High-Speed Response Single Inductor Multi Output DC-DC Converter with Hysteretic Control
Outline

• Research Objective
• SIDO Converter with Exclusive Control
  – Circuit and Operation
  – Simulation and Experimental Results
• Proposed SIDO Converter with Hysteretic Control
  – Basic Converter with Hysteretic Control
  – Circuit and Operation of Proposed Converter
  – Simulation and Experimental Results
• Proposed SIMO Converter with Hysteretic Control
• Conclusion
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Background

Many DC-DC Converters in Cell phones, manufacturing machinery, etc.

AC-DC converter
(Fly back, Forward Type)

$V_B = 24/12$ V

Many Power Supplies
(DC-DC converters)

Load Circuit
- 5.0 V, 4.2 V
- 3.5 V, 2.5 V
- 1.2 V etc.

Fig. 1 background
Background

Single Inductor Dual Output Power Supply (SIDO converter)

Conventional approach

- Reduce inductor
- Reduce cost
- Reduce volume

Our New Method

Reduce inductor
Reduce cost
Reduce volume

Fig.2 Background
Research Objective

● Single Inductor Dual Output (SIDO) converter
  ➢ Our Previous SIDO converter with Exclusive Control
    buck-buck or boost-boost converter
  ➢ Control Speed becomes slow
    because of sharing a Inductor and a switch

● New SIDO/SIMO Converter with Hysteretic Control
  ➢ Using few additional components, no current sensor
  ➢ Does not depend on the value of Vo or Io.
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Previous SIDO Converter with Exclusive Control

\[ V_1 = 6V, \quad V_2 = 4V \]

\[ \Delta V_1 > \Delta V_2 \Rightarrow \text{SEL} 'L' \Rightarrow S2:OFF \Rightarrow V_1 \]

\[ \Delta V_1 < \Delta V_2 \Rightarrow \text{SEL} 'H' \Rightarrow S2:ON \Rightarrow V_2 \]

Fig. 3 Simulation Circuit

Fig. 4 Timing Chart

\[ F = 500kHz \]
Previous SIDO Converter

**Simulation Result 1**  Output Ripple

![Graph showing simulation results with output ripple levels and values.](image)

**V1**  
- $V_1 = 6.0V$  
- $\Delta V_1 = 11mVpp$

**V2**  
- $V_2 = 4.0V$
- $\Delta V_2 = 19mVpp$

-\[ I_1 = 2A, I_2 = 0.2A \]

- $\Delta V_1, \Delta V_2 < 0.5\%V_o$

*(Io Ratio: 10 × ) $I_1/I_2 = 2A/0.2A = 10$*

Fig.5  Simulation Result (Output Ripple)
Previous SIDO Converter

【Simulation Result 2】 (Transient Response)

Red Arrow: Self-regulation
Blue Arrow: Cross-regulation

$\Delta V_{SR}, \Delta V_{CR} < 27mV$

- $I_1 = 2.0A / 1.0A$
- $I_2 = 2.2A / 1.2A$

Fig.6 Simulation Result (Dynamic Load Regulation)
Previous SIDO Converter

【Experimental Result 1】

- **Output Voltage**

Vi=9.0V ⇒ V1=6.0V, V2=4.5V, f=200kHz

I1=0.25A
I2=0.36A

V1=5.98V
V2=4.54V

Fig.7 Experimental Result (Static Load Regulation)
Experimental Result 2

- Dynamic Load Regulation

\[ I_2 = 0.60A / 0.36A \]

\[ \Delta V_1 = 10 \text{ mVpp (Cross Regulation)} \]
\[ \Delta V_2 = 12 \text{ mVpp (Self Regulation)} \]
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Proposed SIDO Converter with Hysteretic Control

- Non-Linear Control (High-Speed Control)
- Simple Circuit (Comparator only)
  (Window Control Method is called Bang-Bang Control)

【Basic SISO Converter】 (Future)

SISO: Single Inductor Single Output

Upper/Bottom Control Method

Window Control Method

Fig.9 Basic Hysteretic Control Method
Proposed SIDO Converter with Hysteretic Control

【Basic SISO Converter】 (Circuit)
- Upper Level Control Method (Energy supply control)
- Simple Circuit (Comparator only. No clock, no PWM signal)
- Control frequency is depend on Loop Delay, Load Current etc.

Fig.10(a)  Circuit of Upper Level Control

Fig.10(b)  Timing Chart

★ $T_{on}$ depends on Delay, $I_o$ etc.
Proposed SIDO Converter with Hysteretic Control

【Basic SISO Converter】(Simulation Result)

- $V_i = 9.0 V$, $V_o = 5.0 V$
- $\Delta I_o = 1.0 A / 0.5 A$
- $F \approx 1 MHz$
- $\Delta V_o = 2.5 \text{ mVpp}$
- Overshoot: $\pm 6.0 \text{ mV}$

Fig. 11 Simulation Result of SISO Converter

★ Parameters
L = 10uH, C = 470uF
Proposed SIDO Converter with Hysteretic Control

【Circuit of Buck Converter】
- \( V_i = 9.0V \Rightarrow V_1 = 5.0V, \ V_2 = 3.0V, \ I_o = 0.25A \)
- \( L = 1\mu H, \ C = 470\mu F \)

Fig.12 Proposed SIDO Circuit with Hysteretic Control
Proposed SIDO Converter with Hysteretic Control

【Simulation Result】
- $\Delta V1, \Delta V2 < 10\text{mV}$
- Overshoot $\equiv 0\text{mV}$

- $V_i=9.0\text{V} \Rightarrow V_1=6.0\text{V}, V_2=4.0\text{V}$
- $I_{o1}=1.0\text{A}/0.5\text{A}, I_{o2}=0.5\text{A}$
- $L=0.5\text{uH}, C=470\text{uF}$

Fig. 13 Simulation Result of SIDO Buck Converter
Proposed SIDO Converter with Hysteretic Control

【Circuit and Operation】(Boost Converter)

- $V_i=3.0V \Rightarrow V_1=5.0V, \ V_2=4.0V$
- $I_o1=1.0A/0.5A, \ I_o2=0.5A$
- $L=1\mu H, \ C=470\mu F$
- Clock is used for starter.

Fig.14 Simulation Circuit

Fig.15 Simulation Result

【Simulation Result】

- $\Delta V_1=\Delta V_2 < 10mVpp$
- Little Overshoot
【Experimental Result】 (Buck Converter)

- Static Load Regulation (Output Ripple)
  \( \Delta V_1 = 20\, \text{mV}, \quad \Delta V_2 = 15\, \text{mV} \)
  \( F = 850\, \text{kHz} \)
  @ Io1=0.50 A, Io2=0.20 A

- Dynamic Load Regulation (Transient Response)
  \( \Delta V_1 = 25\, \text{mV} : \text{Self Regulation} \)
  \( \Delta V_2 = 5\, \text{mV} : \text{Cross Regulation} \)
  @ Io1=0.35A/0.18A
  Io2=0.10A

Fig. 16 Experimental Result 1

Fig. 17 Experimental Result 2
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【Circuit of Buck Converter】
- \( V_i = 9.0\) V, \( V_o = 6.0/5.0/4.0/3.0\) V
- Priority: \( V_4 > V_3 > V_2 > V_1 \)
  \[ V_4 < V_3 < V_2 < V_1 \]
- Period E: \( I_L \) is back to source.

SIMO: Single Inductor Multi Output

★ Each converter: Plug-in type

Fig.18 Simulation Circuit

Fig.19 Timing Chart

200 kHz  \((D=0.5)\)
【Simulation Result】
(Buck Converter: 4 outputs)
a) \(I_{o1} = 0.5\)A \((I_{o2}\sim I_{o4} = 0.5\)A\)
   • \(3\)mV=\(\Delta V_1 \approx \Delta V_2 \approx \Delta V_3 \approx \Delta V_4\)

b) \(I_{o1} = 1.0\)A \((I_{o2}\sim I_{o4} = 0.5\)A\)
   • \(7\)mV=\(\Delta V_1 > \Delta V_2 \approx \Delta V_3 \approx \Delta V_4\)
   \[\therefore \text{Priority: } V_4 > V_3 > V_2 > V_1\]

• \(F = 200\) kHz \((D = 0.5)\)

Fig.20 Simulation Result
【 Circuit of Boost Converter 】
- $V_i = 4.0\,\text{V}$, $V_o = 6.0/5.5/5.0/4.5\,\text{V}$
- $I_{o1}=0.5\,\text{A}/0.25\,\text{A}$, $I_{o2}\sim I_{o4}=0.25\,\text{A}$

![Simulation Circuit](image)

Fig. 21 Simulation Circuit

![Simulation Result](image)

Fig. 22 Simulation Result

$4\,\text{mV}=\Delta V_1 > \Delta V_2 \div \Delta V_3 \div \Delta V_4$
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Conclusion

1. **SIDO Converter with Hysteretic Converter**
   a) Simulation Result (Buck: 9.0V ⇒ 6.0V, 4.0V)
      \[ \Delta V_{o} < 10 \text{ mV} \] (Boost: 3.0V ⇒ 5.0V, 4.0V)
      @ \( I_{o1} = 1.0A / 0.5A \), \( I_{o2} = 0.50A \)
   b) Experimental Result (Buck Converter)
      \[ \Delta V_{o} < 25 \text{ mV} \] @ \( I_{o1} = 0.35A / 0.18A \), \( I_{o2} = 0.10A \)
      \[ \Delta V_{o} < 20 \text{ mV} \] @ \( I_{o1} = 0.18A \), \( I_{o2} = 0.20A / 0.10A \)

2. Simulation Result of **SIMO Converter** (4 outputs)
   a) **Buck** Converter: (\( I_{o2} \sim I_{o4} = 0.5A \))
      \[ \Delta V_{o} < 7 \text{ mV} \] (\( I_{o1} = 1.0A / 0.5A \))
   b) **Boost** Converter: (\( I_{o2} \sim I_{o4} = 0.25A \))
      \[ \Delta V_{o} < 4 \text{ mV} \] (\( I_{o1} = 0.5A / 0.25A \))
Thank you
for your kind attention.
【Circuit of SIDO Buck Converter】
Output Ripple $\Delta V$ 1 and $\Delta V$ 2

Ratio $\times 2.2$

$I_1 = 1A,$
$I_2 = 2.2A$

$\Delta V1 = 12mVpp$

$\Delta V2 = 20mVpp$

$\Delta V1, \Delta V2 < 0.5%V_o$

SEL $\rightarrow$ High : $V_1$

SEL $\rightarrow$ Low : $V_2$

Voltage

$8/23/2013$
Proposed SIDO Converter
with Hysteretic Control

【Operation of Buck Converter】
• ON/OFF signal: ON1+ON2
• SEL signal: Compare ($\Delta V2 > \Delta V1$)

Proposed SIDO Buck Circuit

Timing Chart
【Experimental Result 1】
(Buck Converter)

● Output Ripple
(Static Load Regulation)
(a) $\Delta V_1=25\text{mV}, \Delta V_2=20\text{mV}$
   $F=950\ \text{kHz}$
   @ $I_{o1}=0.35\ \text{A}, I_{o2}=0.20\ \text{A}$

(b) $\Delta V_1=20\text{mV}, \Delta V_2=15\text{mV}$
   $F=850\ \text{kHz}$
   @ $I_{o1}=0.50\ \text{A}, I_{o2}=0.20\ \text{A}$

● Polarity of each ripple is complementary
Proposed SIDO Converter with Hysteretic Control

【Experimental Result 2】
(Buck Converter)

● Dynamic Load Regulation
(a) $\Delta V_1=25 \text{ mV} : \text{Self Regulation}$
$\Delta V_2=5 \text{ mV} : \text{Cross Regulation}$
@ $I_{o1}=0.35A \div 0.18A$
$I_{o2}=0.10A$

(b) $\Delta V_1=30 \text{ mV} : \text{Cross Regulation}$
$\Delta V_2=15 \text{ mV} : \text{Self Regulation}$
@ $I_{o1}=0.18A$
$I_{o2}=0.20A \div 0.10A$

Fig.17(a) Experimental Result 1

Fig.17(b) Experimental Result 2
【Simulation Result of SIMO Converter】 4 outputs
$V_o = 6.0V, 5.0V, 4.0V, 3.0V$
【Simulation Result】
(Boost Converter: 4 outputs)
a) \( I_{o1} = 0.25A \) (\( I_{o2}\sim I_{o4}=0.25A \))
  \- 2mV = \( \Delta V_1 \approx \Delta V_2 \approx \Delta V_3 \approx \Delta V_4 \)
b) \( I_{o1} = 0.5A \) (\( I_{o2}\sim I_{o4}=0.25A \))
  \- 4mV = \( \Delta V_1 > \Delta V_2 \approx \Delta V_3 \approx \Delta V_4 \)
  \therefore Priority: \( V_4 > V_3 > V_2 > V_1 \)

Fig.22 Simulation Result
【Experimental Result of SISO Converter】
Vo=4V, Io=0.35A (on Universal Board)

Pulse Noises because of Z of GND line