Single-Inductor Multi-Output Converter with Four-level Output Voltages

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Outline

• Research Objective
• SIDO Converter with Exclusive Control
  – SIDO Buck Converter (Simulation & Experimentation)
  – SIDO Boost Converter (Simulation & Experimentation)
• SIMO Converter with Four Output
  – Previous SIMO Converter with Ripple Control
  – Proposed SIMO Converter with Exclusive Control
    * SIMO Buck Converter (Simulation)
    * SIMO Boost Converter (Simulation)
• Conclusion

* SIDO : Single-Inductor Dual-Output
* SIMO : Single-Inductor Multi-Output
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Background

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

AC-DC converter  
(Fly back, Forward Type)

$V_B = 24/12 \text{ V}$

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)

Fig. 2 Background

Conventional approach

Single Inductor

Our New Method

Reduce inductor

Reduce cost

Reduce volume
Research Objective

● Single Inductor Dual Output (SIDO) converter
  ➢ Our Previous SIDO converters with **Exclusive Control**
    buck-buck or boost-boost converter

● New SIMO Converters with Four Sub-Converters
  Four buck or four boost sub-converters
  ➢ How to select the most hungry sub-converter?
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Previous SIDO Converter with Exclusive Control

\[ \Delta V_1 > \Delta V_2 \Rightarrow \text{SEL} 'L' \Rightarrow S2:OFF \Rightarrow V1 \]

\[ \Delta V_1 < \Delta V_2 \Rightarrow \text{SEL} 'H' \Rightarrow S2:ON \Rightarrow V2 \]

\[ V_i = 9V \Rightarrow V1 = 6V, V2 = 5V \]

Fig. 3 Simulation Circuit of Buck Converter

Fig. 4 Timing Chart

F = 500kHz
Previous SIDO Buck Converter

【Simulation Result 1】 Vi=9V ⇒ V1=6V, V2=5V

Fig.5  Simulation Results (Buck Converter)
Fig. 6  Output Ripples (Buck Converter)

Simulation Result 1

\[ V_1 = 6.0\, \text{V} \]
\[ \Delta V_1 = 8\, \text{mVpp} \]

\[ V_2 = 5.0\, \text{V} \]
\[ \Delta V_2 = 10\, \text{mVpp} \]

\[ I_1 = 1.0\, \text{A}, \quad I_2 = 0.5\, \text{A} \]
Fig. 7  Ripples & Transient Responses

Simulation Result 1

I_1 = 1.0A  
I_2 = 1.0A

V_1

V_2

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

±10mV  
±10mV

I_1 = I_2 = 0.5A
Previous SIDO **Buck** Converter

【Experimental Result 1】

- **Output Voltage**

  \[ V_i = 9.0V \Rightarrow V1 = 6.0V, V2 = 4.5V, f = 200kHz \]

Fig.8 Experimental Result (Output Voltages)
Previous SIDO Buck Converter

Experimental Result 1

- Ripples & Transient Responses
  - $I_2 = 0.50A \div 0.25A$

  - Static Ripples: 20 mVpp
  - Transient Resp.: 10 mVop

Fig. 9 Experimental Result
Previous SIDO Boost Converter

\[ V_i = 3V \Rightarrow V_1 = 5V, \; V_2 = 4V \]

\[ \Delta V_1 > \Delta V_2 \Rightarrow \text{SEL}['L'] \Rightarrow S_2:\text{OFF} \Rightarrow V_1 \]

\[ \Delta V_1 < \Delta V_2 \Rightarrow \text{SEL}['H'] \Rightarrow S_2:\text{ON} \Rightarrow V_2 \]

Fig. 10  Simulation Circuit of Boost Converter
Previous SIDO Boost Converter

【Simulation Result 2】
- Static Ripples: 5mVpp
- Transient Resp.: ±10 mV
- $V_1=5.0V, V_2=4.0V$
- $I_{o1}=I_{o2}=0.4A/0.2A$
- $L=0.5\mu H, C=470\mu F, F=200kHz$

Fig.11 Simulation Result of SIDO Boost Converter
Proposed SIDO Boost Converter

【Experimental Result 2】 $V_i=3.0V \Rightarrow V_1=5.0V, V_2=4.0V, f=200kHz$

- Ripples & Transient Responses
  $I_1 = 0.40A/0.20A$
  
  ![Diagram showing experimental results with SEL, $\Delta I_1$, $\Delta V_1$, and $\Delta V_2$.]

Fig.12 Experimental Result of SIDO Boost Converter
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Previous SIIMO Buck Converter with Ripple-Based Control

【Simulation Circuit 1】
- $V_i = 10.0\text{V}$, $V_o = 6.0/5.0/4.0/3.0\text{V}$
- Hysteretic Control (Buck Converter)
- Priority: $V_4 > V_3 > V_2 > V_1$ (fixed)
  - $V_4 < V_3 < V_2 < V_1$

Fig.13 Simulation Circuit 1

Fig.14 Wave form of SEL signals
【Simulation Result 1】 Buck Converter

● Ripple-Based Control

Vi=10v, Vo=6, 5, 4, 3V

a) When Io1~Io4=0.5A

$\Delta V_1 \sim \Delta V_4 \equiv 3\text{mV}$

b) When Io1=1.0A (Io2~Io4=0.5A)

$\Delta V_1 = 7\text{mV} > \Delta V_2 \equiv \Delta V_3 \equiv \Delta V_4$

∴ Priority is fixed.

: $V_4 > V_3 > V_2 > V_1$

V1 is served last.

★ Improve the priority order!
Previous SIMO Converter

【Simulation Result 2】 Boost Converter
- $V_i = 4.0V$, $V_o = 6.0/5.5/5.0/4.5V$
- $I_{o1}=0.5A/0.25A$, $I_{o2}~I_{o4}=0.25A$

$\Delta V1=4mV > \Delta V2 \sim \Delta V4$

![Simulation Circuit 2](image1)

![Simulation Result 2](image2)

Fig.16 Simulation Circuit 2

Fig.17 Simulation Result 2
Proposed SIMO Converter with Exclusive Control

【 Simulation Circuit 1 】 Buck Converter

- PWM & SEL signal is generated using common $\Delta V$.
- When output V is lower, $\Delta V$ is higher.
- Usually single SEL is 「H」 exclusively.

The highest $\Delta V$ is served for next control cycle.

Fig. 18 Proposed SIMO Circuit (Buck)
SIMO Converter with Exclusive Control

【Simulation Results 1】Buck Converter
- \( V_i = 10V, \) \( V_o = 6.0/5.5/5.0/4.5 \) V
- \( I_o = 0.5A \) each, \( I_1 = I_4 = 1.0/0.5A \)
- \( L = 0.2uH, \)
  \( C = 470uF \) each
- \( F = 500kHz \)

![Fig.19 Simulation Results (Buck Converter)](image-url)
【Simulation Results 1】Buck Converter

- When all SEL signals are 「L」,
  Inductor Current is regenerated to the voltage source.

Fig.20  SEL signals and Regenerated current
【Output ripples】

Buck Converter

- Vi = 10V
  Vo = 6.0/5.5/5.0/4.5 V

- Ripples:
  △V < 20mVpp

- Transient Response:
  Shoot < ±10mV @ △I = 0.5A

Fig.21 Output ripples (Buck Converter)
【Simulation Results 1】Boost Converter

- $V_i = 4.0\, \text{V}$, $V_o = 6.0/5.5/5.0/4.5\, \text{V}$
- $I_o=0.1\, \text{A}$ each, $I_1=I_4=0.2/0.1\, \text{A}$
- $L=1.0\, \mu\text{H}$, $C=470\, \mu\text{F}$ each
- $F=500\, \text{kHz}$

**Fig.22 Simulation Results (Boost Converter)**
SIMO Converter with Exclusive Control

【Output ripples】
*Boost Converter*

- Ripples: \(\Delta V < 5 \text{mVpp}\)
- Transient Response Shoot < ±15mV @ \(\Delta I = 0.1\text{A}\)

![Graph showing output ripples](image)

**Fig.23 Output ripples (Boost Converter)**
SIMO Buck/Boost Converter with Four-level Output Voltages using Exclusive Control and New Priority Circuit.

a) New priority circuit using wired OR voltage $V_{com}$. Sub-converter of most different from reference voltage has the priority to be served for next cycle.

b) Simulation Results:

1) Buck Converter ( $V_i=10V$, $V_o=6.0$, 5.5, 5.0, 4.5V)
   * Output Ripples: $\Delta V_o < 20 \text{ mV}$ @ $I_o=0.5A$ each
   * Transient Response: $\Delta V_o < \pm 10 \text{ mV}$ @ $\Delta I_o=0.5A$

2) Boost Converter ( $V_i=4.0V$, $V_o=6.0$, 5.5, 5.0, 4.5V )
   * Output Ripples: $\Delta V_o < 5 \text{ mV}$ @ $I_o=0.1A$ each
   * Transient Response: $\Delta V_o < \pm 15 \text{ mV}$ @ $\Delta I_o=0.1A$
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