Single Inductor DC-DC Converter with Bipolar Outputs using Charge Pump

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Outline

① Introduction

② SIMO DC-DC Converter

③ Simulation Results

④ Conclusion
Outline

1. Introduction
2. SIMO DC-DC Converter
3. Simulation Results
4. Conclusion
Introduction

Industry Demands
High Efficiency and Extremely Small System Solution

Conventional Power Supply Circuits

<table>
<thead>
<tr>
<th>Power Supply Type</th>
<th>Efficiency</th>
<th>Circuit Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Regulator</td>
<td>30〜60%</td>
<td>Small</td>
</tr>
<tr>
<td>Switching Regulator</td>
<td>70〜90%</td>
<td>Large</td>
</tr>
</tbody>
</table>

Optimize Efficiency

Switching Regulator

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Introduction

Switching Regulator

Multi Output Power Supply Circuit

Digital Camera
- Positive Voltage: 15 V
- Negative Voltage: -8 V

OLED Display
- Positive Voltage: 5 V
- Negative Voltage: -2 V

Multi Output Power Supply Circuit
Introduction

Industry Demands

High Efficiency and Extremely Small System Solution

One Inductor is Removed

SIMO DC-DC Converter

SIMO: single inductor multi output

Multi Output Power Supply Circuit

Single Inductor

Multi Output Power Supply Circuit

V_{op}

V_{om}
Outline

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Conventional Circuit

Negative Voltage: \( V_{om} = -V_{op} + V_F \)

Negative Output Depends on Positive Output

Cause: S2 & S3 are on Simultaneously
Change of Timing Diagram

Conventional Timing Diagram

Proposed Timing Diagram

Inductor Current is Changed

The duty ratio of each switch is fixed

Change!
Change of Timing Diagram

SIMO DC-DC Converter

Operation of Switch Sf
Maintains the value of the current in the inductor.

Proposed timing diagram

INDUCTOR CURRENT WAVEFORM

I_L

I_P

V_{op}

V_{om}

S1
S2
S3
S_f

T_s : 1 cycle

Stages:
Stage 1
Stage 2
Stage 3
Stage 4
Stage 5
Stage 6

S1: ON OFF ON OFF
S2: OFF ON OFF OFF
S3: OFF OFF ON OFF
S_f: OFF ON OFF ON
Change of Timing Diagram

**S1: Turns on**

Inductor L stores energy from voltage $V_{in}$

Current that flows to inductor L

$$I_L = \frac{V_i}{L}t = \frac{I_p - I_B}{T1}t$$

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**SIMO DC-DC Converter**

- **Stage 1:**
  - S1: Turns on
  - Inductor L stores energy from voltage $V_{in}$
  - Current that flows to inductor L

$$I_L = \frac{V_i}{L}t = \frac{I_p - I_B}{T1}t$$

---

**Proposed timing diagram**

- $T_S$: 1 cycle

---

**Inductor Current Waveform**

- $I_L$, $I_B$

---

**Stage 1:**

- S1: ON
- S2: OFF
- S3: OFF
- Sf: OFF

---

**Stage 2:**

- S1: OFF
- S2: ON
- S3: ON
- Sf: OFF

---

**Stage 3:**

- S1: OFF
- S2: OFF
- S3: OFF
- Sf: ON

---

**Stage 4:**

- S1: OFF
- S2: OFF
- S3: ON
- Sf: ON

---

**Stage 5:**

- S1: OFF
- S2: ON
- S3: OFF
- Sf: ON

---

**Stage 6:**

- S1: ON
- S2: OFF
- S3: ON
- Sf: OFF

---

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2010年12月13日月曜日
Change of Timing Diagram

SIMO DC-DC Converter

Stage 2

S 2 : Turn on · · · Inductor L supplies its energy to output terminal of $V_{op}$

$\frac{I_L}{L} = \frac{V_{op} - V_i}{t} = \frac{I_p - I_B}{T^2} t$

Equation of Stage 1

$\frac{I_L}{L} = \frac{V_i}{t} = \frac{I_p - I_B}{T^1} t$

$V_{op} = \frac{T1 + T^2}{T^2} V_i$

Proposed timing diagram

$T_s : 1$ cycle

Inductor Current Waveform

$\frac{I_L}{L} \begin{cases} I_p & T_1 \\ T_2 & T_s \\ I_{p2} & T_3 \\ T_4 & T_5 \\ T_6 & S \end{cases}$

$\frac{I_B}{B} \begin{cases} \text{ON} & \text{OFF} & \text{ON} & \text{OFF} & \text{ON} & \text{OFF} \end{cases}$

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Change of Timing Diagram

SIMO DC-DC Converter

Stage3

Sf : Turn on ・ ・ ・ The current of the inductor is maintained with the free wheel switch

Proposed timing diagram

Ts : 1 cycle

Inductor Current Waveform

Stage1  Stage2  Stage3  Stage4  Stage5  Stage6

S1  ON  OFF  ON  OFF  OFF  OFF

S2  OFF  ON  OFF  OFF  OFF  OFF

S3  OFF  OFF  ON  OFF  OFF  OFF

Sf  OFF  ON  OFF  OFF  OFF  ON

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**Change of Timing Diagram**

**SIMO DC-DC Converter**

**Stage 4**

S1: Turn on • • • Inductor L stores energy from voltage $V_{in}$

Current that flows to inductor L

$$I_L = \frac{V_i}{L}t = \frac{I_{p2} - I_B}{T_4}t$$
**Change of Timing Diagram**

**SIMO DC-DC Converter**

**Inductor Current Waveform**

Proposed timing diagram

Ts : 1 cycle

Inductor Current Waveform

Stage 1: S1 ON, Sf OFF
Stage 2: S1 OFF, S3 ON
Stage 3: S3 OFF, S2 ON
Stage 4: S2 OFF, Sf ON
Stage 5: Sf OFF, S3 ON
Stage 6: S3 OFF

**Stage 5**

S3 : Turn on • • • Charge pump capacitor Cc charges energy from the inductor

Current that flows to inductor L

\[ I_L = -\frac{V_i - V_c}{L}t = -\frac{I_{p2} - I_B}{T^5}t \]
Change of Timing Diagram

SIMO DC-DC Converter

Vop

Vom

S1

S2

S3

Sf

I_L

I_B

Ts : 1 cycle

Stage1

Stage2

Stage3

Stage4

Stage5

Stage6

S1: ON

OFF

ON

OFF

S2: OFF

ON

OFF

S3: OFF

ON

OFF

Sf: OFF

ON

OFF

Inductor Current Waveform

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The current of the inductor is maintained with the free wheel switch.
Change of Timing Diagram

**SIMO DC-DC Converter**

**Stage 1**
- **S1**: Turn on
- Energy of capacitor is discharged
- and negative voltage $V_{om}$ are given

**Equation of Stage 4**

$$I_L = \frac{V_i}{L} t = \frac{I_{p2} - I_B}{T_4} t$$

**Equation of Stage 5**

$$I_L = -\frac{V_i - V_c}{L} t = -\frac{I_{p2} - I_B}{T_5} t$$

**Proposed timing diagram**
- $T_s$: 1 cycle
- $T_s$: Inductor Current Waveform

**Inductor Current Waveform**
- $I_L$
- $I_B$
- $I_{p2}$
- $V_{op}$
- $V_{om}$

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Change of Timing Diagram

SIMO DC-DC Converter

V_{op} = \frac{T1 + T2}{T2} V_i = \frac{D1 + D2}{D2} V_i

V_{om} = -\frac{T4 + T5}{T5} V_i + V_F = -\frac{D4 + D5}{D5} V_i + V_F

Negative output voltage can be changed independently
Outline

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Simulation Results

Simulation Condition

Switching Frequency: 500kHz
Input Voltage $V_{in}$: 3.5V
Inductor $L$: 2u
Output Capacitor $C_{out}$: 10u
Load Resistance $R_o$: 15Ω
Charge Pump Capacitor $C_c$: 5u

![SIMO DC-DC Converter Diagram]
Simulation Results (Conventional)

Positive Output Voltage: 7V

Positive Voltage

Negative Voltage

Negative Output Voltage: -5.93V

Positive Output Voltage: 10.5V

Positive Voltage

Negative Voltage

Negative Output Voltage: -9V
Simulation Results (Conventional)

<table>
<thead>
<tr>
<th>Positive Voltage</th>
<th>Positive Voltage Ripple (Vpp)</th>
<th>Negative Voltage</th>
<th>Negative Voltage Ripple (Vpp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.89V</td>
<td>75.5mV</td>
<td>-5.9V</td>
<td>54.3mV</td>
</tr>
<tr>
<td>10.1V</td>
<td>119.7mV</td>
<td>-9.1V</td>
<td>87.9mV</td>
</tr>
</tbody>
</table>

Negatives Voltage: $V_{om} = -V_{op} + V_F$

Conventional Circuit

A negative voltage depends on a positive voltage
Simulation Results (Proposed)

Positive Output Voltage: 6.7V

Negative Output Voltage: -4.54V

Negative Output Voltage: -6.3V
## Simulation Results

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<th>Negative Voltage</th>
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</thead>
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<tr>
<td>6.7V</td>
<td>50.8mV</td>
<td>-4.5V</td>
<td>20.8mV</td>
</tr>
<tr>
<td>6.7V</td>
<td>50.8mV</td>
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**Proposed Timing Diagram**

**Conventional Timing Diagram**

Voltage Ripple has Decreased
**Inductor Current Waveform**

<table>
<thead>
<tr>
<th></th>
<th>Current Ripple (Vpp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>1.35 A</td>
</tr>
<tr>
<td>Proposed</td>
<td>630.4mA</td>
</tr>
</tbody>
</table>

Inductor Current Ripple is Reduced by 50%

At The One Cycle

Conventional

Inductor L is one charge & discharge

Proposed

Inductor L is two charge & discharge

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Transient Response (Conventional)

Negative output voltage depends on positive output voltage

Output Voltage Waveform
Transient response (Proposed)

- Negative output voltage independent of positive output voltage
- Cross-regulation is Improved

Output Voltage Waveform
Outline

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A new timing diagram is proposed

- Independent positive and negative output voltage
- Voltage ripple and inductor ripple less than conventional timing diagram
- Cross-regulation is improved