Single-Inductor Dual-Output Soft-Switching Converter with Voltage-mode Resonant Switch

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Outline

1. Introduction
2. Conventional Soft Switching Converter
   - 2-1 Half-wave type Converter
   - 2-2 Full-wave type Converter
3. Proposed Soft Switching Converters
   - 3-1 Voltage-mode Converter with Clamp Circuit
   - 3-2 Simulation Results
4. Single-Inductor Dual-Output (SIDO) Converters
   - 4-1 Soft Switching SIDO Converter with Clamp
   - 4-2 Simulation Results
5. Conclusion

SIDO : Single-Inductor Dual-Output

1. Introduction

●Our Research

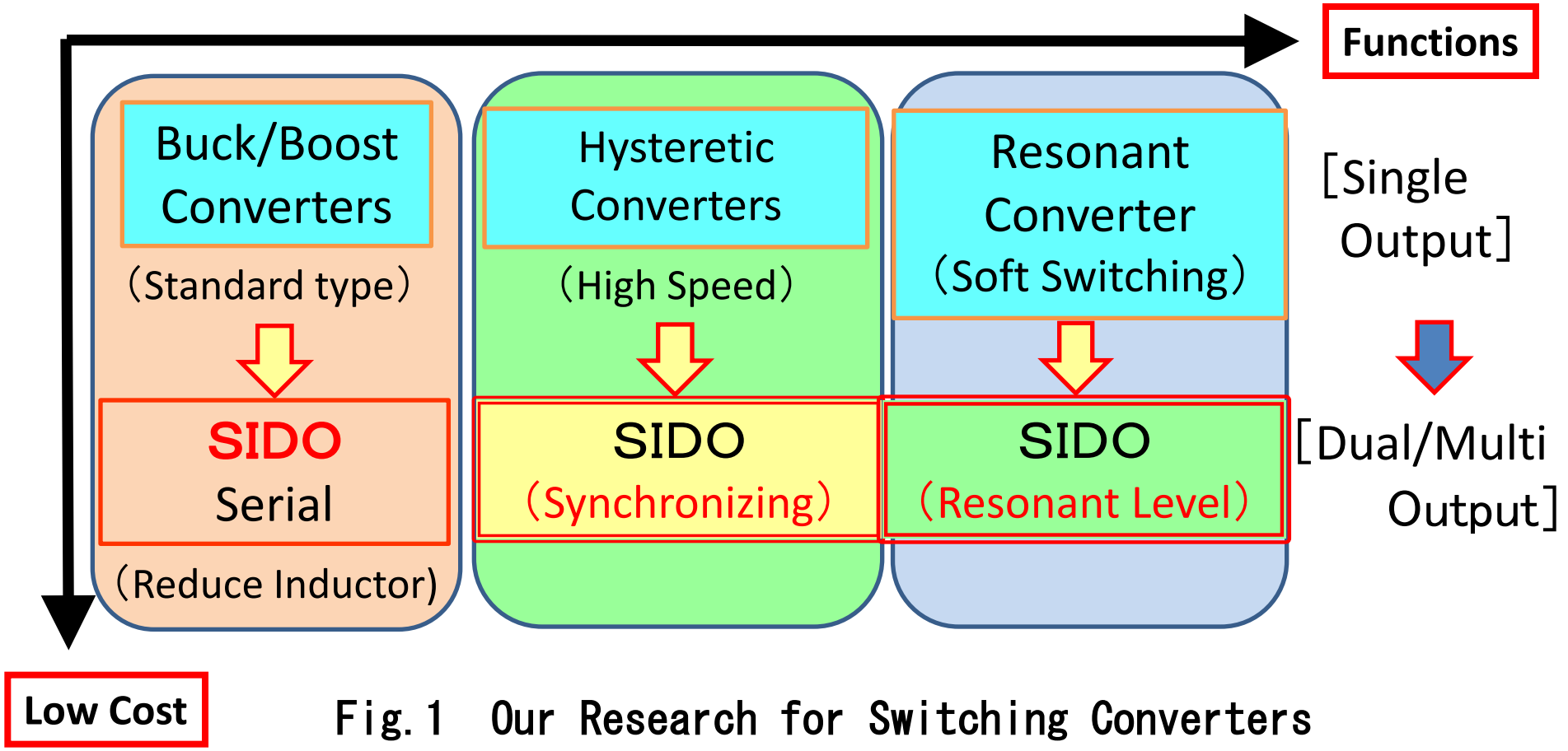

Fig.1 Our Research for Switching Converters

Outline

SIDO : Single-Inductor Dual-Output

2. Conventional Soft Switching Converter

- Normal Buck Converter
  - ＊ Clock pulse generates Saw-tooth(SAW) signal.
  - ＊ SW is controlled by PWM signal,
  - ＊ PWM is generated by comparing ⊿Vo and SAW signal.

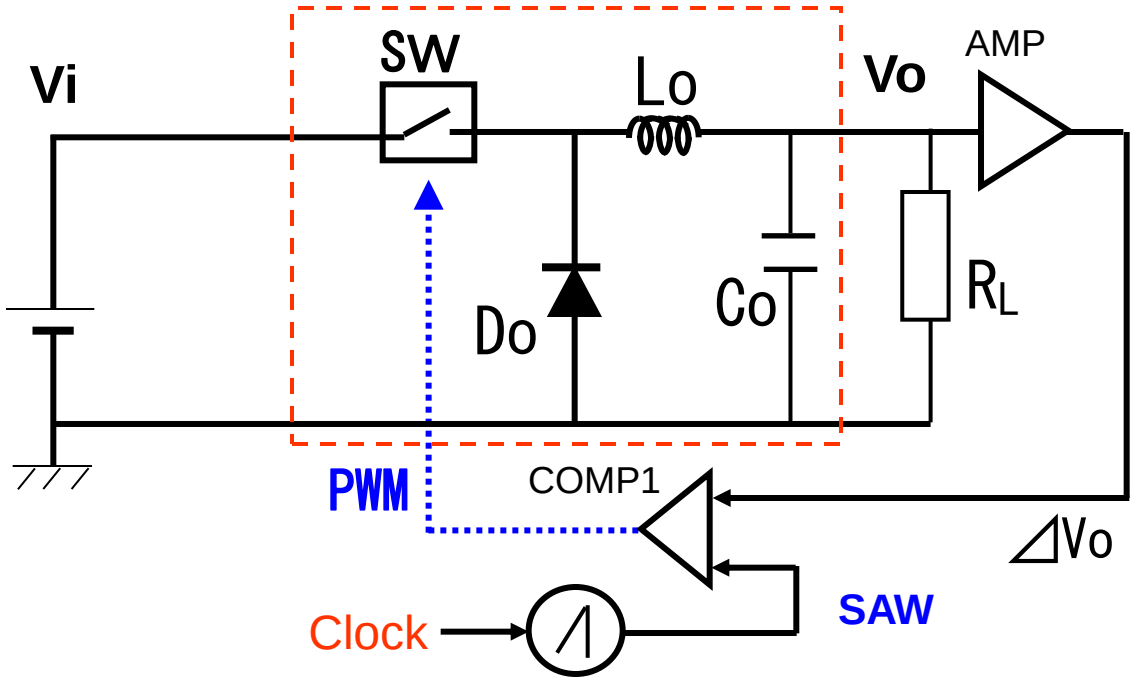

Fig.2 Standard Buck Converter

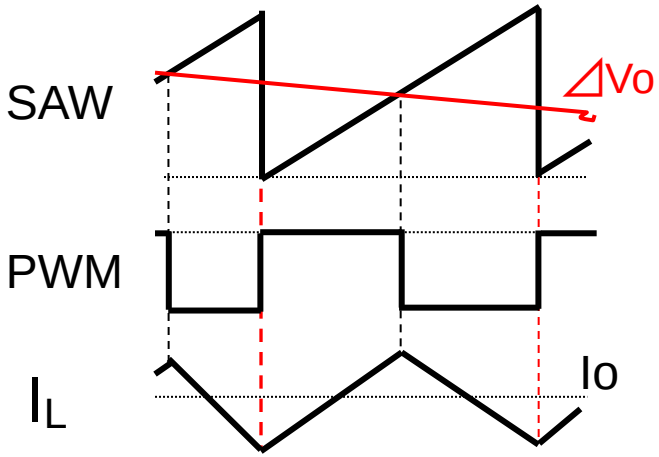

Fig.3 Major Signals

PWM: Pulse Width Modulation

2-1 Voltage-mode Soft Switching Converter

【Half-wave type converter】

- Resonant Inductor Lr & Resonant Capacitor Cr are added.
- When SW is OFF, resonant voltage Vr goes up & down.
- No clock, so SAW is triggered & PWM turns [H], when $Vr = V_D$.

  ⇒ Zero-Voltage Switching (ZVS) ⇒ Reduce Switching Loss

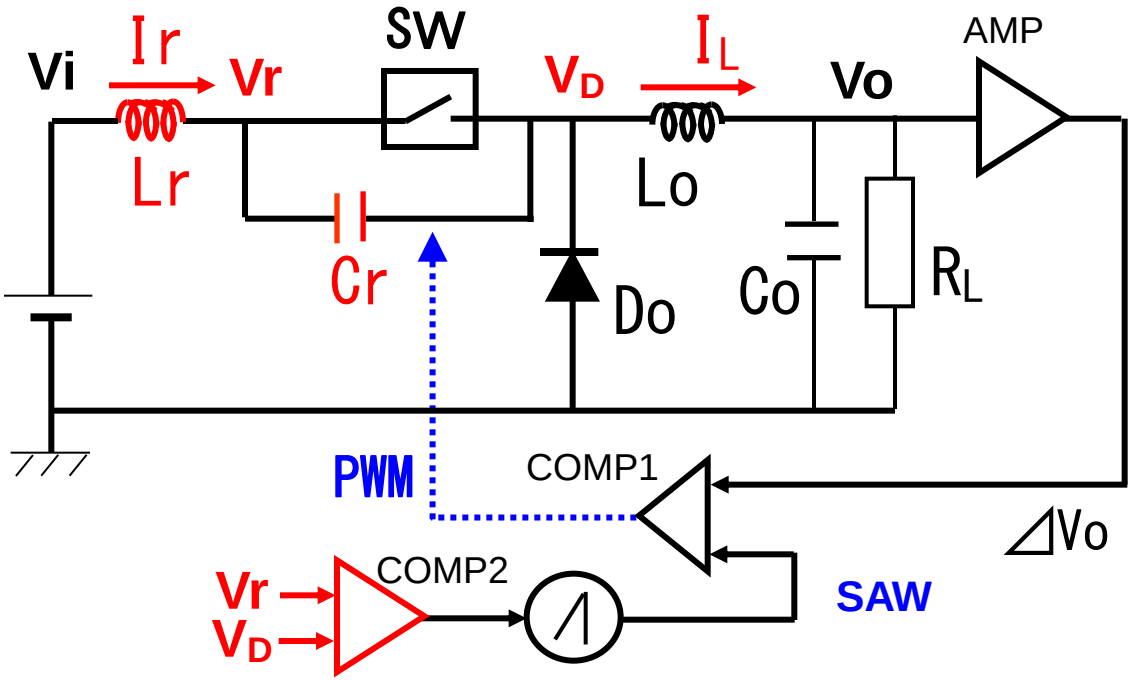

Fig.4 Half-wave Converter

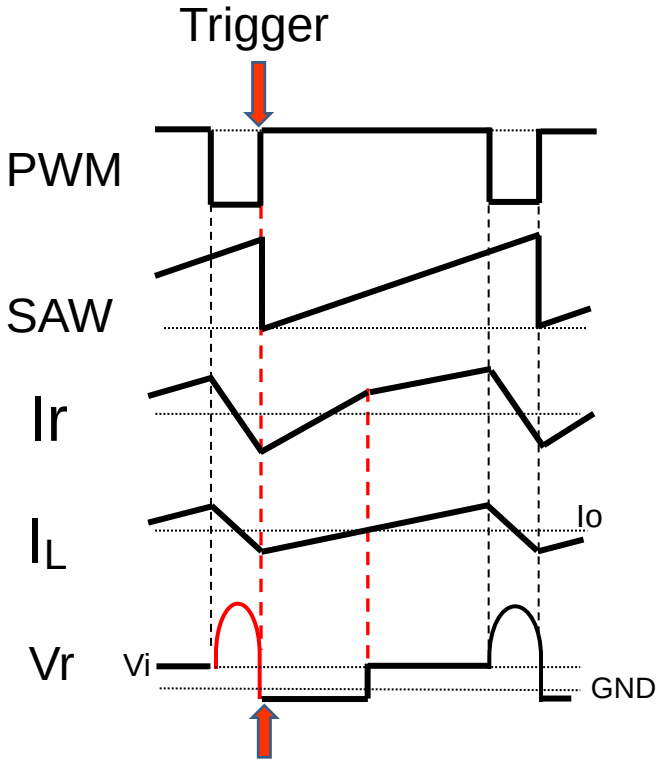

Fig.5 Major Signals

● Simulation Results (SIMPLIS 7.0)

* Simulation Conditions:
  - Vi=10V, Vo=5V, Io=0.25A
    Lr=20uH, Cr=100pF
* Simulation Results:
  F_{OP} = 380kHz, Vr = 125V
  Ir = −0.25A, I_D = 0.50A

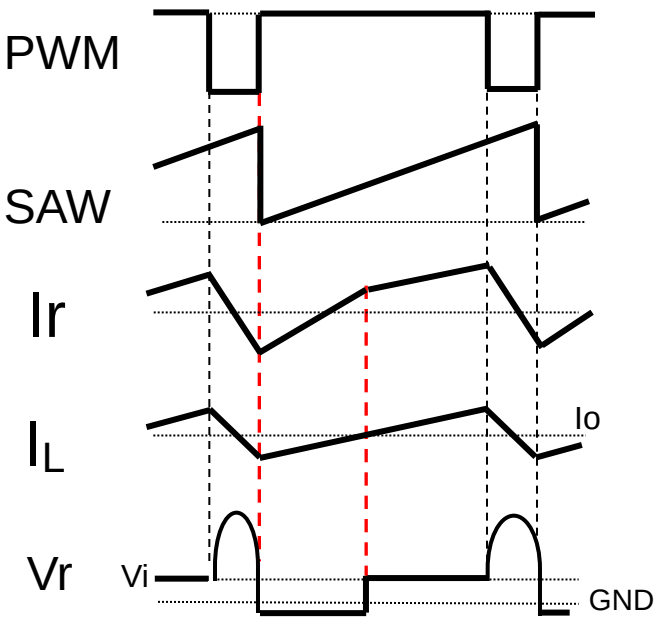

Fig.5 Major Signals

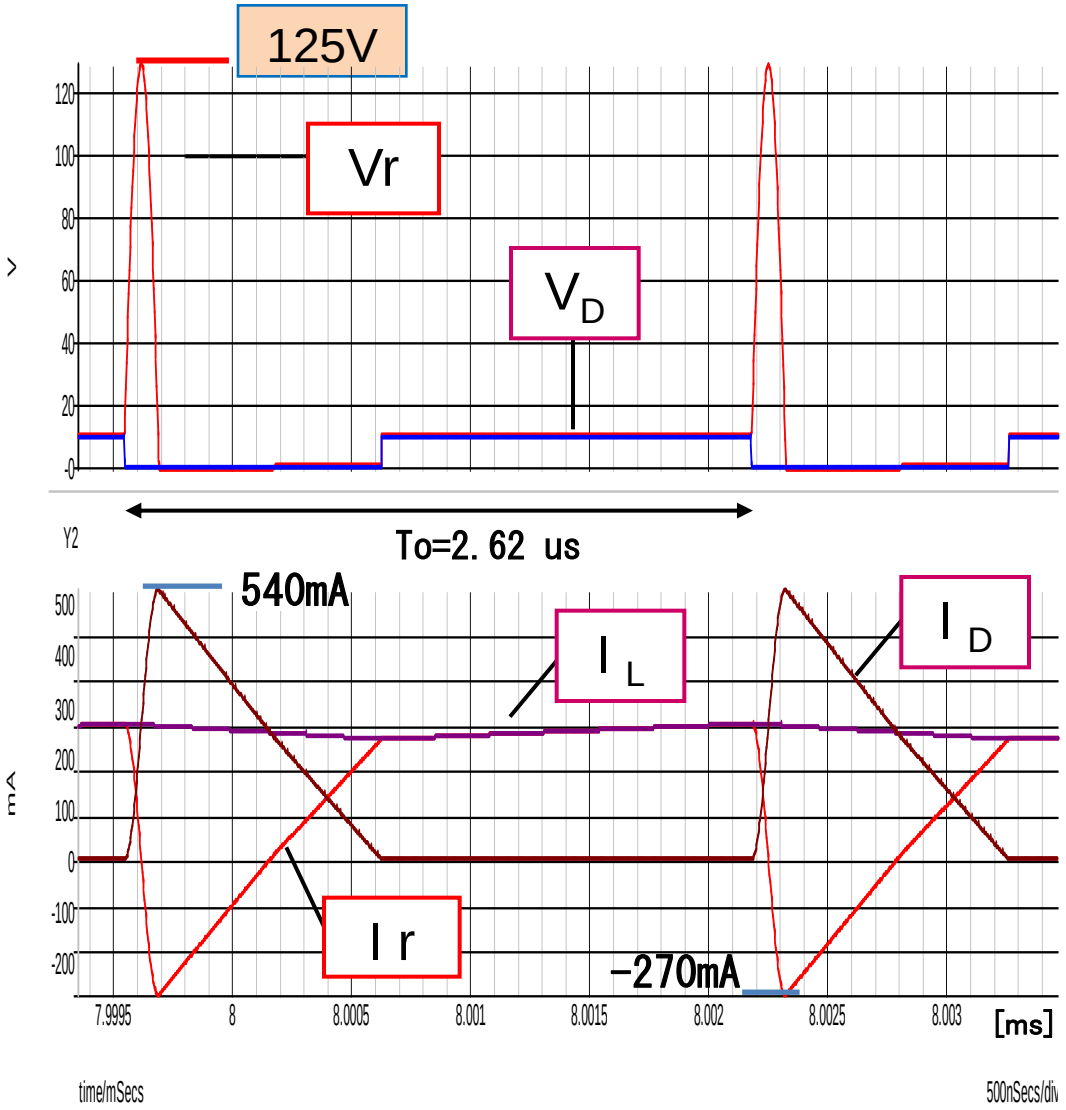

Fig.8 Simulation Results

【Full-wave type converter】

- Only Diode is added to Half-wave type converter.
- The resonant voltage Vr goes positive & negative.
  ⇒ Diode blocks conduction of Body-Diode BD, when Vr < 0.

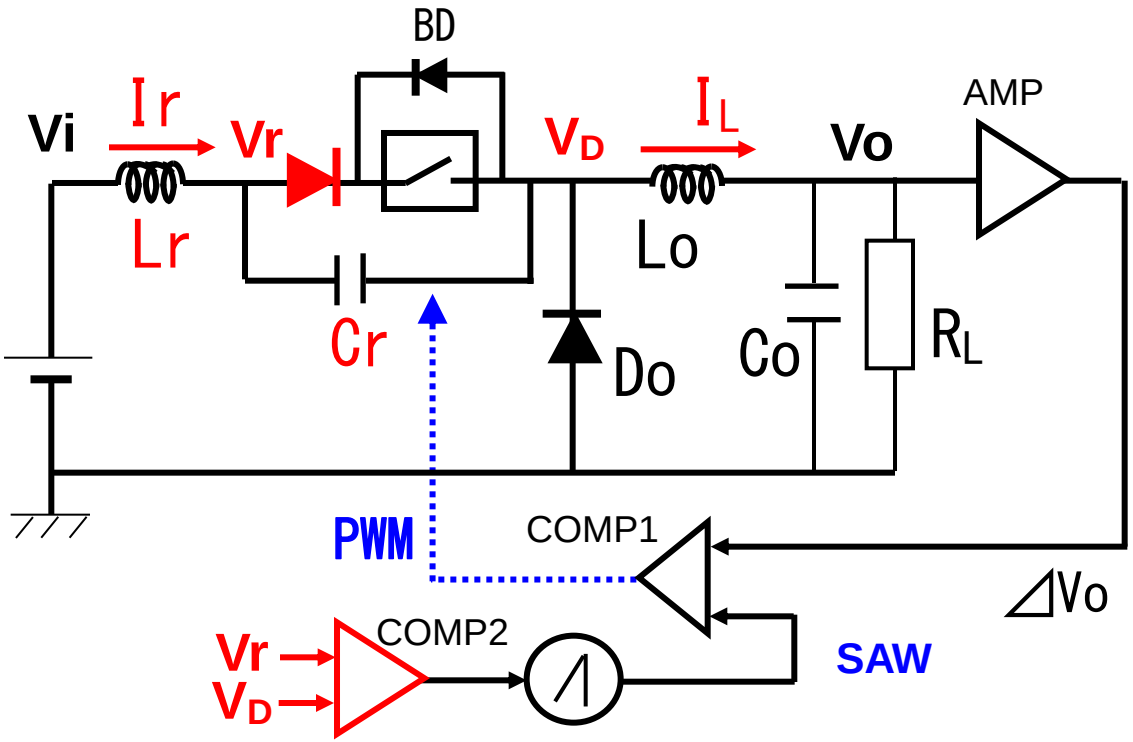

Fig.6 Full-wave Converter

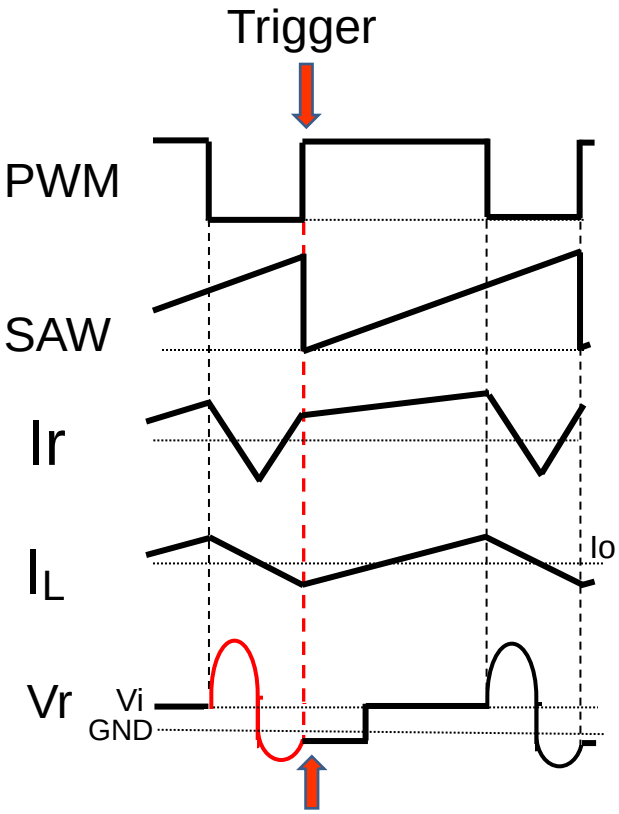

Fig.7 Major Signals

●Simulation Results

- Simulation Conditions are same.
- Resonant Results:

Fop=830 kHz, Vr=Vi±115V,
Ir = −0.25A, Id = 0.50A

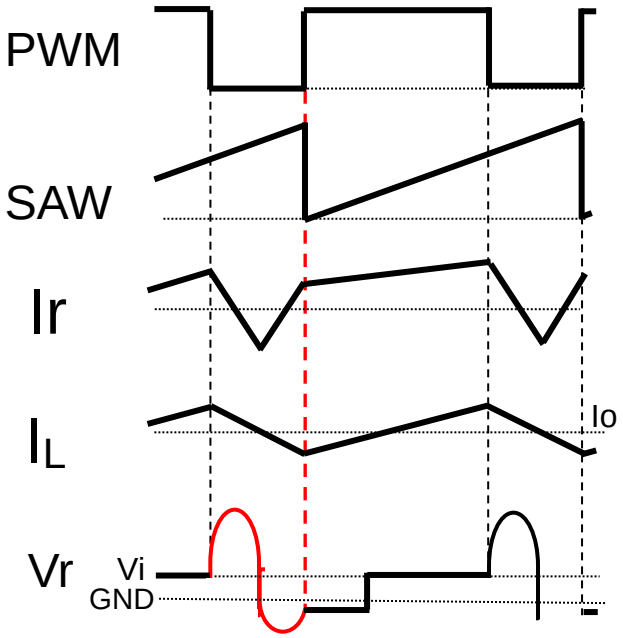

Fig.7 Major Signals

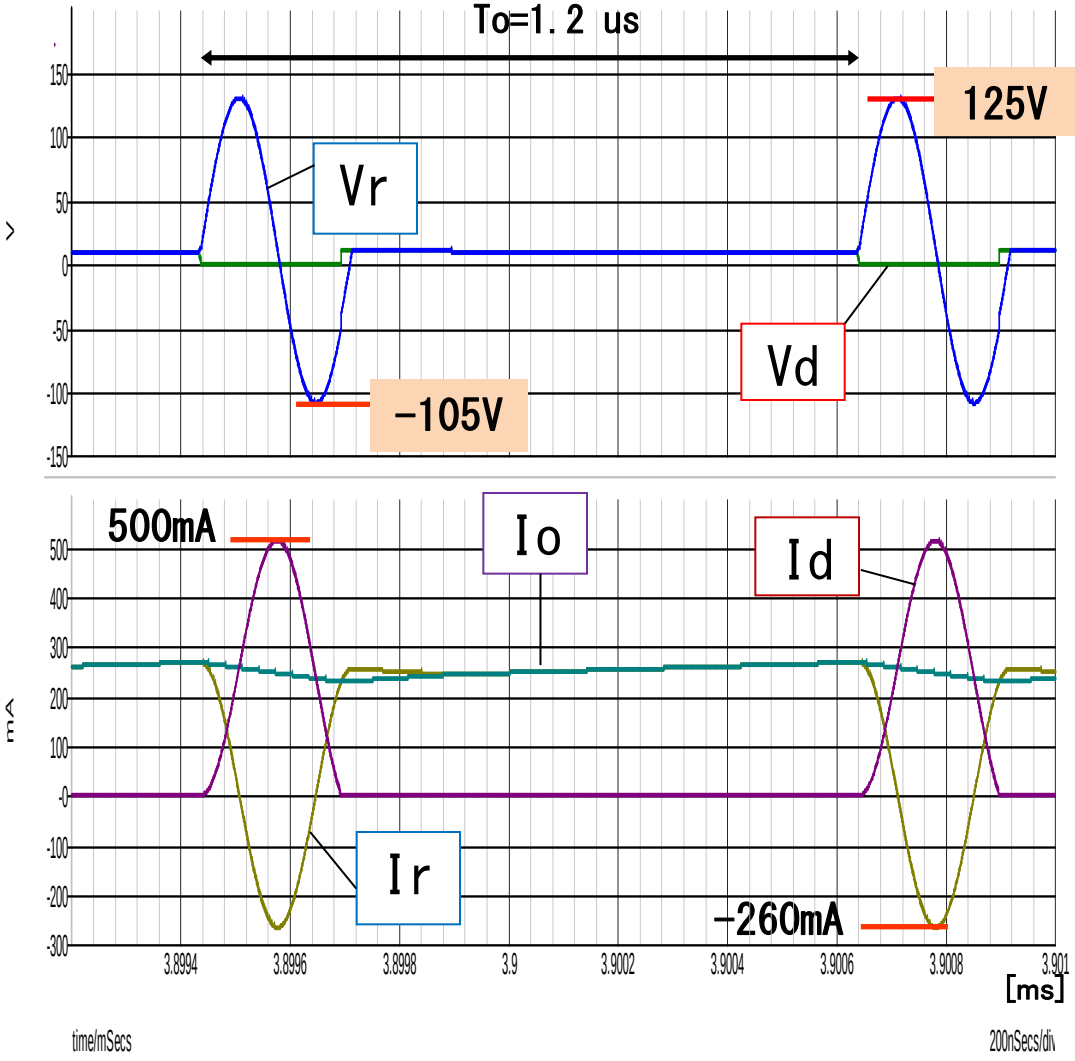

Fig.9 Simulation Results

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SIDO : Single-Inductor Dual-Output

3. Proposed Soft-Switching Converter

3-1 Voltage-mode Converter with Clamp Circuit

【Half-wave type converter】

- Add clamp circuit with Zener Diode. (Vz is 40V.)
- Peak voltage of Vr is suppressed from at 125V to 44V. (35%)
- Resonant current Ir is suppressed from 250mA to 70mA. (30%)
- Operating period Top is changed from 2.62us to 2.02us. (77%)

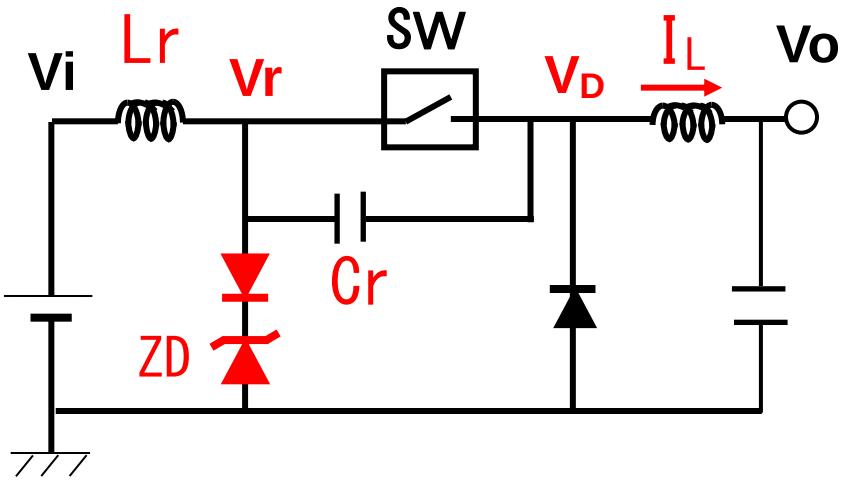

Fig.10 Proposed Half-wave Converter

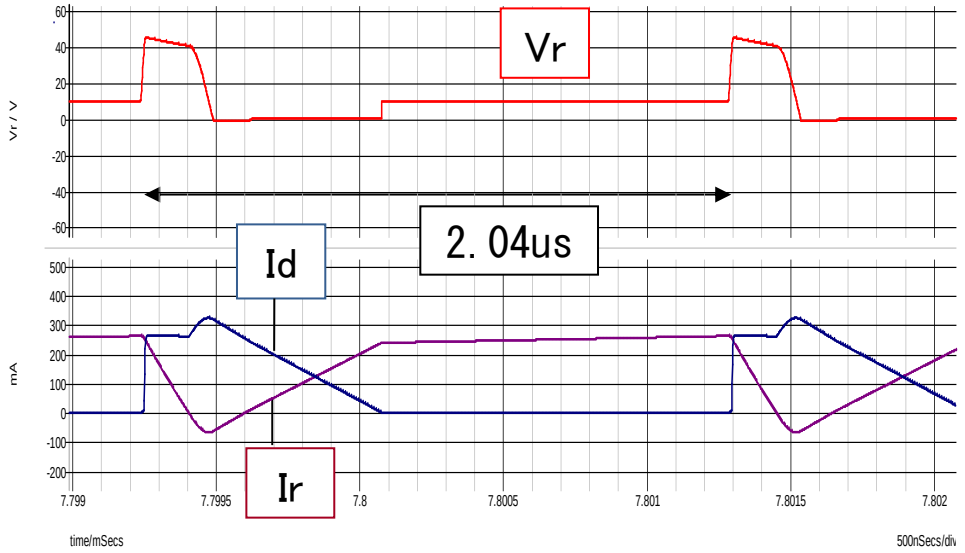

Fig.11 Simulation Results

【Full-wave type converter】

- Clamp circuit like Half-wave type.
- Peak voltage of Vr is suppressed from at 125V to 44V. (35%)
  ⇒ Low break-voltage BV_{DS} MOSFETs can be used.
- Resonant current Ir is suppressed from 250mA to 90mA. (35%)
- Operating period Top is changed from 1.2us to 3.7us. (X3.1)

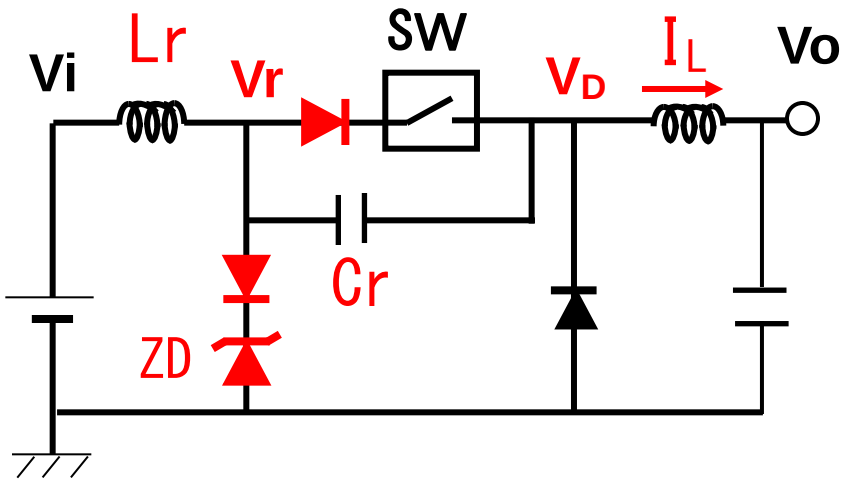

Fig.12 Full-wave Converter

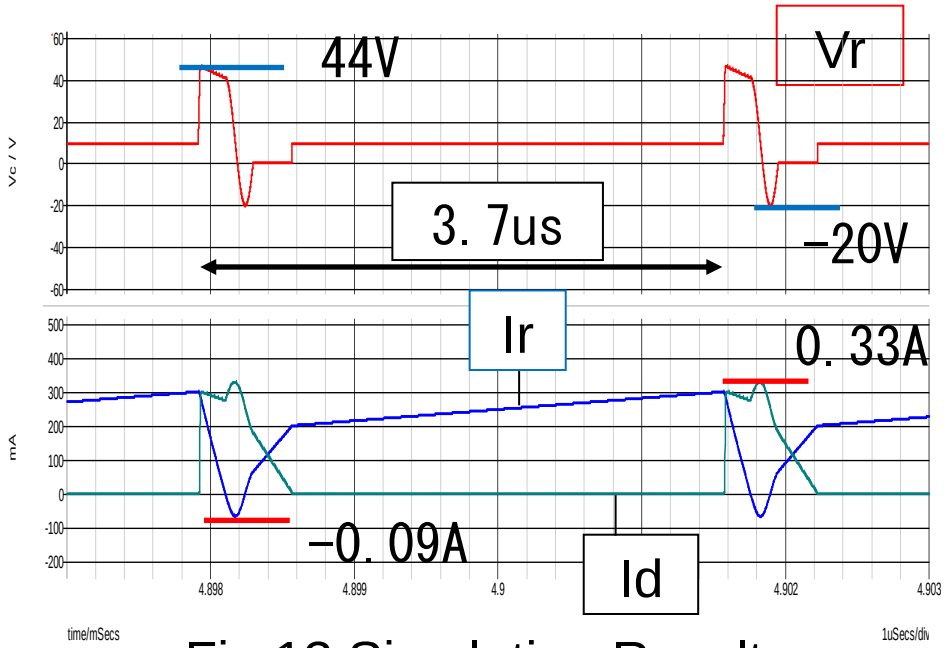

Fig.13 Simulation Results

3-2 Simulation Results

【Output Voltage Ripples】

＊ Vo=5.0V (Half-wave), Vo=7.0V (Full-wave)

- Stable output ripples are less than 2 mVpp @ Io=0.50A.
- Over/Under-shoots are less than ±15mV @⊿Io=0.25A.

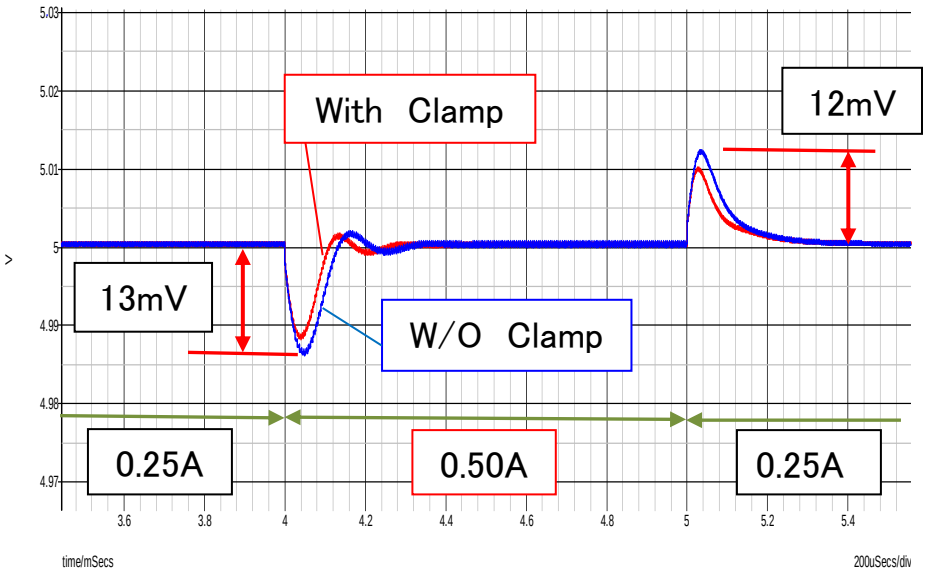

Fig.14 Ripple of Half-wave Converter

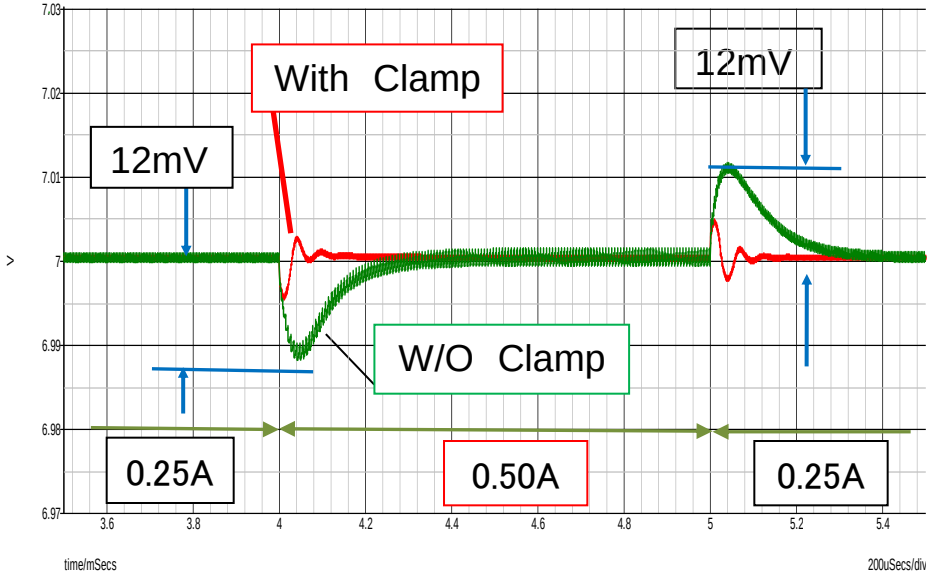

Fig.15 Ripple of Full-wave Converter

Outline

SIDO : Single-Inductor Dual-Output

4. Single-Inductor Dual-output Converter

4-1 Soft Switching SIDO Converter with Clamp

- It consists of Power stage, Two sub-converters and controller.
- SEL signal is decided by comparing ⊿V1 and ⊿V2.
- Each period is different. SEL & SAW are synchronized with PWM.

★Reduce Lo, Lr, Cr, ZD.

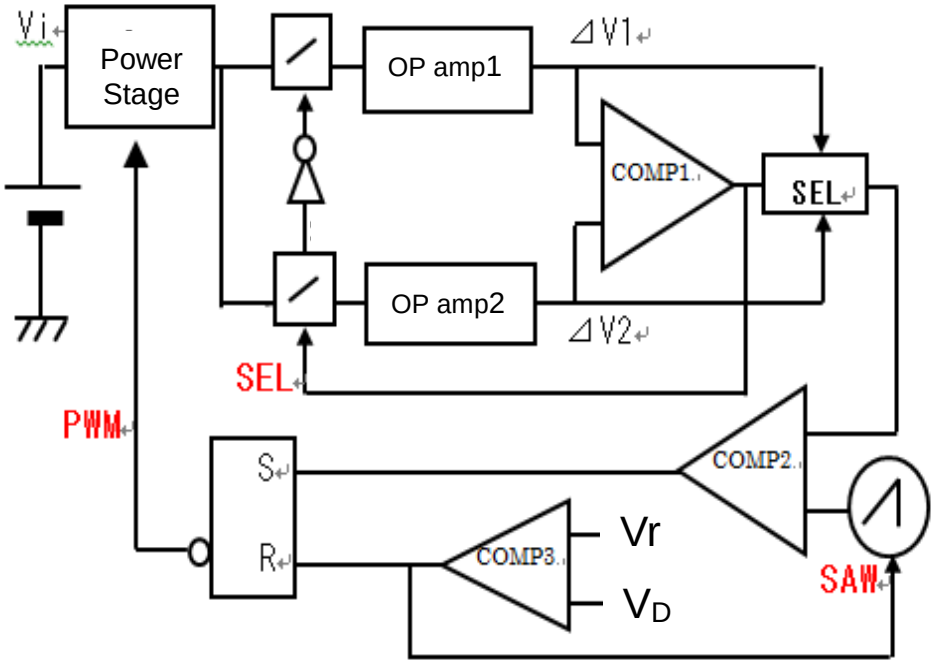

Fig.16 SIDO Converter with Clamp

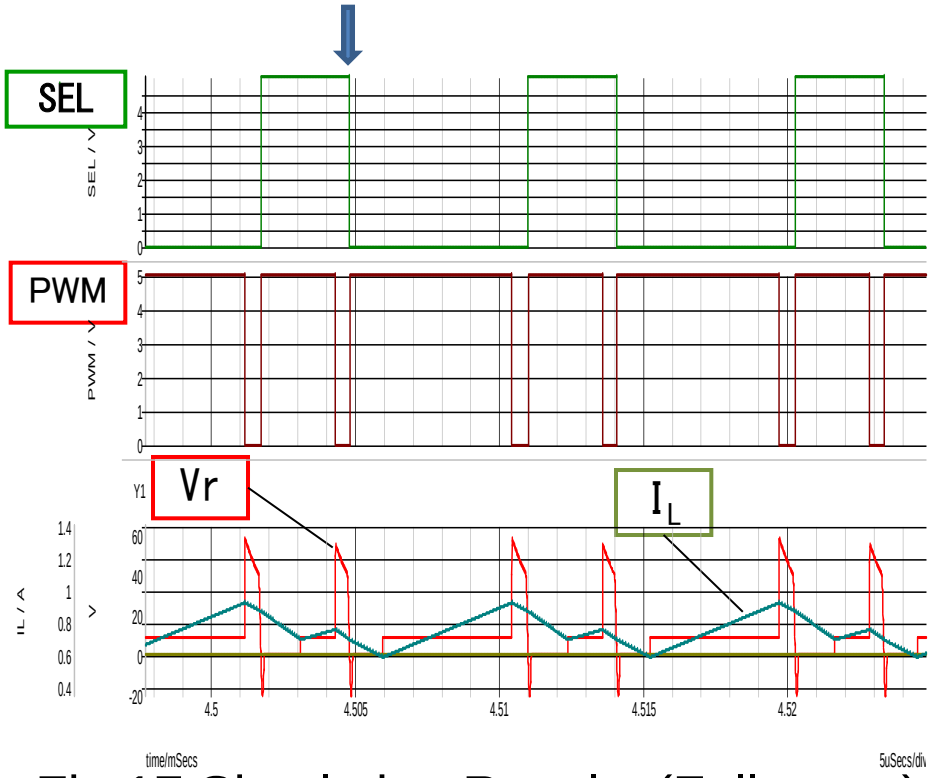

Fig.17 Simulation Results (Full-wave)

4-2 Simulation Results

A) Output Voltage Ripples (Vo1=5.0V, Vo2=4.0V, Vz=40V)

- Current step: Io1= 0.50A ⇔ 0.75A, Io2= 0.25A ⇔ 0.50A
- Stable Ripples : ＜ 5mVpp (<0.2%) @ Io=0.75A
- Overt/Under-shoots: ≒±12mV (≒0.25%) @⊿Io=0.25A

(Blue Arrows show Self-Regulation, Red Arrows do Cross-Regulation.)

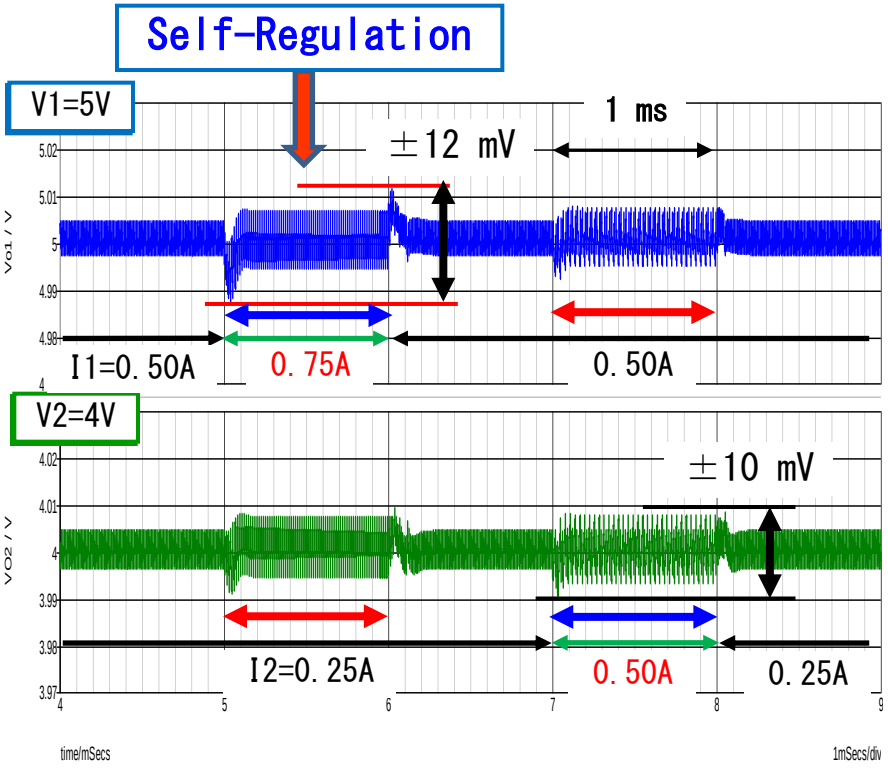

Fig.18 Ripple of Full-wave Converter

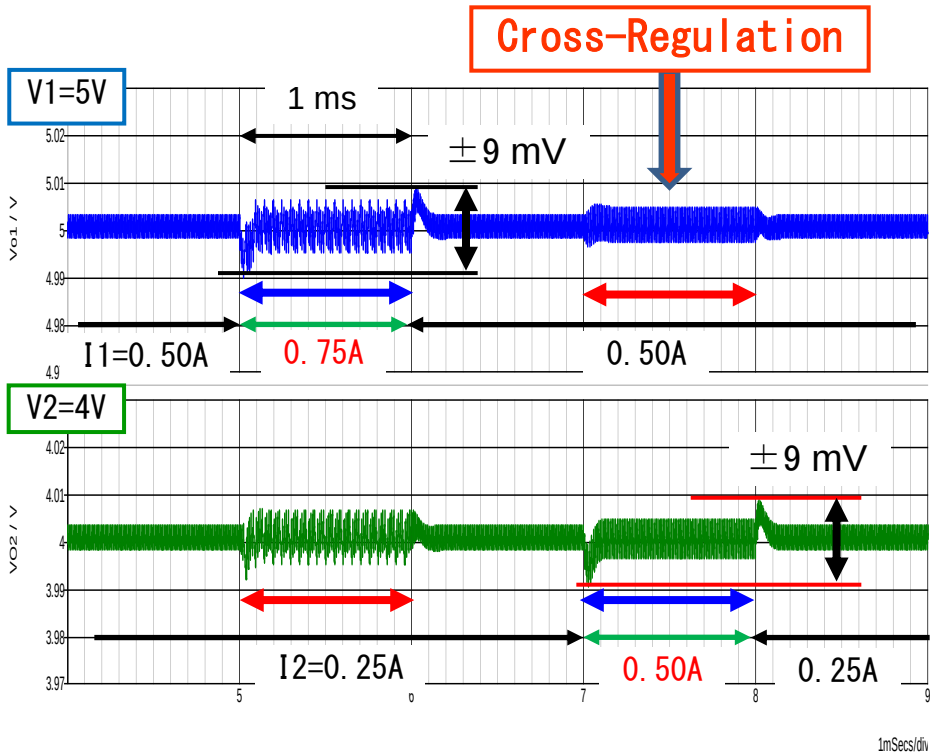

Fig.19 Ripple of Half-wave Converter

5. Conclusion

1. Proposed Soft Switching Converters with Zener Clamp

＊ Conditions: Vo=5.0V, Io=0.25A, Vz=40V

1) Suppress resonant voltage from 125V to 44V (35%).

⇒ MOSFETs with Low BV_{DS} can be used.

2) Suppress resonant current from 260mA to 90mA (35%).

3) Stable output ripples : < 2mVpp @ Io = 0.50A.

4) Over/Under-shoots : ±15mV @⊿Io = 0.25A.

2. SIDO Soft Switching Converters with Clamp

＊ Conditions: Vo1=5.0V, Vo2=4.0V, Io1=0.5A, Io2=0.25A

1) Stable output ripples : < 5mVpp @ Io = 0.75A.

2) Over/Under-shoots : ±12mV @⊿Io = 0.25A.

Thank you for your attention!

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3-2 Simulation Results

【Operation Period Top vs. Output Current Io 】

- In Full-wave converter, Top changes from 1.7us to 13.2us. (X7.5)
- In Half-wave converter, Top is reduced from 10us to 6.2us. (62%)
- Clamp method is good for Half-wave converter.

[TF: Full-wave, TH: Half-wave] [Tw: with Clamp, To: without Clamp]

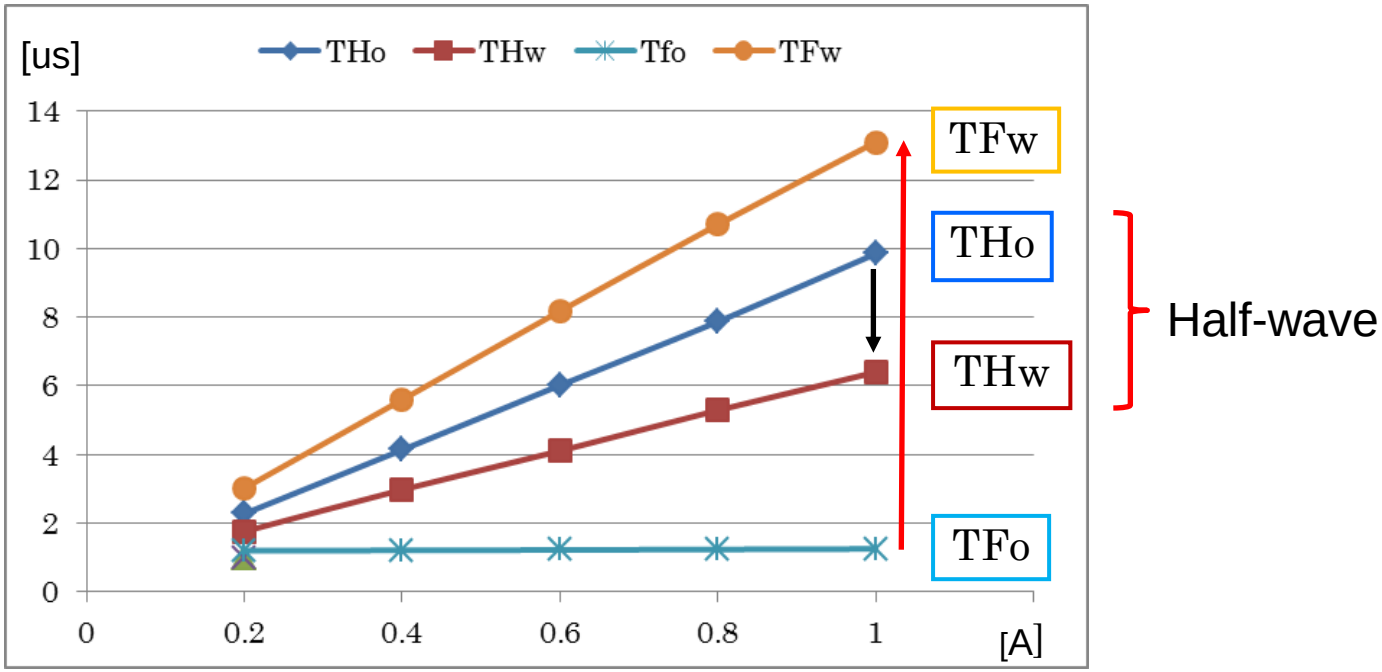


Fig.16 Operating Period Top vs. Output current Io

B) Power Loss vs. Output Current Io

- Power loss of W/O clamp is better than that of with clamp.
- It is difficult to improve the efficiency in Soft Switching.

But ・・・

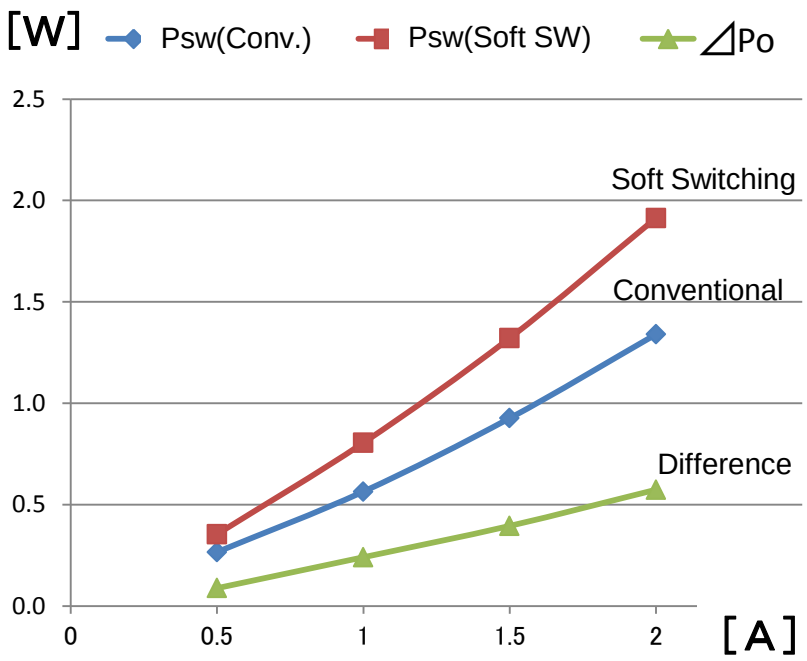


Fig.21 Power Loss of SISO
(SISO: Single-Inductor Single-Output)

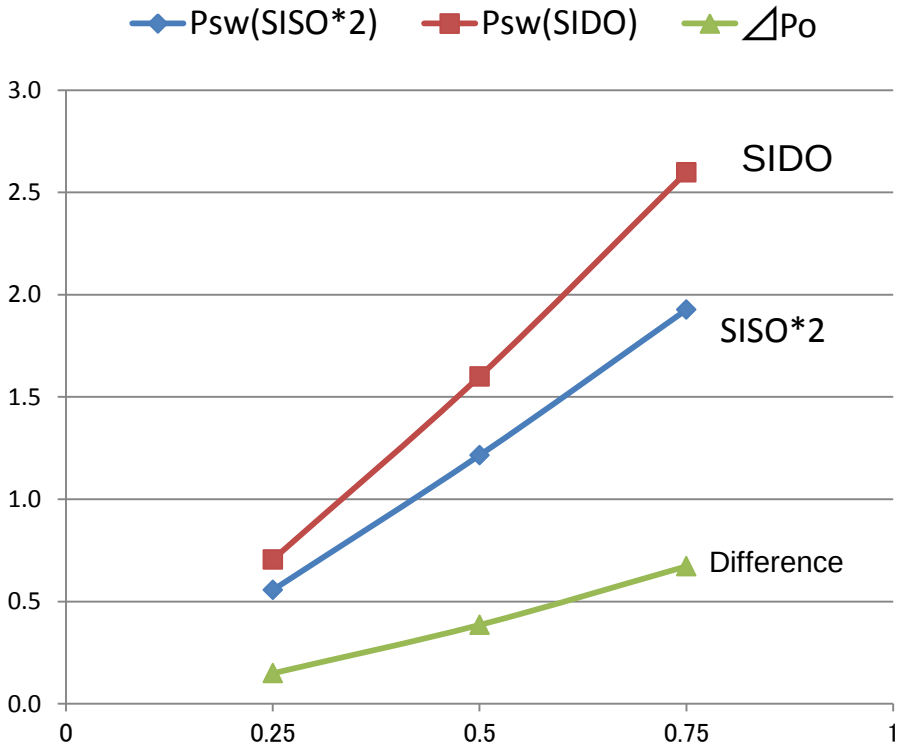
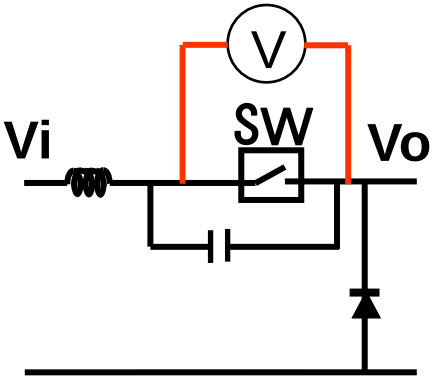


Fig.22 Power Loss of SIDO

C) Spread Spectrum of Vsw

- Spectrum of Voltage between Switching element.
- More than 50MHz,
  spectrum level of soft switching converter
  is better than that of the conventional one.
- Soft switching converter may be good for EMI reduction.



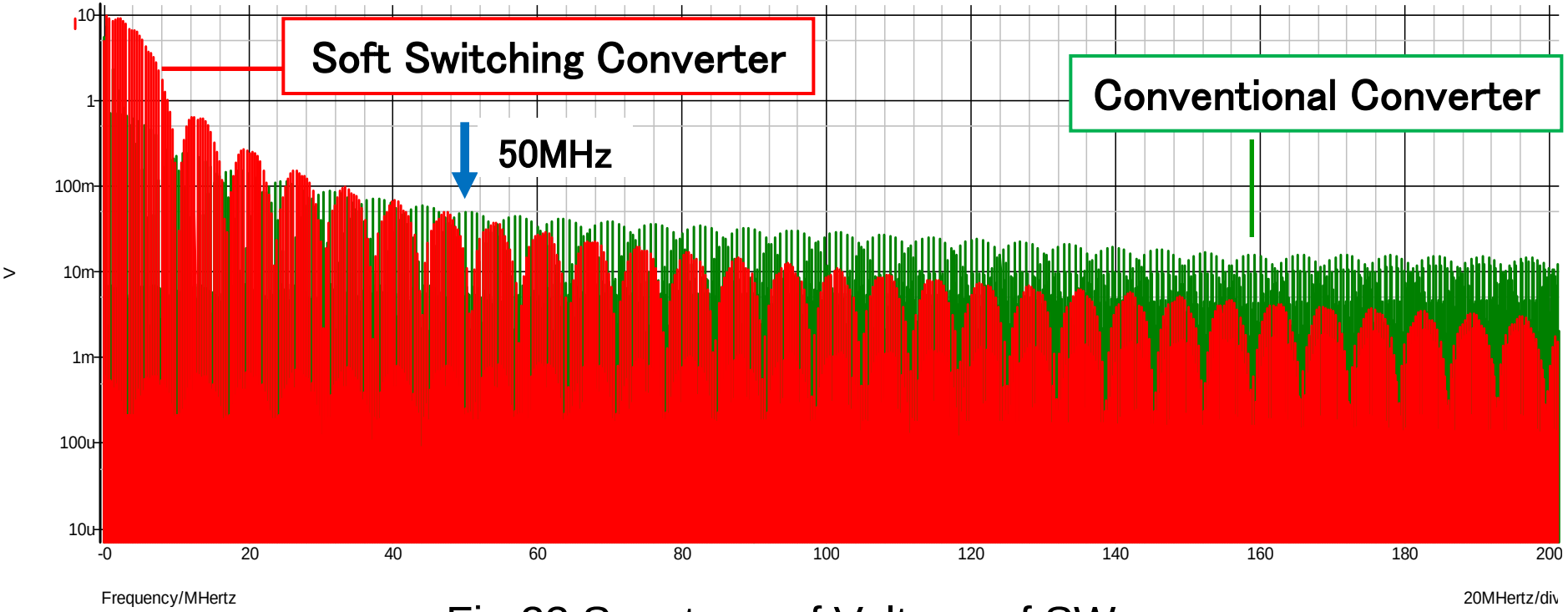


Fig.23 Spectrum of Voltage of SW

【Conditions】

＊Resonant Condition：Vi＜Vr = Io・Zr　(Zr=√(Lr/Cr) Characteristics Z

＊Resonant Frequency：Fr= 1/2π√(Lr・Cr)　(≠ Operating Frequency)

【 Operating 0】

＊State 0：

・First, PWM=[H] & SW=ON

・V_D = Vi,　Do = OFF ⇒ Ir = I_L (Increasing)

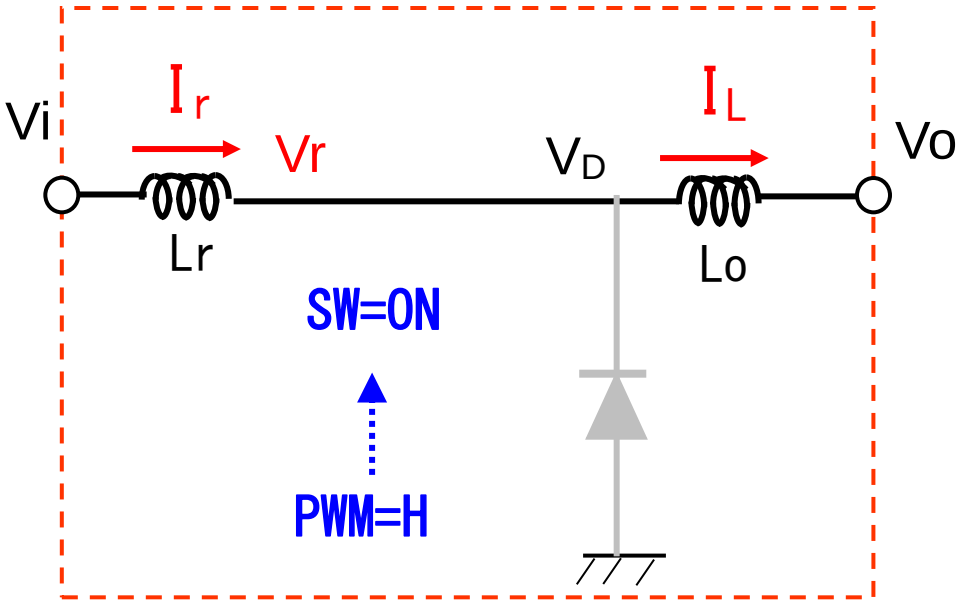


Fig.4-1 Half-wave Converter

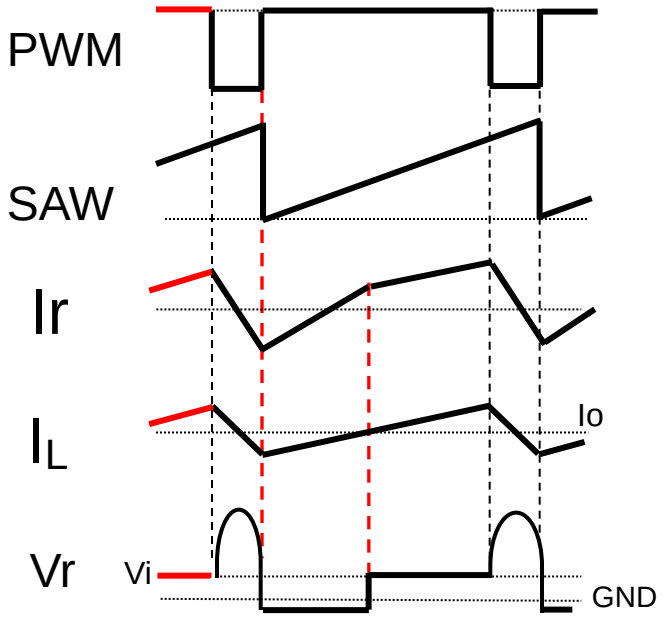


Fig.5-1 Major Signals

【 Operating 1】

＊ State 1：

- Vo is increasing & Vo > Vref, then PWM turns [L] & SW=OFF
- L & C start resonating. ⇒ Ir is charging C and Vr goes up.
  Diode turns ON and V_D is $-V_F$.
- After Ir=0, Ir direction turns reverse and Vr lowers to 0V.
- Finally, Vr reaches to $V_D = -V_F$.

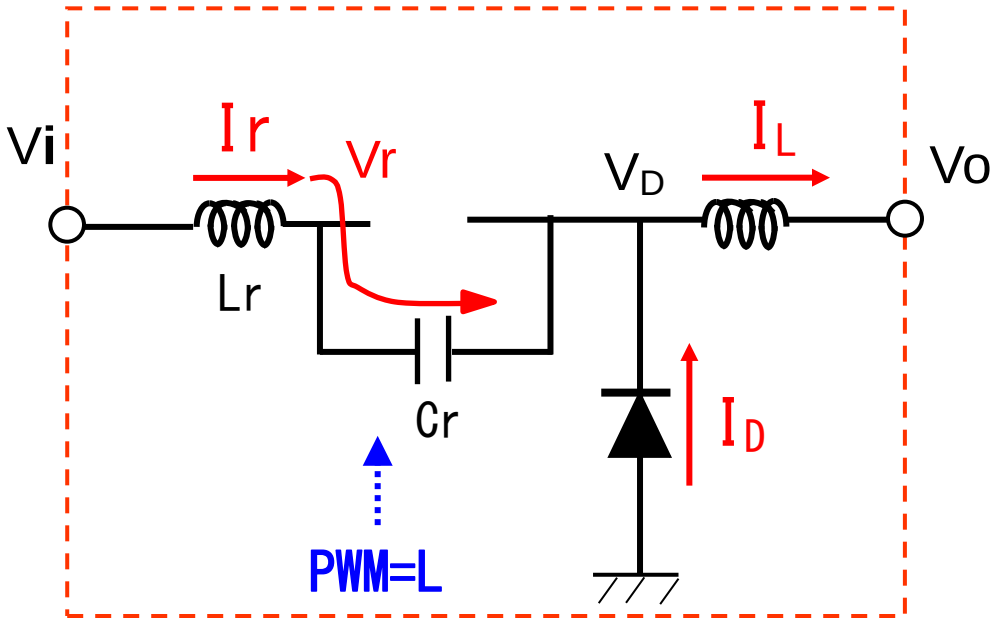


Fig.4-2 Half-wave Converter

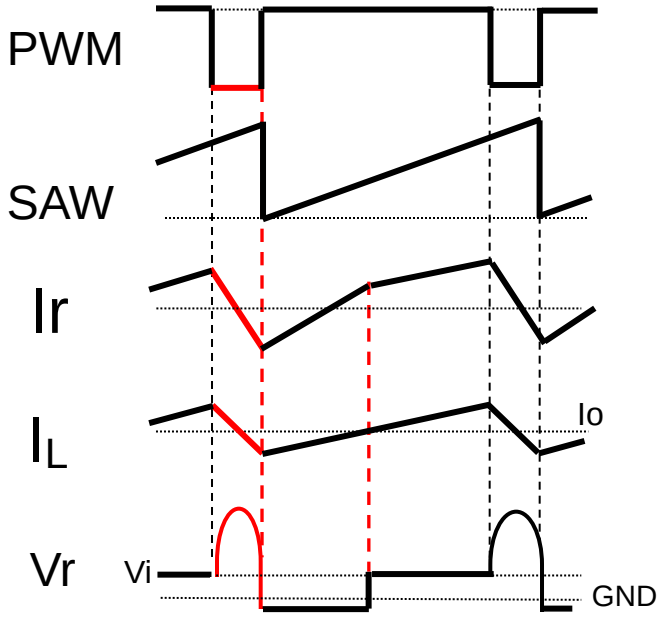


Fig.5-2 Major Signals

【 Operating 2】

＊State 2：

- When detect $V_D = -V_F$, SAW is reset & PWM turns [H] & SW=ON
- L & C resonance stops. ⇒
- After Ir=0, Ir direction turns reverse and Vr lowers to 0V.
- Finally, Vr reaches to $V_D = -V_F$.

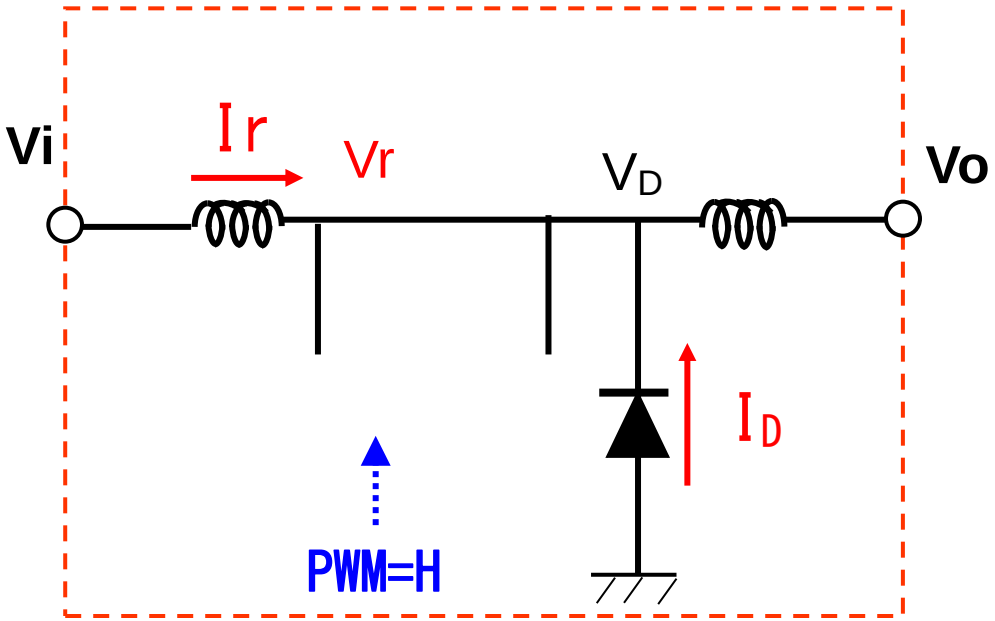


Fig.4-3 Half-wave Converter

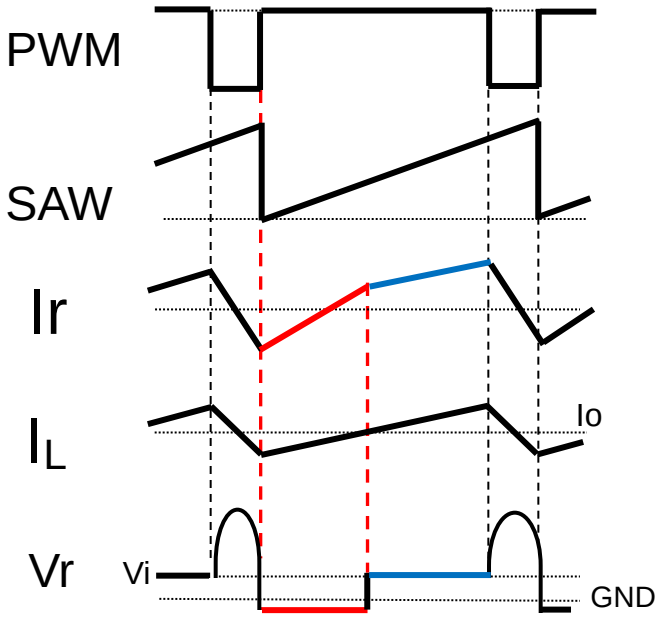


Fig.5-3 Major Signals

2-2 Simulation Results

【 Output Voltage Ripples 】

＊Step Response: Io = 0.25A ⇔ 0.50A

- Stable output ripples ＜2mVpp @ Io= 0.5A
- Step Responses (Over/Under shoots)＜±15mV

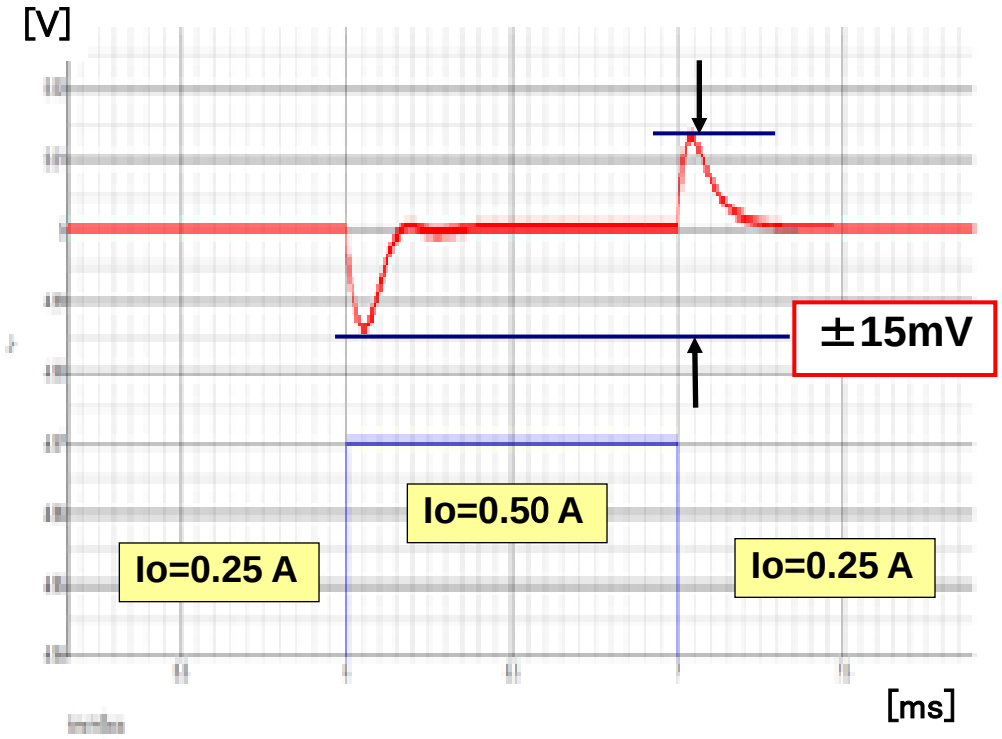


Fig. 10 Step Responses