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
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Transient Response

• Three disturbance sources
  • Output reference signal
  • Input voltage
  • Load

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
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**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 load transient response, 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)

Deviation
\[ \Delta v = V_{ref} - V_{out} \]

Error signal modulation
proportional

Duty cycle
\[ \Delta d \]

Slope of triangular wave
\[ \Delta M \]

Slope modulation
\textit{inversely proportional}

Slope modulation
\textit{proportional}
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

\[ I_D = K_n \left( (V_{GS} - V_{th})V_{DS} - \frac{V_{DS}^2}{2} \right) \]

where \( K_n = \mu_n C_{ox} W / L \)

\[ \frac{1}{R_{DS}} = \frac{i_D}{V_{DS}} = K_n \left( V_{GS} - V_{th} - \frac{V_{DS}}{2} \right) \]

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

\[ R_{DS} = \frac{1}{K_n V_{con}} \quad \ldots \ldots (1) \]

If \( R_B \gg R_{DS} \)

\[ V_{DS} = \frac{1}{K_n R_B} \frac{V_{in}}{V_{con}} \quad \ldots \ldots (2) \]

\( V_{DS} \) 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)

\[ V_T = \frac{V_{in}}{K_n R_B R_{CS} C_T V_{con}} t = M \left( \frac{1}{V_{con}}, V_{in} \right) t \quad \ldots \ldots (3) \]
Transfer function from error signal to output voltage (VMC buck converter)

\[ V_{out} = \frac{1}{LC s^2 + \frac{L}{R} s + 1} \frac{V_{in}}{V_P} V_E \]

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

\[ \Delta d_1 \text{ is caused by slope modulation} \]
\[ \Delta d_1 = \frac{V_E}{T_s} \left( \frac{1}{M_1} - \frac{1}{M_2} \right) = \frac{V_E}{T_s} \Delta \frac{1}{M} \]

\[ \Delta d_2 \text{ is caused by slope modulation and error signal modulation} \]
\[ \Delta d_2 = \frac{G_c \Delta v}{T_s} \left( \frac{1}{M_1} - \Delta \frac{1}{M} \right) = \frac{G_c \Delta v}{T_s M_1} - \frac{G_c \Delta v}{T_s} \Delta \frac{1}{M} \]

\[ \Delta d = \Delta d_1 + \Delta d_2 = \left( \frac{V_E}{T_s} - \frac{G_c \Delta v}{T_s} \right) \Delta \frac{1}{M} + \frac{G_c \Delta v}{T_s M_1} \ldots (4) \]

Conventional VMC

Additional duty cycle modulation by proposed TWG
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System Block Diagram

Ignore non-linear terms

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

\[ A = \frac{K_n R_B R_{CSC} T V_E G_k}{T_s V_{in}} \]

\[ V_{p\_static} = T_s M_1 \]

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

Design for conventional VMC

**TWG**

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

$A \approx 30$
Bode Plot

Compare to conventional VMC

\[ (G_c G_{vd}/V_p) \]

- Bandwidth is increased
  
  \[ 50\text{kHz} \rightarrow 109\text{kHz} \]

- Phase margin is decreased
  
  \[ 40^\circ \rightarrow 10^\circ \]
Increase Phase Margin

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

- Bandwidth
  109kHz → 130kHz

- Phase Margin
  10° → 30°
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Line Transient Response (1)

\[ V_{in}: 5V \leftrightarrow 8V \]

\[ V_{in} \]

\[ V_{out} \]

Without proposed TWG

With proposed TWG

( Simulation conditions is shown in P19)
Line Transient Response (2)

Without proposed TWG

With proposed TWG

55mV

5mV
Load Transient Response (1)

$I_{out}$: $100mA \leftrightarrow 420mA$

$I_{out}$

Without proposed TWG

With proposed TWG

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Load Transient Response (2) --- step up

Without proposed TWG

With proposed TWG
Load Transient Response (3) --- step down

- **Without proposed TWG**
  - $V_{ou\text{t}}$: 16mV, 22$\mu$s
  - $V_{E \& TW}$: 
  - $PWM$:
  - $I_{L \& I_{out}}$:

- **With proposed TWG**
  - $V_{ou\text{t}}$: 10mV, 12$\mu$s
  - $V_{E \& TW}$: 
  - $PWM$:
  - $I_{L \& I_{out}}$:
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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.