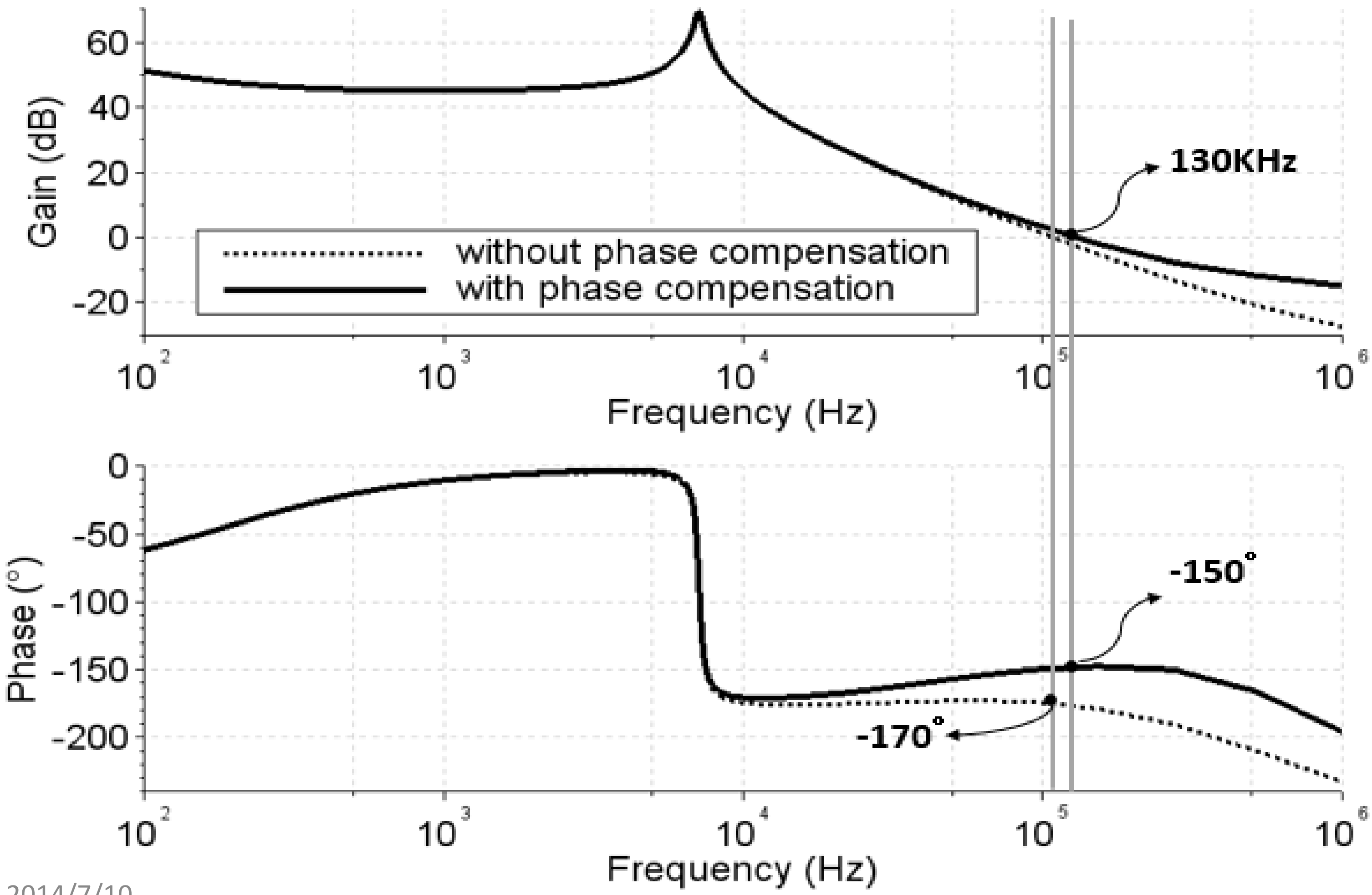


Compare to conventional VMC --- $(G_c G_{vd}/V_p)$

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

Increase Phase Margin

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



- Bandwidth

109kHz → 130kHz

- Phase Margin

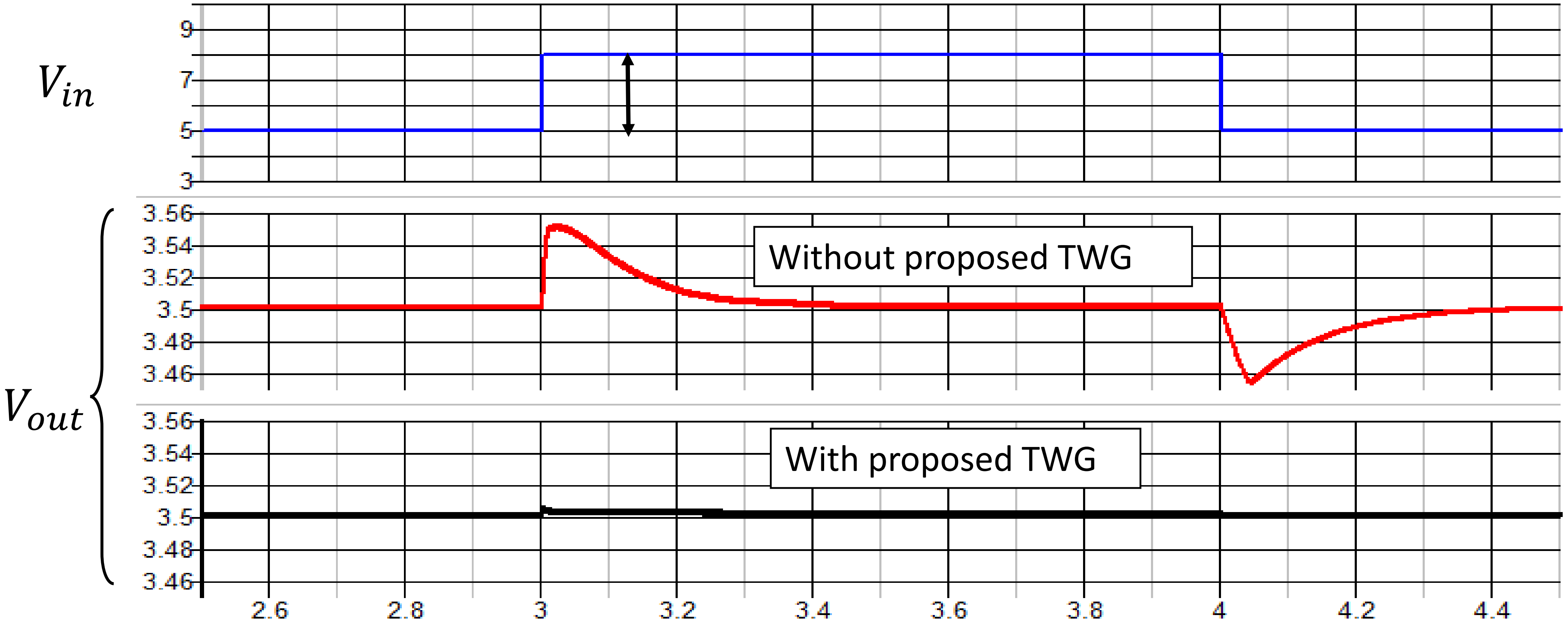
10° → 30 °

OUTLINE

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

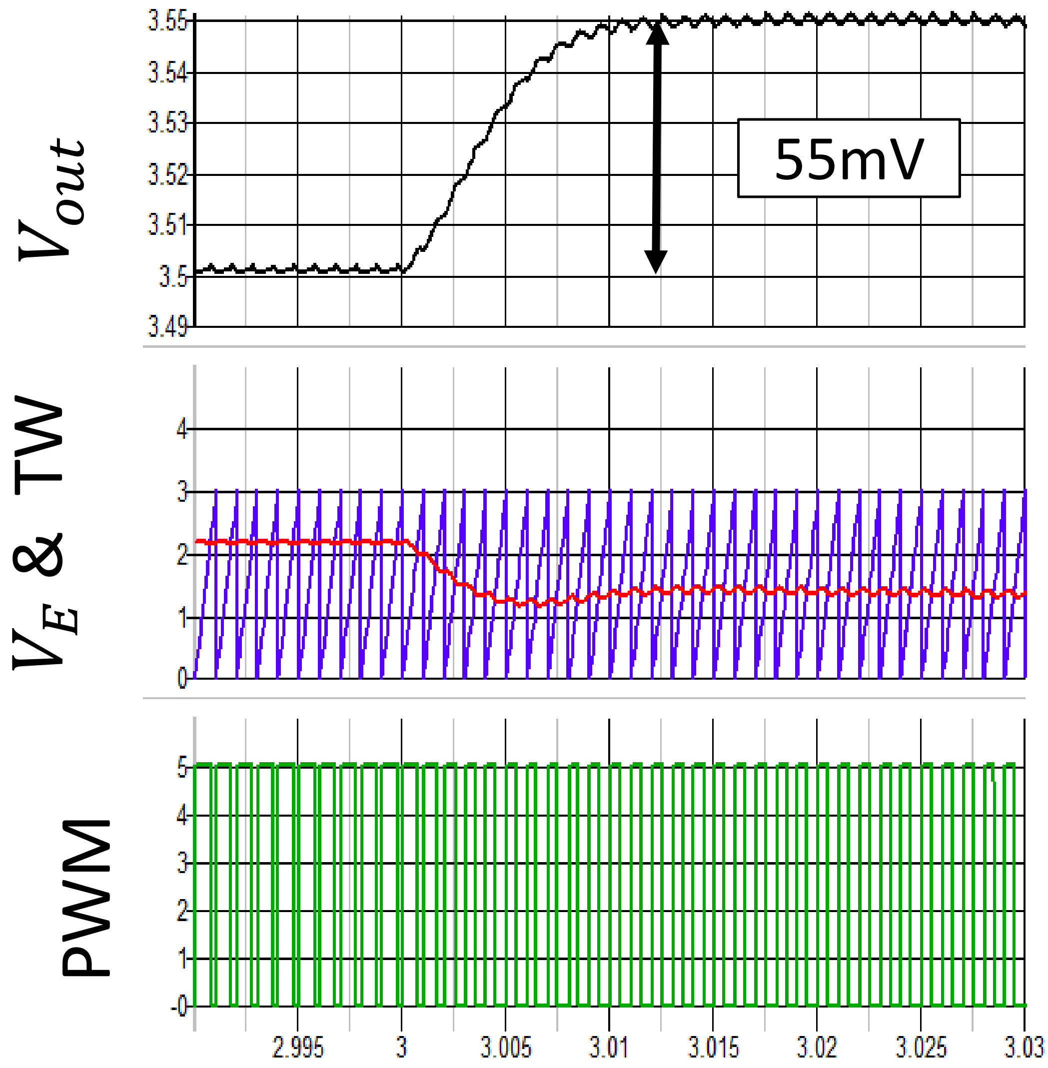
Line Transient Response (1)

V_{in}: 5V ↔ 8V

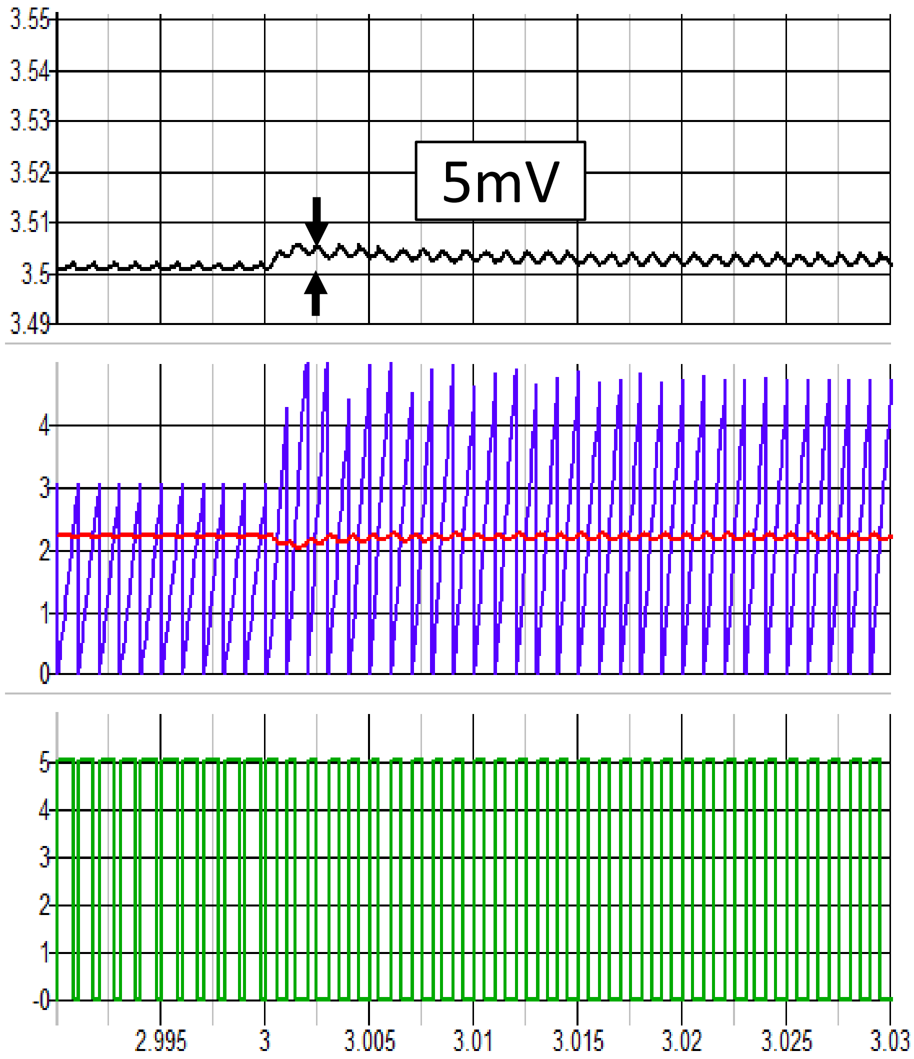


(Simulation conditions are shown in P16)

Line Transient Response (2)



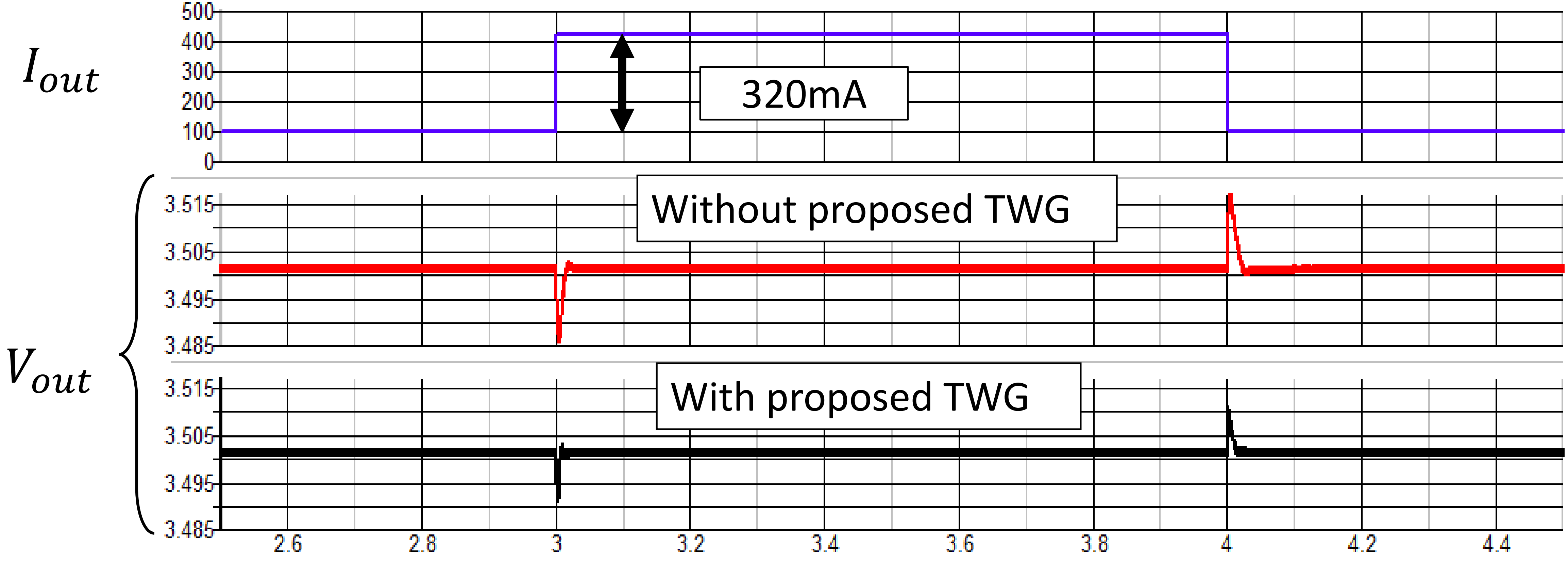
Without proposed TWG



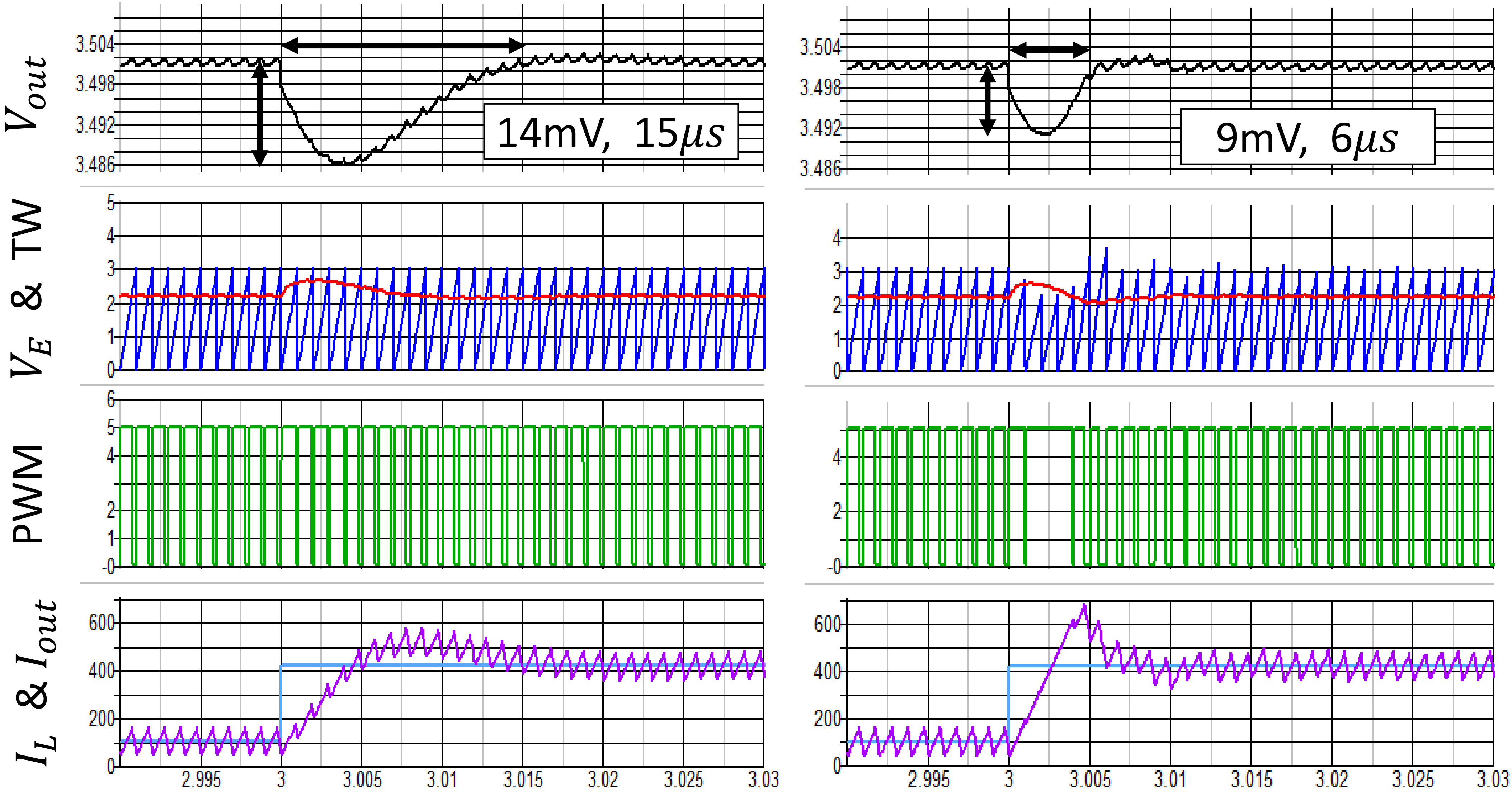
With proposed TWG

Load Transient Response (1)

I_{out}: 100mA ↔ 420mA

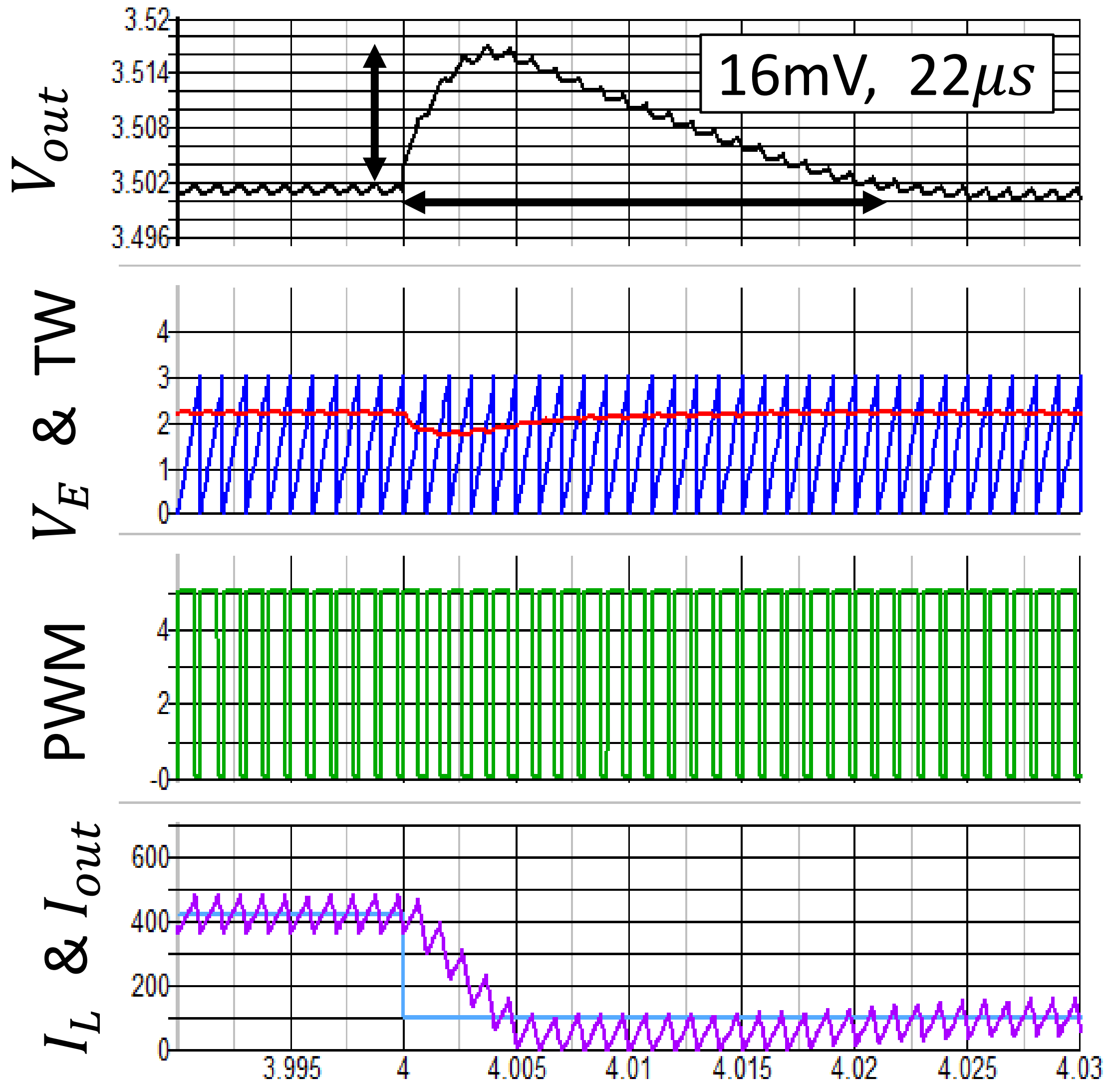


Load Transient Response (2) --- step up

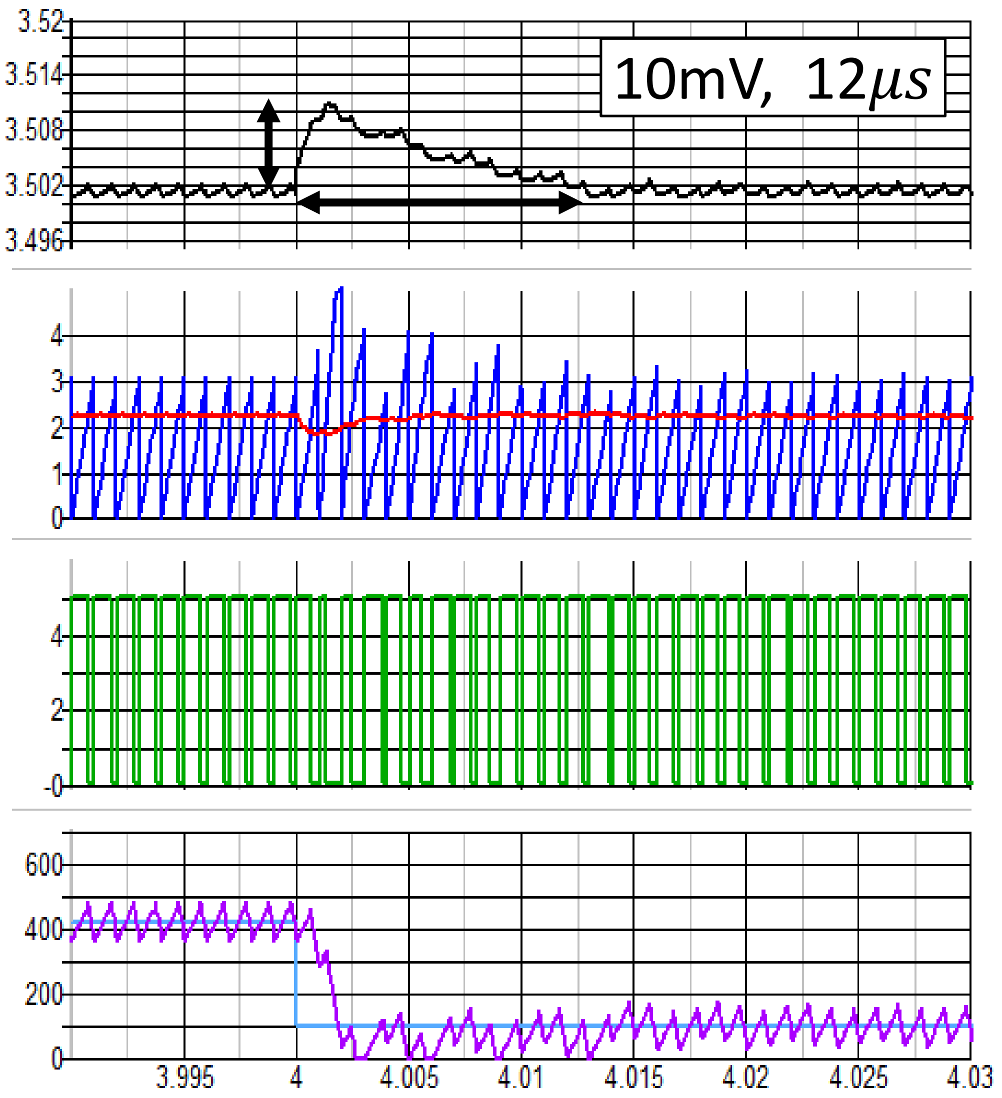


Without proposed TWG **With** proposed TWG

Load Transient Response (3) --- step down



Without proposed TWG



With proposed TWG

OUTLINE

- Research Objective
- Proposed Triangular Wave Generator
  - 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.
  - Line and load transient response improvement
  - Simple

    - Not require current sensor or slope compensation

- Next Step

  Circuit implementation

The End

Thanks for your attention

Q&A

- The proposed method causes the phase margin decrease. How do you deal with this problem?

A: the reason of phase margin decrease is the phase of additional feedback loop (A*Gvd) is too low. Therefore I try to increase the phase of A*Gvd at high frequency. We can add a high-frequency zero point in A. This can be realized through insert a appropriate capacitor in op-amp2 (Page 8) or op-amp3 (Page 9). By this way, the phase of A*Gvd is increased at the crossover frequency, the phase margin also increase.