Derivation of Loop Gain and Phase from Output Impedances in Analog Circuit with Negative Feedback

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(IPS01-04)

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Outline

• Research Background
• Purpose of This Work
• Derivation of Proposed Method
• Simulation and Measurement Result
• Summary
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There are a lot of applications using negative feedback systems.

Low Drop Out Regulator

Switching Regulator
Research Background(2)

- Measurement of the loop gain is important to evaluate the stability of the negative feedback system.

\[
\text{Loop Gain } T = A\beta
\]
• Conventional loop gain measurement method
Disadvantage of Conventional Method

- It is necessary to inject a voltage signal into the feedback loop by breaking the loop.
- If the control circuits are implemented on an IC, this method is NOT applicable.

Diagram:
- DC/DC converter
- Error Amp
- PWM
- Load
- FRA (Frequency Response Analyzer)
- Ri (50~100ohm)
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Purpose of This Work

• To measure the loop gain without breaking the feedback loop.
• To develop a new method to derive the loop gain from output impedances in dc-dc buck converter.
• To demonstrate the proposed method by simulation and experimental evaluations.
Negative feedback reduces the noise by a factor of $\frac{1}{1+T}$.

This theory can be applied to loop gain measurement.
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DC-DC Buck Converter Circuit in Open Loop

Converter power stage

- Power input
- Converter power stage
- Transistor gate driver
- Load

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Slide 12
Functional Block Diagram in Open Loop

\[ \Delta V_o = G_{vd} \Delta D + G_{vi} \Delta V_{in} - Z_o \Delta I_o \]

\[ Z_o \equiv -\left. \frac{\Delta V_o}{\Delta I_o} \right|_{\Delta D=0, \Delta V_{in}=0} \]

Converter output impedance in open loop

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DC-DC Buck Converter Circuit in Closed Loop

- Power input
- Converter power stage
- Load
- Sensor gain
- Pulse-width modulator
- Compensator
- Reference input
- Converter power stage
- Transistor gate driver
- Error signal
- Output voltage
- Reference input
- Sensor gain

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Functional Block Diagram in Closed Loop

\[
\Delta V_o = \frac{1}{H} \frac{T}{1 + T} \Delta V_{\text{ref}} + \frac{G_{vi}}{1 + T} \Delta V_{\text{in}} - \frac{Z_o}{1 + T} \Delta I_o
\]

\[
Z_{oc} \equiv -\frac{\Delta V_o}{\Delta I_o} \bigg|_{\Delta V_{\text{ref}}=0, \Delta V_{\text{in}}=0} = \frac{Z_o}{1 + T}
\]

Converter output impedance in closed loop

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Derivation of Proposed Method

\[ Z_{oc}(s) = \frac{Z_o(s)}{1 + T(s)} \]

\[ T(s) = \frac{Z_o(s) - Z_{oc}(s)}{Z_{oc}(s)} \]

Magnitude of Loop Gain

\[ 20 \log_{10} |T| = 20 \log_{10} \left( \frac{|Z_o - Z_{oc}|}{|Z_{oc}|} \right) \]

Phase of Loop Gain

\[ \arg(T) = \arg(Z_o - Z_{oc}) - \arg(Z_{oc}) \]
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Simulation Circuits

Conventional

Vin

\[ Q_1 \]

\[ V_{Sw} \]

\[ L \]

\[ V_o \]

Error Amp

\[ R_L \]

\[ Co \]

Comparator

\[ D_1 \]

Saw-Tooth Generator

\( V_{ref} \)

\[ R_1 \]

\[ R_2 \]

Loop Gain \( T = \frac{V_o}{V_o'} \)

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Simulation Circuits

Proposed

Vin $Q_1$ Vsw L Vo

Comparator $D_1$

Saw-Tooth Generator

Error Amp

$V_c$

SW=On: Zo meas.

SW=Off: Zoc meas.

$V_{ref}$

$R_L$

$I_o$

$R_1$

$R_2$

Parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Vin</td>
<td>12V</td>
</tr>
<tr>
<td>Vo</td>
<td>5V</td>
</tr>
<tr>
<td>RL</td>
<td>5Ω</td>
</tr>
<tr>
<td>L</td>
<td>120μH</td>
</tr>
<tr>
<td>Co</td>
<td>1.2mF x 2 (ESR=40mΩ)</td>
</tr>
</tbody>
</table>

Loop Gain $T = (Zo-Zoc)/Zoc$
Simulation Results

**Impedance [ohm]**

- $\frac{1}{1 + T}$

**Phase [deg]**

- arg($Z_o$)
- arg($Z_{oc}$)

**Frequency [Hz]**

- 10
- 100
- 1000
- 10000
- 100000

**Gain [dB]**

- Conventional
- Proposed

**Phase [deg]**

- Conventional
- Proposed

**Frequency [Hz]**

- 10
- 100
- 1000
- 10000
- 100000

Experimental Setup

- IC: BD9329A (Rohm Semiconductor)
  - Synchronous buck converter with integrated FET
  - Switching frequency: 380kHz

Evaluation board

Parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<td>3.3V</td>
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<tr>
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<td>L</td>
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</tr>
<tr>
<td>Co</td>
<td>10uF x 2</td>
</tr>
<tr>
<td>Ri</td>
<td>1Ω</td>
</tr>
<tr>
<td>Rs</td>
<td>1kΩ</td>
</tr>
</tbody>
</table>

\[ Z_x = \frac{V_{ch1}}{V_{ch2}} \cdot R_i \]
Experimental Results

**Graphs:***

- **Impedance (Ω):**
  - Frequency [Hz]
  - |Zo|
  - |Zoc|

- **Phase [deg]:**
  - Frequency [Hz]
  - arg(Zo)
  - arg(Zoc)

- **Gain [dB]:**
  - Frequency [Hz]
  - Conventional
  - Proposed

- **Phase Margin = 90°:**

- **Fbw:**

**Mathematical Expressions:**

\[
\frac{1}{1 + T}
\]
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• We have proposed a method to derive the loop gain from the output impedances in dc-dc buck converter.
• We showed effectiveness of the proposed method with simulations and experiments of dc-dc buck converter.
• We found out that sufficient evaluation of phase margin and gain margin is possible.
Thank you for listening !!