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High Efficiency ZVS-PWM Dual-Output Buck Converters with EMI Reduction Method

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Outline

- Research Objective
- SISO Converter with ZVS-PWM Control
  - Circuit and Operation
  - Simulation and Experimental Results
- Proposed SIDO Converter with ZVS-PWM Control
  - Circuit and Operation
  - Simulation Results
- New EMI Reduction Method
  - Spread Spectrum in Switching Converter
  - Simulation Results
- Conclusion

ZVS : Zero Voltage Switching
SISO: Single Inductor Single Output
SIDO: Single Inductor Dual Output
EMI : Electro-Magnetic Interference

Background

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

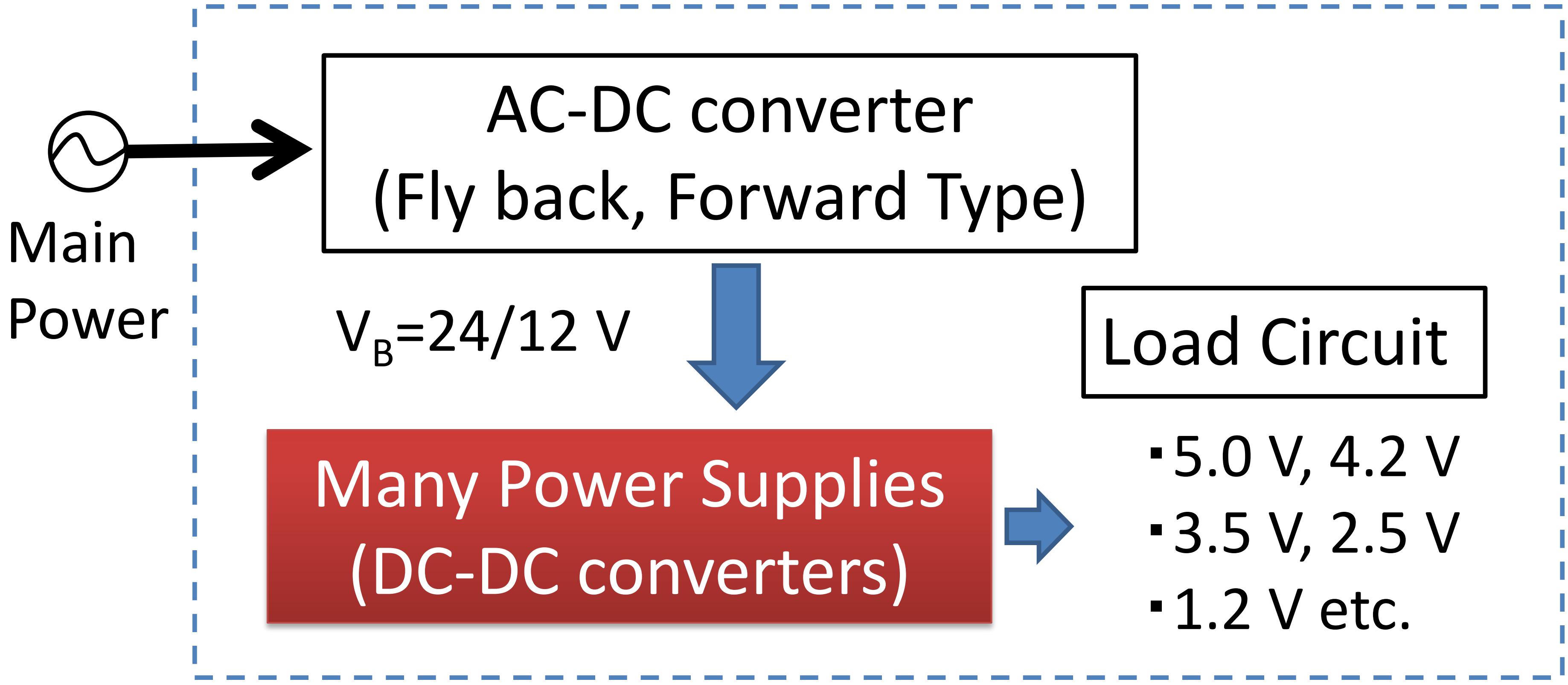

Fig.1 background

1） Low Cost, Size, Weight, etc.
2） Function: Ripple, Efficiency, EMI

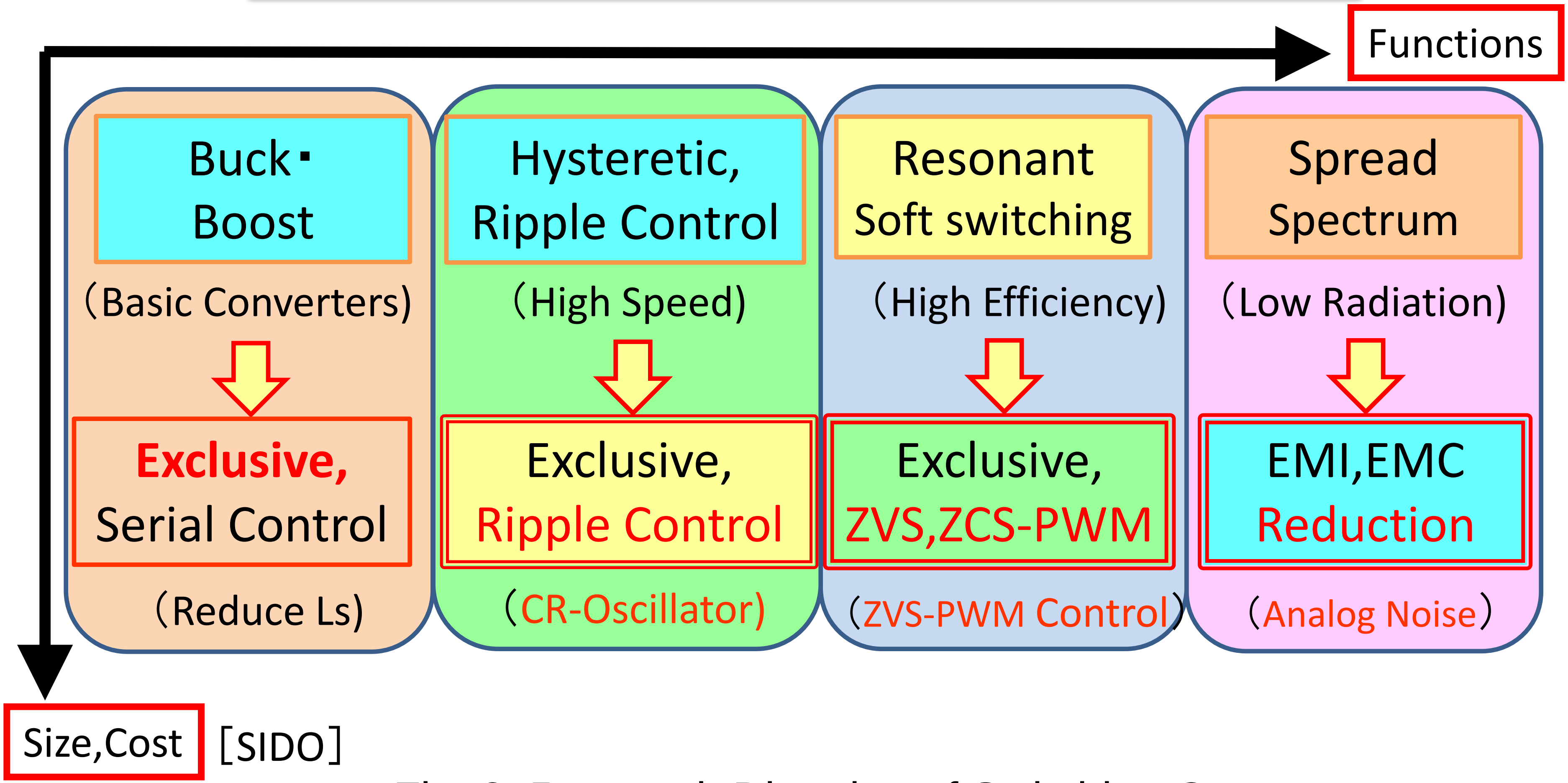

Fig. 2 Research Direction of Switching Converters

＊ **ZVS**：Zero−Voltage Switching
＊ **ZCS**：Zero−Current Switching

＊ **SISO**：Single Inductor Single Output
＊ **SIDO**：Single Inductor Dual Output

＊ **EMI**：Electro−Magnetic Interference
＊ **EMC**： Electro−Magnetic Compatible

Research Objective

●SIDO Converter with ZVS-PWM Control

Experimental SISO converter with **ZVS-PWM**

Our Previous SIDO converter with **Exclusive Control**

⬇

★New SIDO Converter with **ZVS-PWM Control**

Using no clock

★New **EMI Reduction** with Pseudo Analog Noise

Adding analog noise to the reference voltage

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SISO Buck Converter with ZVS-PWM Control

1. Circuit and Operation

1）Normal Buck Converter （No Resonant)

Duty Ratio: H ⇒ Vo ↑
H ⇒ Vo ↓

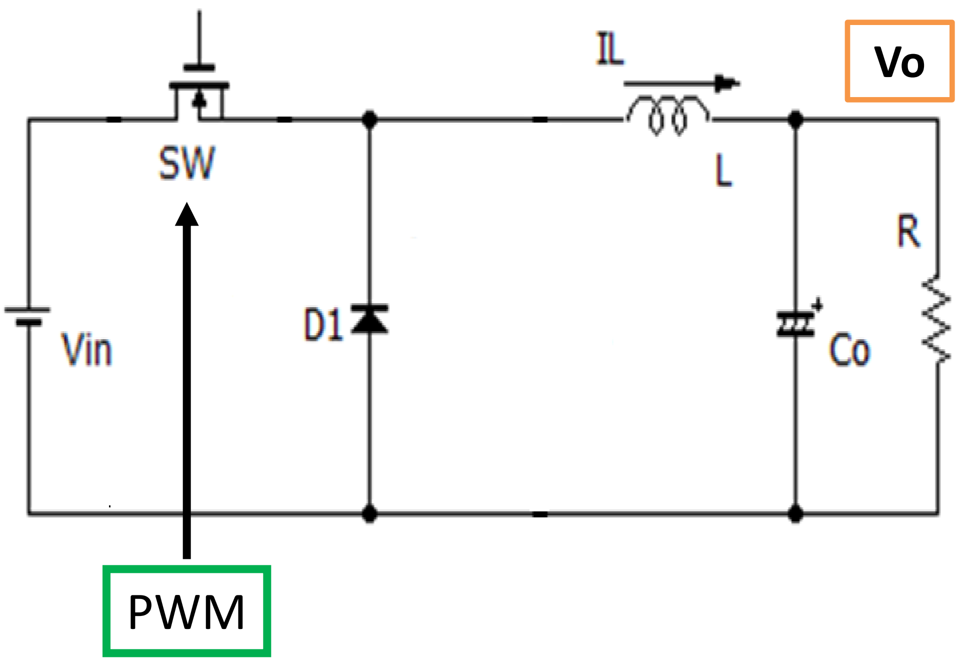


Fig.3 Circuit of Normal Buck Converter

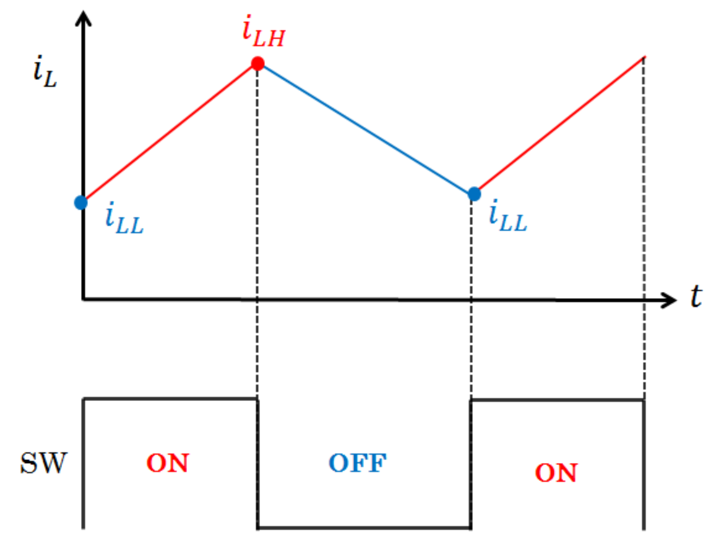


Fig.4 Timing Chart

SISO Buck Converter with ZVS-PWM Control

2) Circuit of Buck Converter with ZVS−PWM

- Circuit: Adding Resonant Capacitor & Body Diode

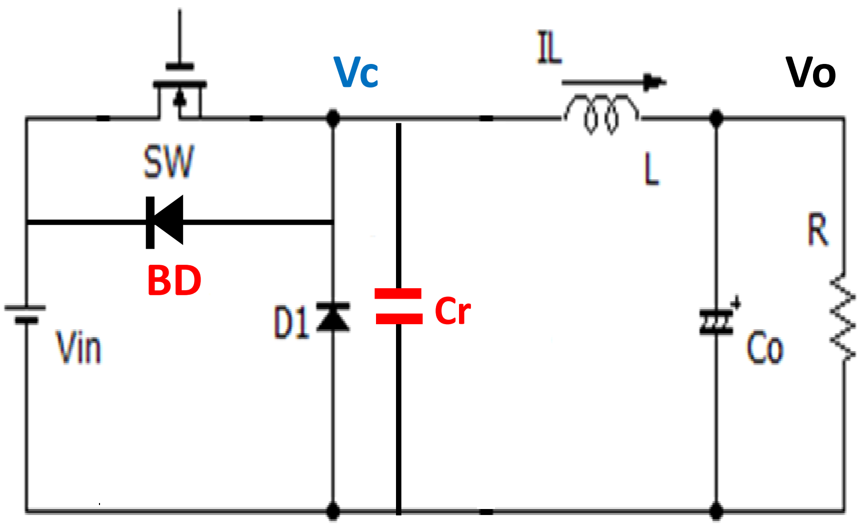


Fig.5 Circuit of Normal Buck Converter

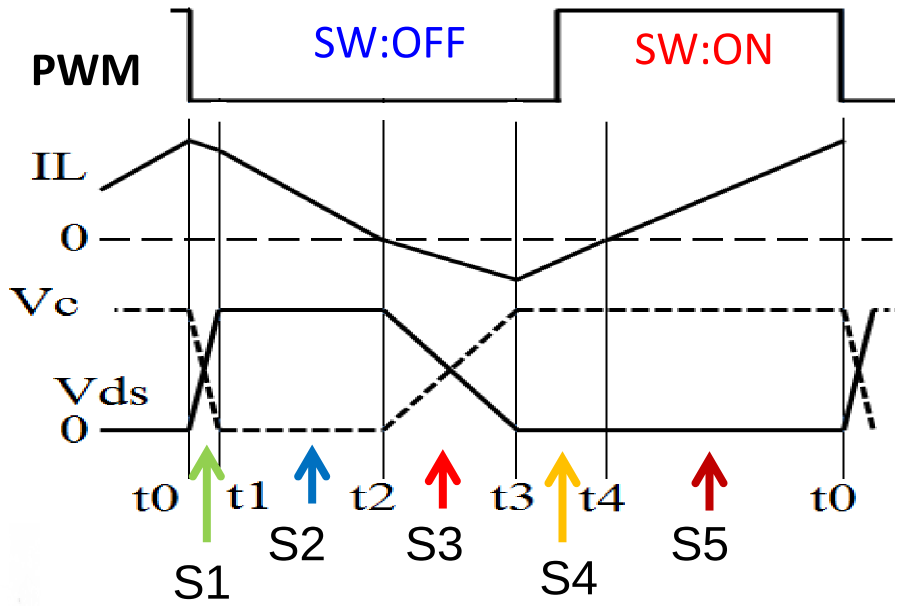


Fig.6 Waveform of Major Signals

3）Operation of ZVS-PWM Converter

★ State 1: PWM turns to OFF

Current flows from Cr to Co and Vc decreases.

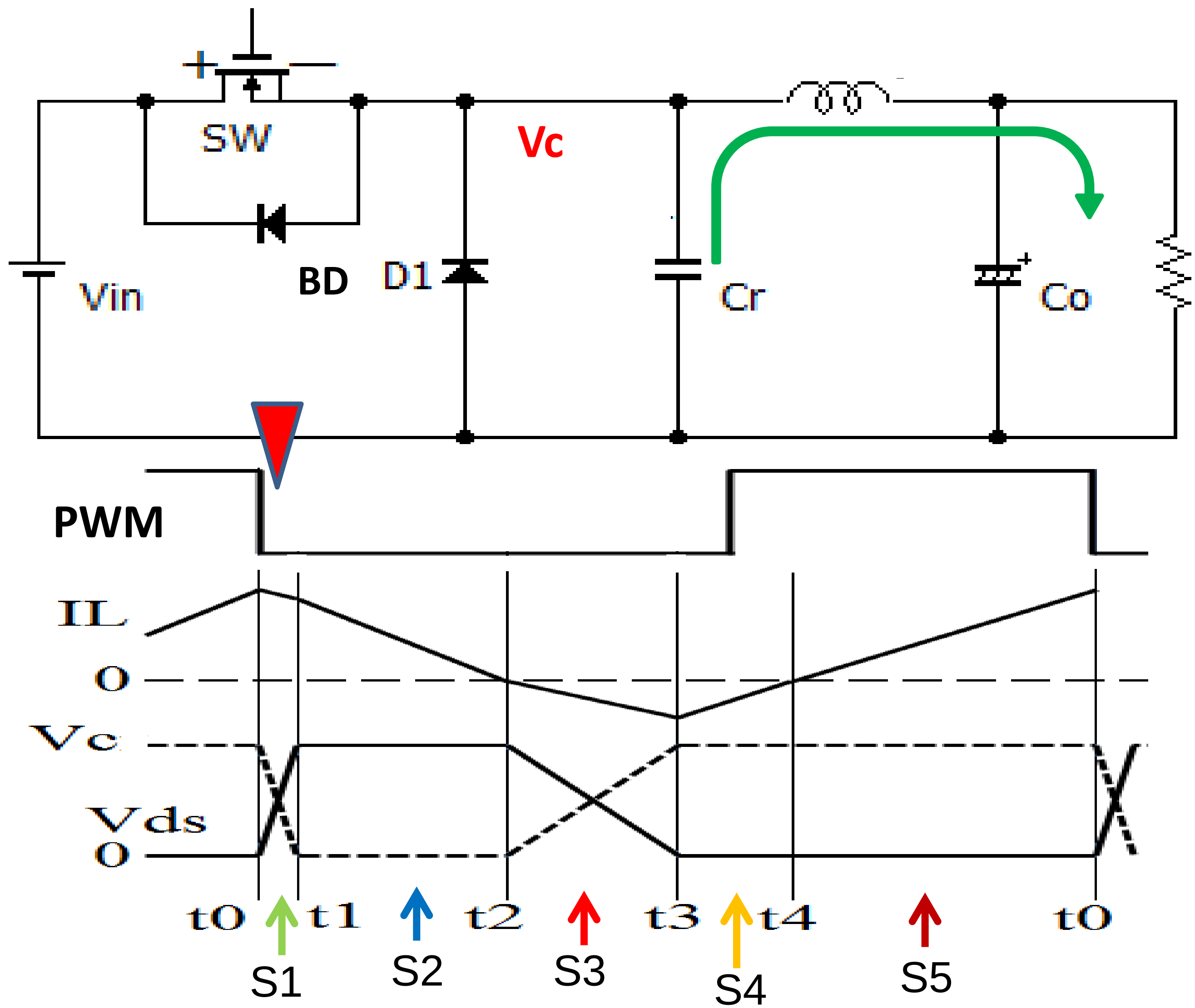


Fig.6 Major Signals

3) Operation of ZVS-PWM Converter

★ State 2: PWM keeps OFF and Vc has reached 0V.
D1 turns ON and Inductor is discharging energy via D1.
Vo is increasing.

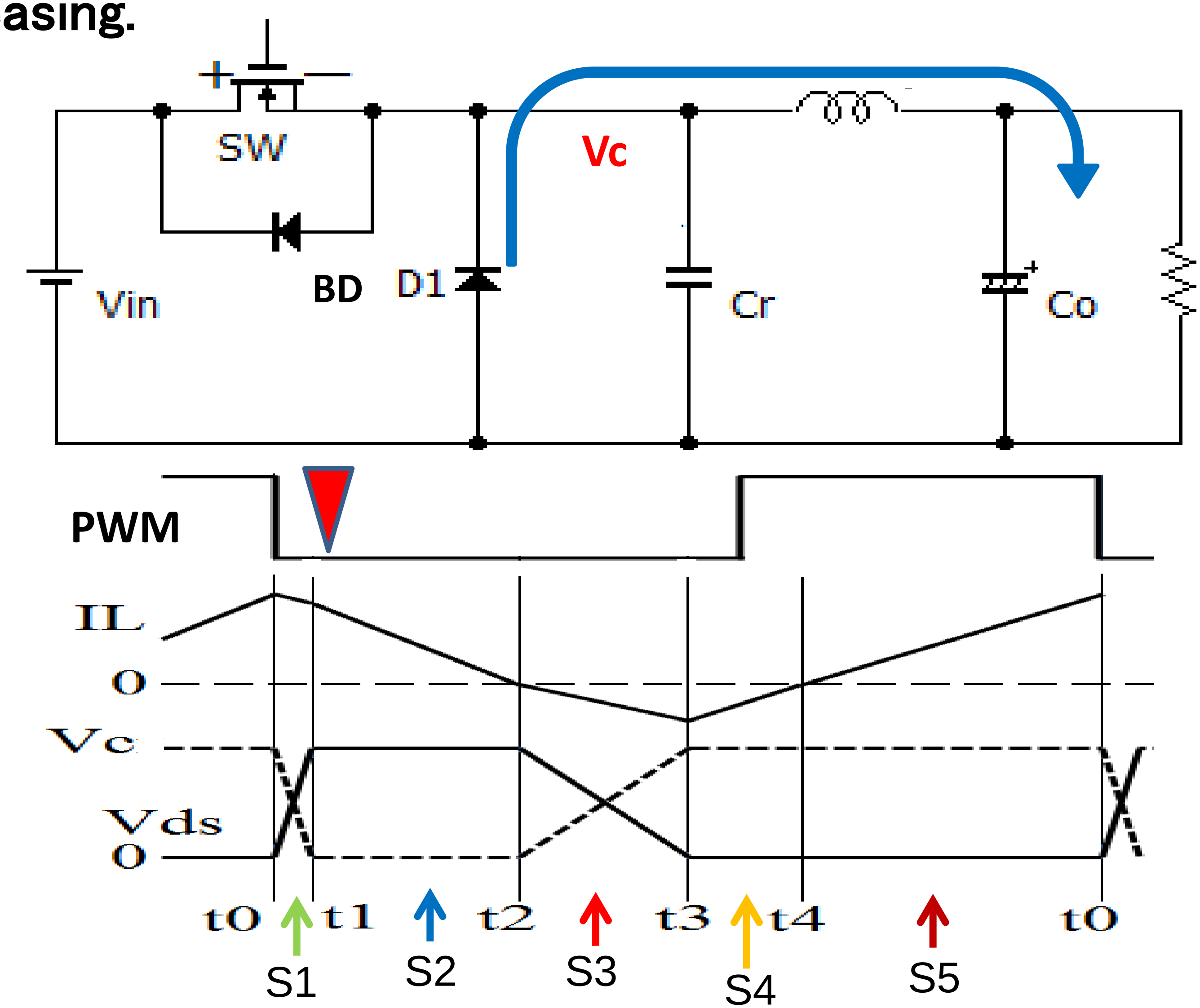


Fig.6 Major Signals

3) Operation of ZVS-PWM Converter

★ **State 3:** PWM keeps OFF and Inductor has discharged all energy.

I_L flows reverse direction and Cr is charging.

Vc is increasing.

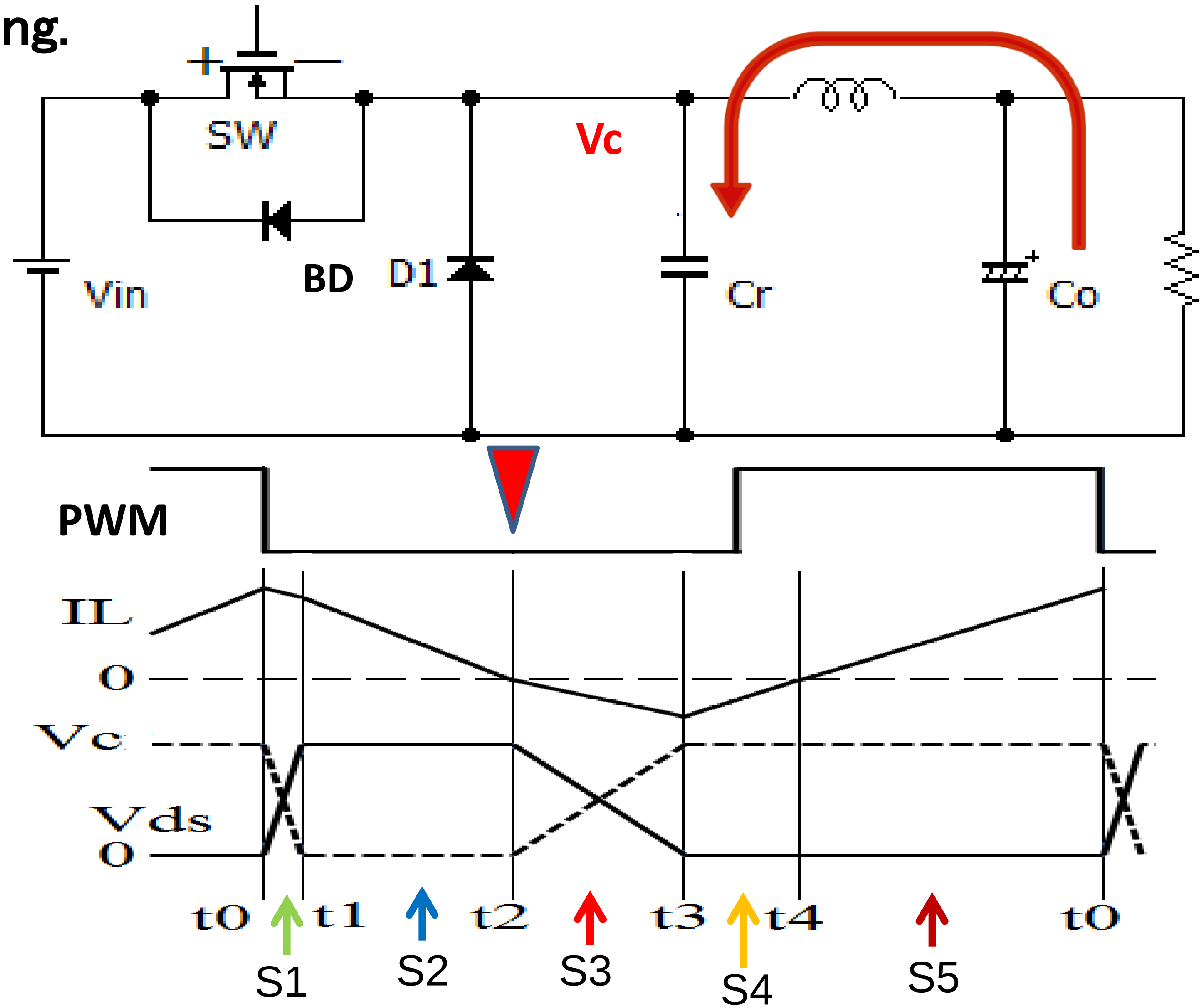


Fig.6 Major Signals

3） Operation of ZVS-PWM Converter

★ State 4: Vc has reached to Vin and BD turns ON. Negative flow of I_L is decreasing to 0A. PWM turns Hi and SW turns ON.

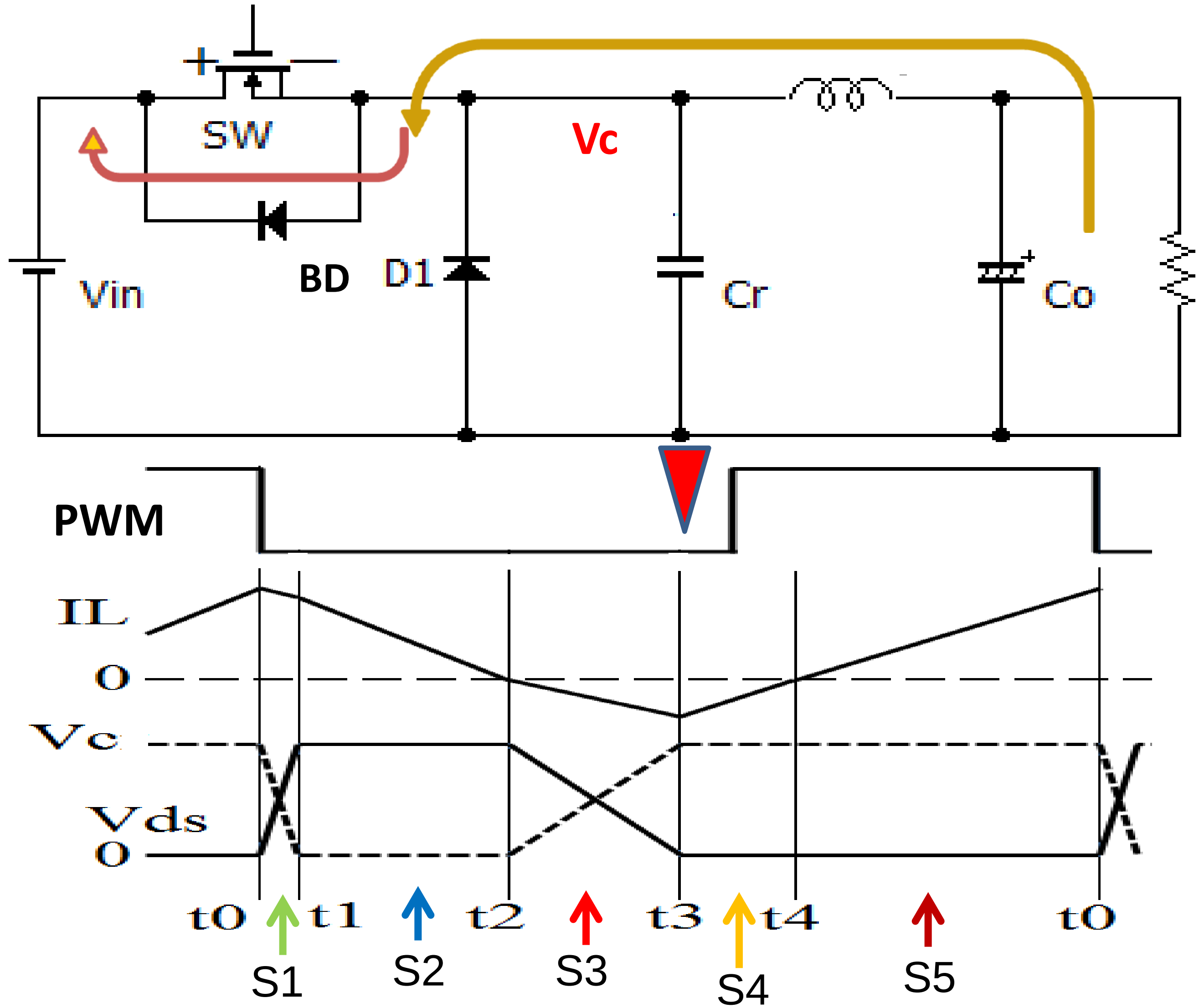


Fig.6 Major Signals

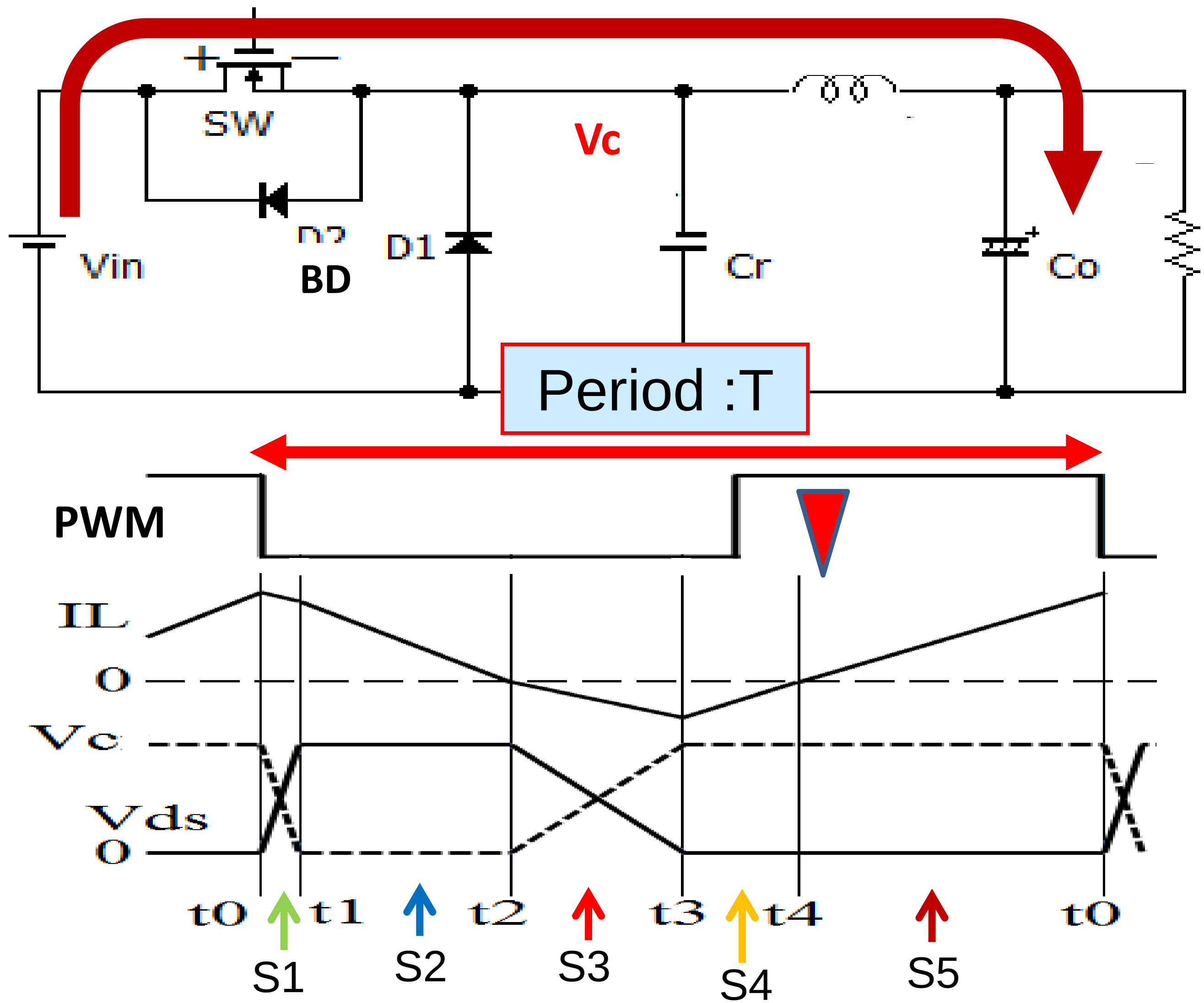
3) Operation of ZVS-PWM Converter

★ **State 5: PWM keeps Hi and SW keeps ON.**

I_L is increasing until Vo reaches reference voltage.

PWM turns Lo.

Then return to S1.



Period depends on
Cr, L, Vin, Vo, Io.

Fig.6 Major Signals

SISO Buck Converter with ZVS-PWM Control

2. Simulation Results

- Vo is compared with Vref and amplified.
- Then compared with Saw-tooth signal and get PWM pulse.

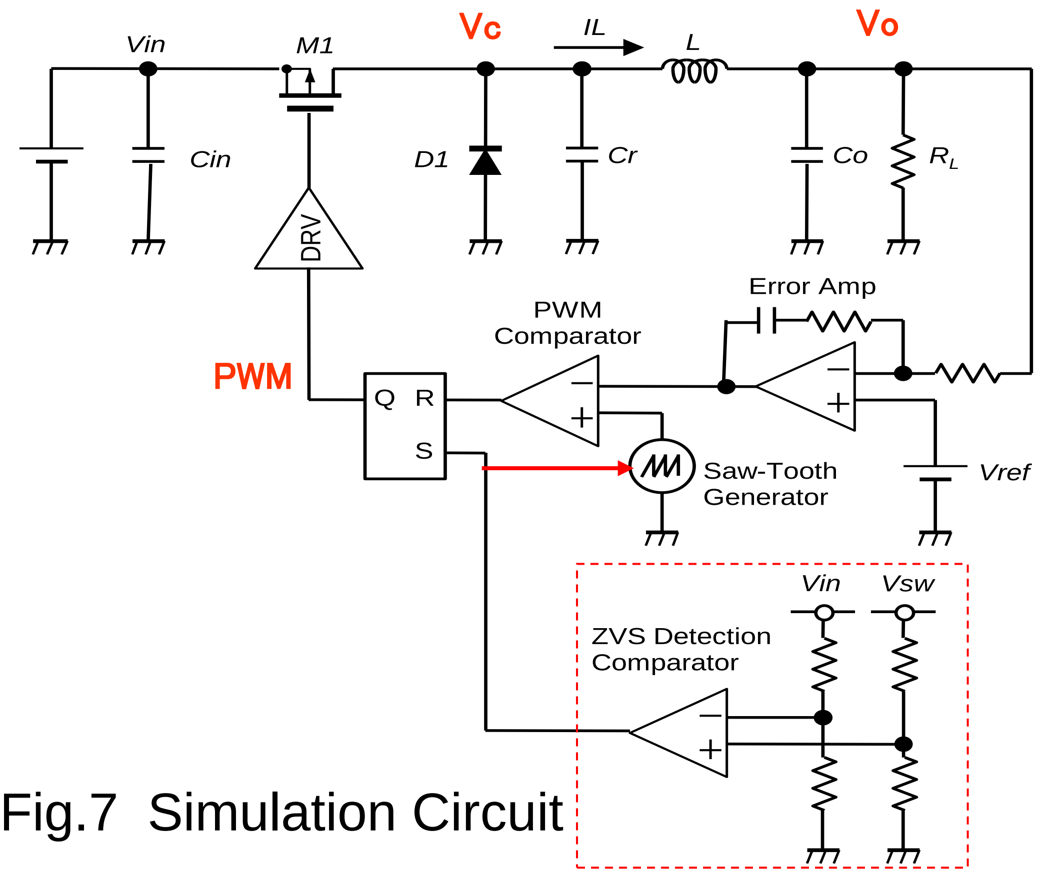


Fig.7 Simulation Circuit

Table 1. Simulation Parameters

Parameter	Value
Vin	10 V
Vo	6.0 V
L	1.0 uH
Cr	47 nF
Co	470 uF
Io	0.30 A

SISO Buck Converter with ZVS-PWM Control

2. Simulation Results

* ＊Vo is stable at 6.0V.
* ＊I_L flows positive and negative.
* ＊PWM width is determined by feedback loop.

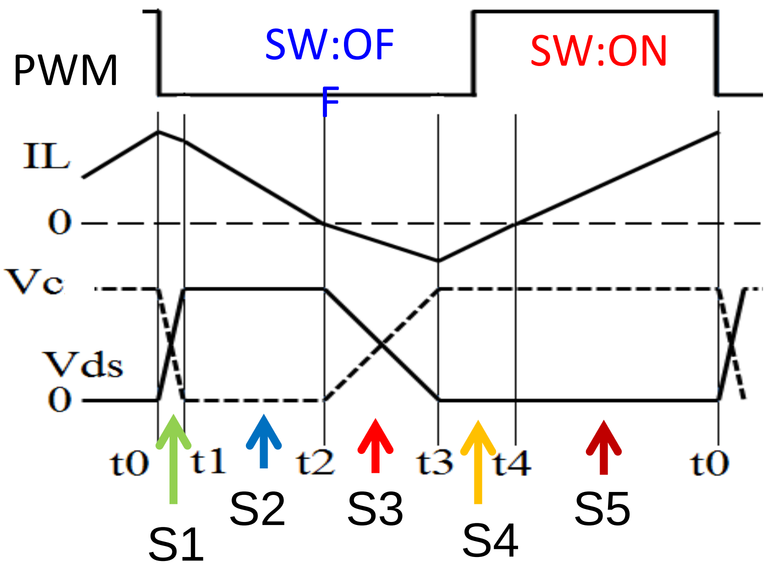


Fig.6 Major Signals

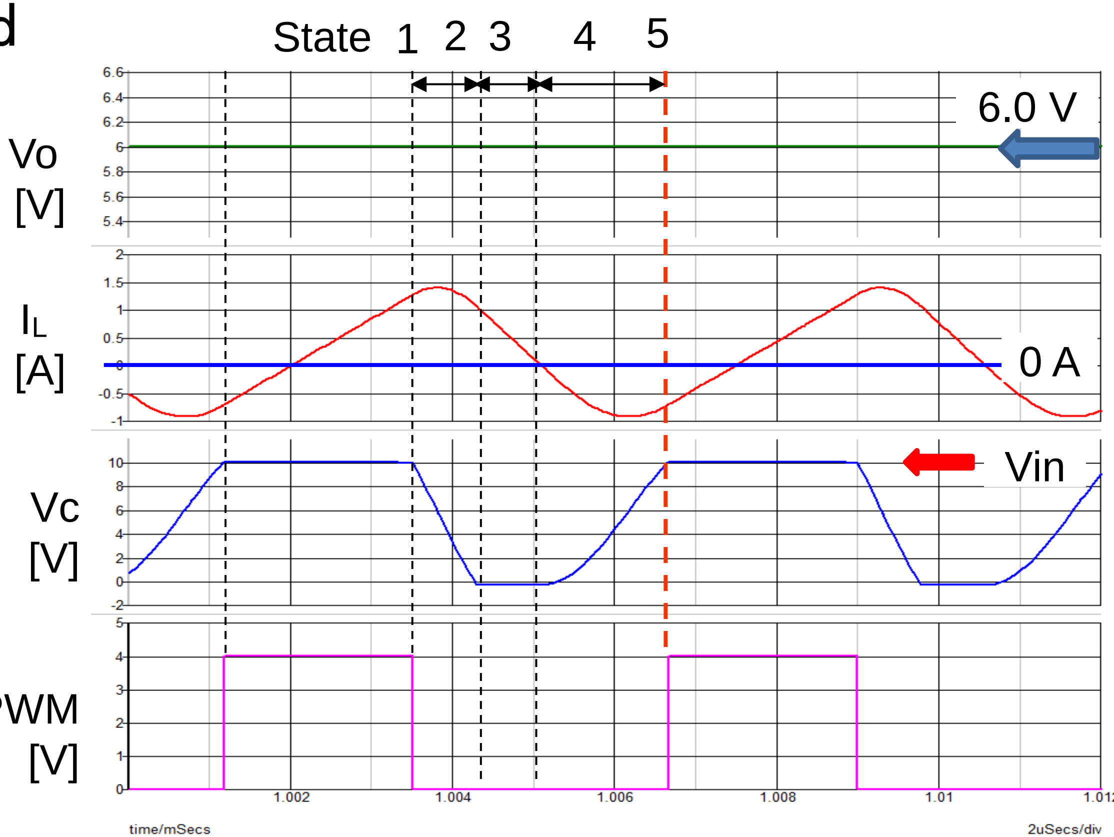


Fig.8 Simulation Result (Major signals)

SISO Buck Converter with ZVS-PWM Control

3. Experimental Results

＊ Output ripple: 50mV

＊ I_L peak : 7.0 A

＊ Fop: 250 kHz

Vi=10 V, Vo=6.0 V, Io=0.3 A

▼Most of ripple is because of ground line impedance. This circuit is made on universal board.

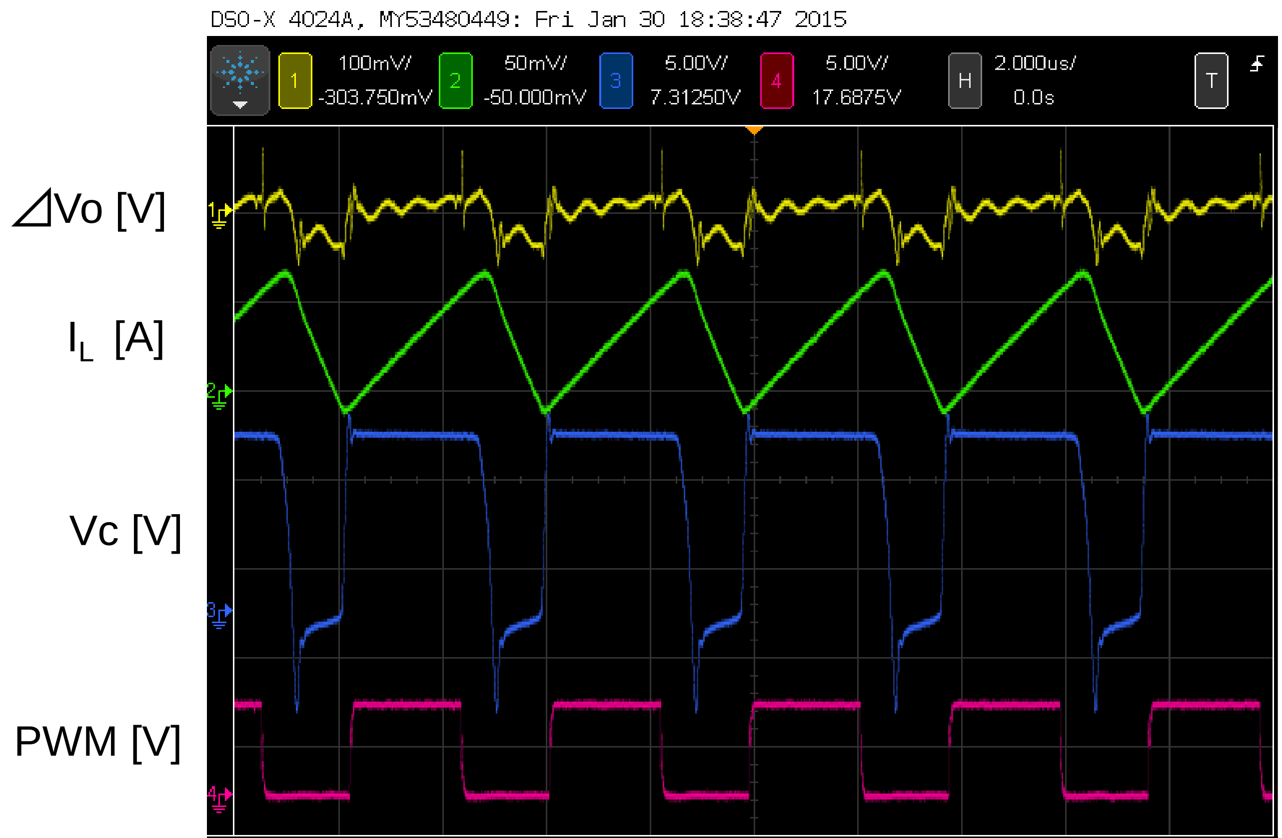


Fig.9 Experimental Results

SISO Buck Converter with ZVS-PWM Control

＊ Voltage & Current

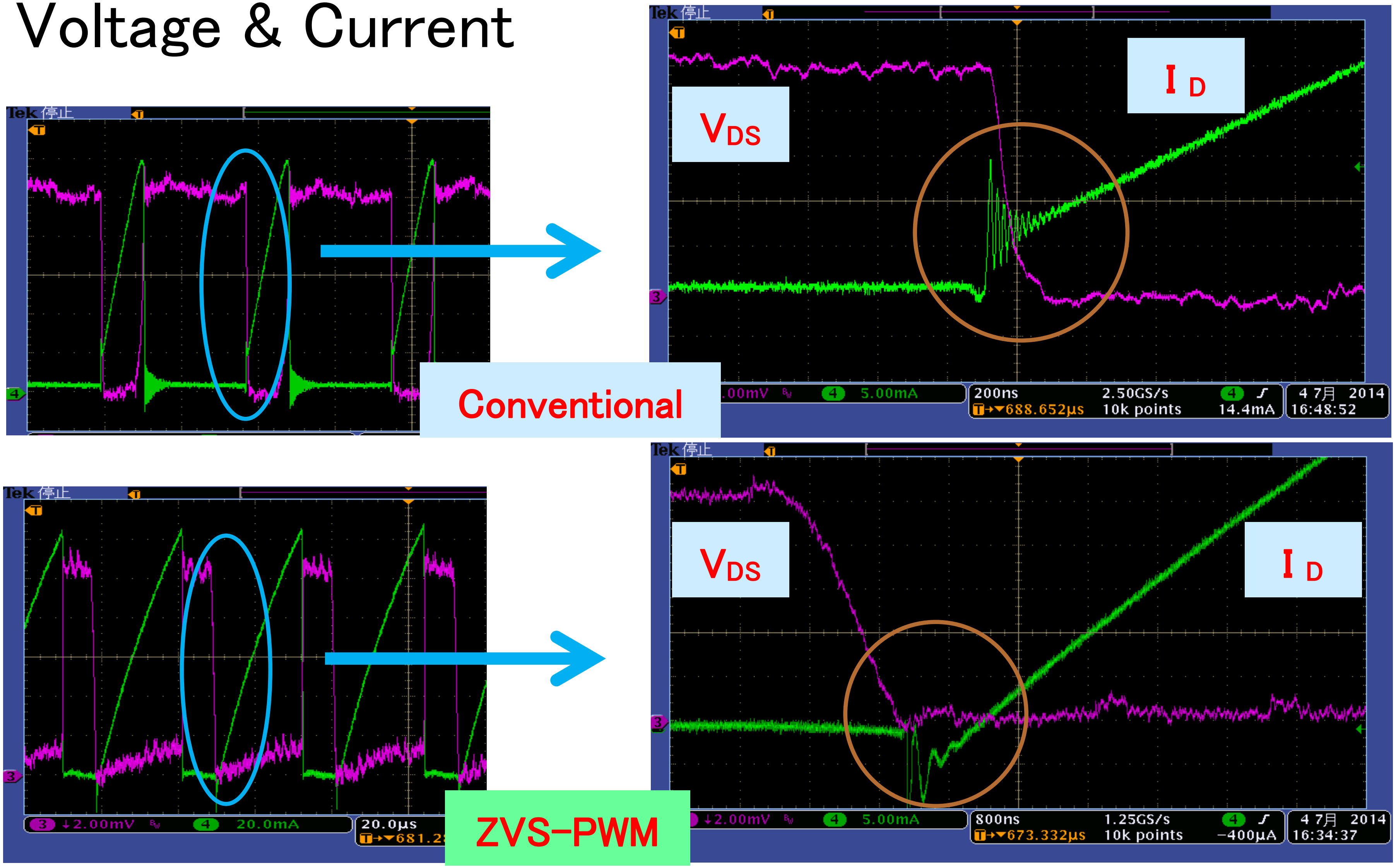


Fig.10 Waveform of Switching Voltage & Current

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Proposed SIDO Converter with ZVS–PWM Control

1. Circuit and Operation (1)

∗ Two sub-converters are selected by SEL signal.

∗ SEL signal is made by comparing ⊿V1 & ⊿V2.

Sub-conv. 1 is selected when ⊿V1 > ⊿V2 .

∗ V1 > V2.

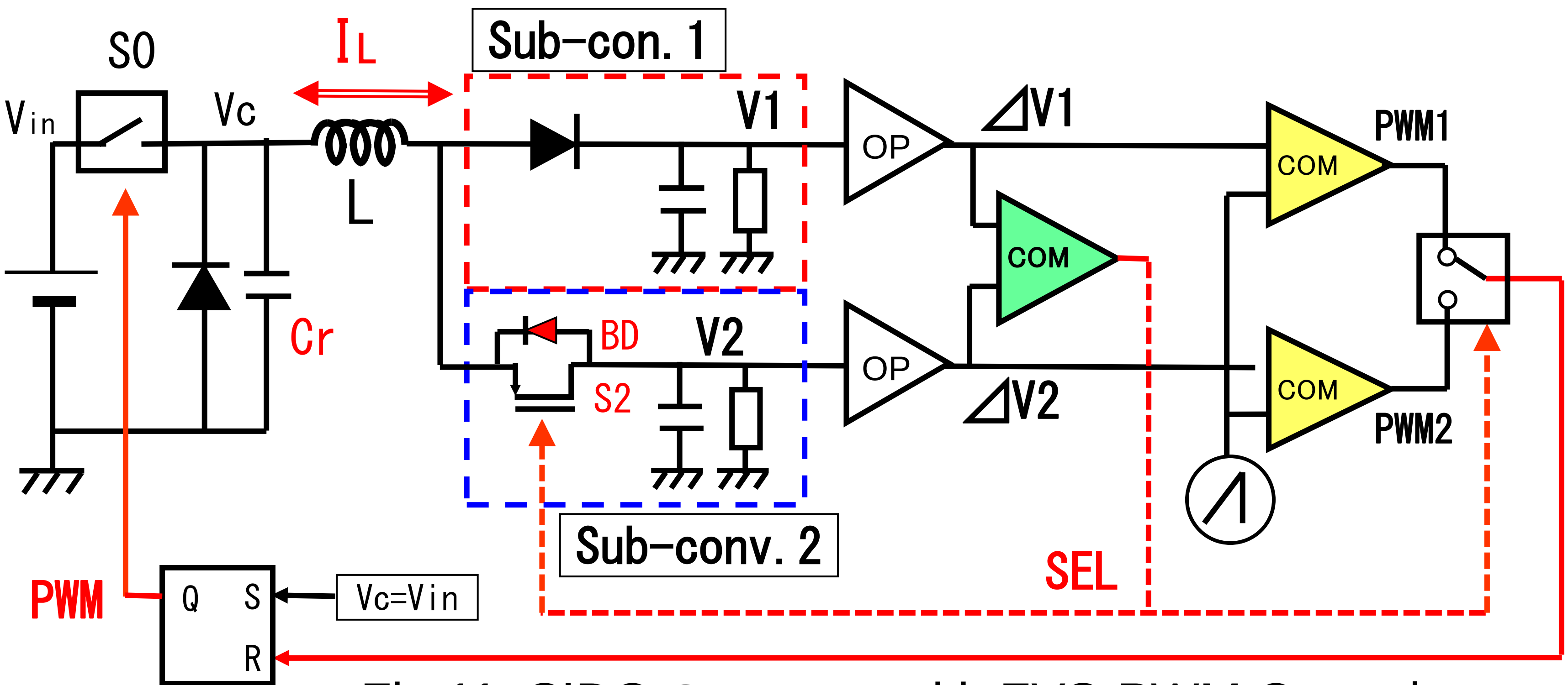


Fig.11 SIDO Converter with ZVS-PWM Control

Proposed SIDO Converter with ZVS-PWM Control

1. Circuit and Operation (2)

＊ Sub-converters are selected with SW2 and Di.

＊ Inductor Current **IL** flows forward & reverse.
Body Di is important for reverse I**L** when con.1 is selected.

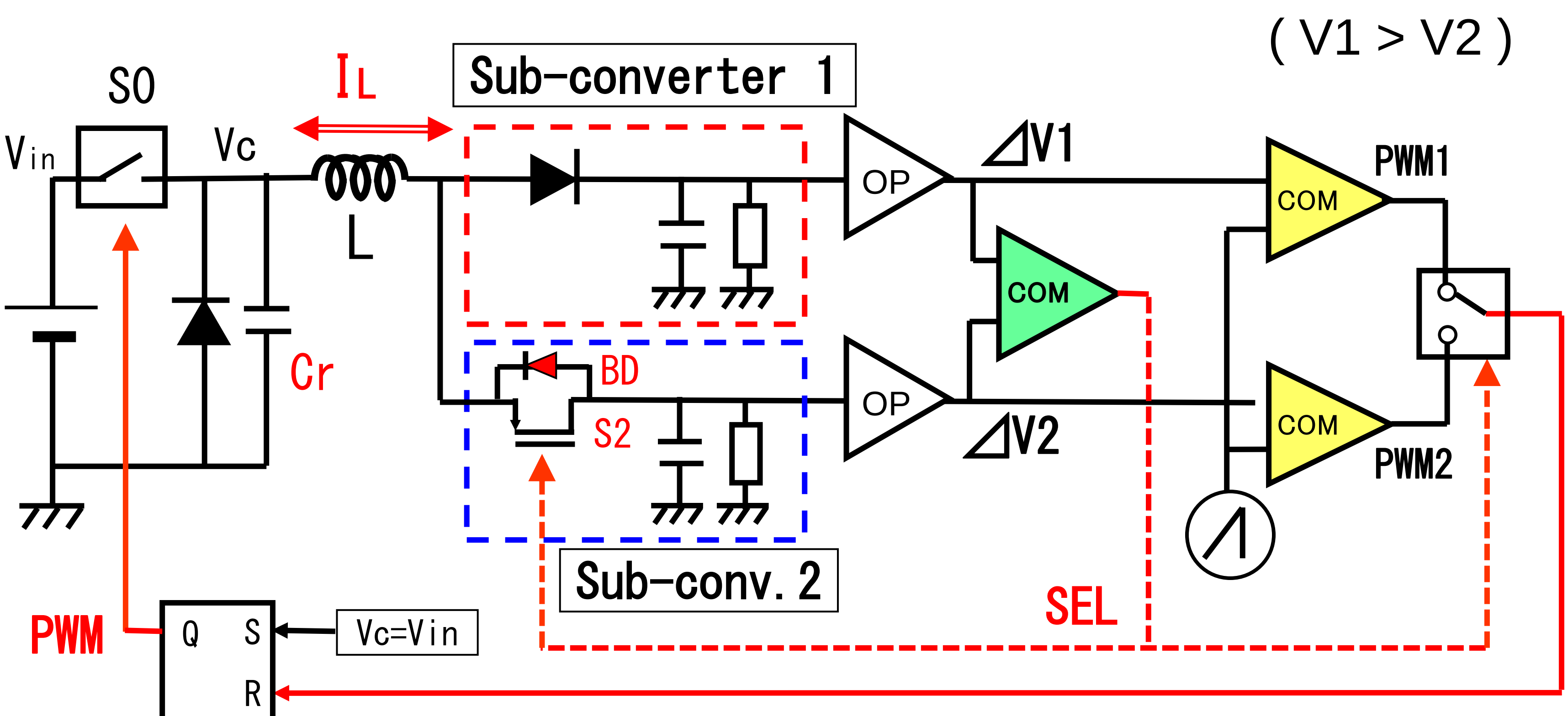


Fig.11 SIDO Converter with ZVS-PWM Control

Proposed SIDO Converter with ZVS-PWM Control

2. Simulation Results (1)

- Vi=10V
  ⇒ V1=6.0V, V2=5.5V
- Io1=Io2 =0.5A
- L=2.2uH,
  Cr=1.0nF, C=470uF

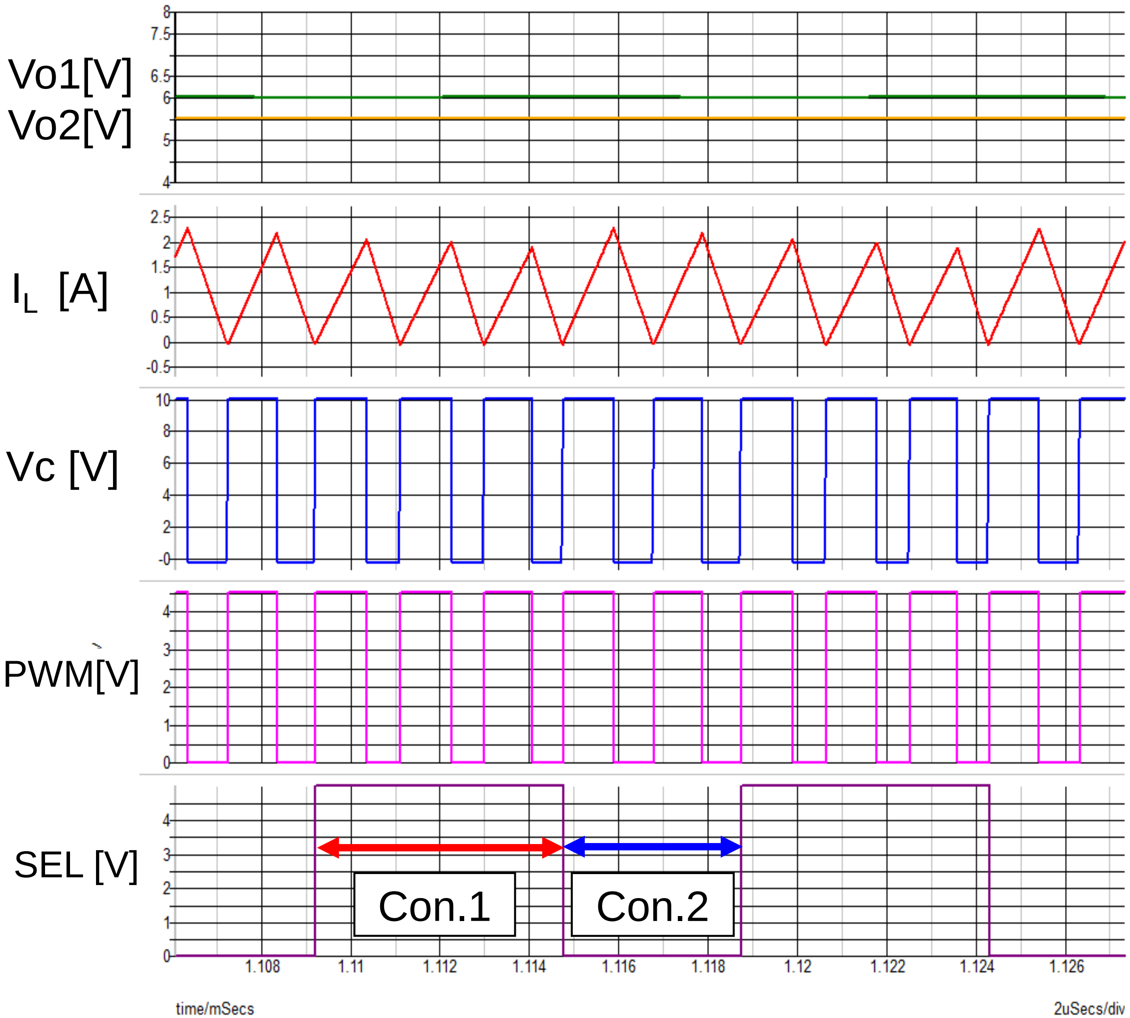


Fig.12 Simulation Result

Proposed SIDO Converter with ZVS-PWM Control

2. Simulation Results (2)

- Output Voltage Ripple

  ⊿V1, ⊿V2 ＜10mV

- Over-shoot≒±10 mV

＊Self-reg. ＞ Cross-reg.

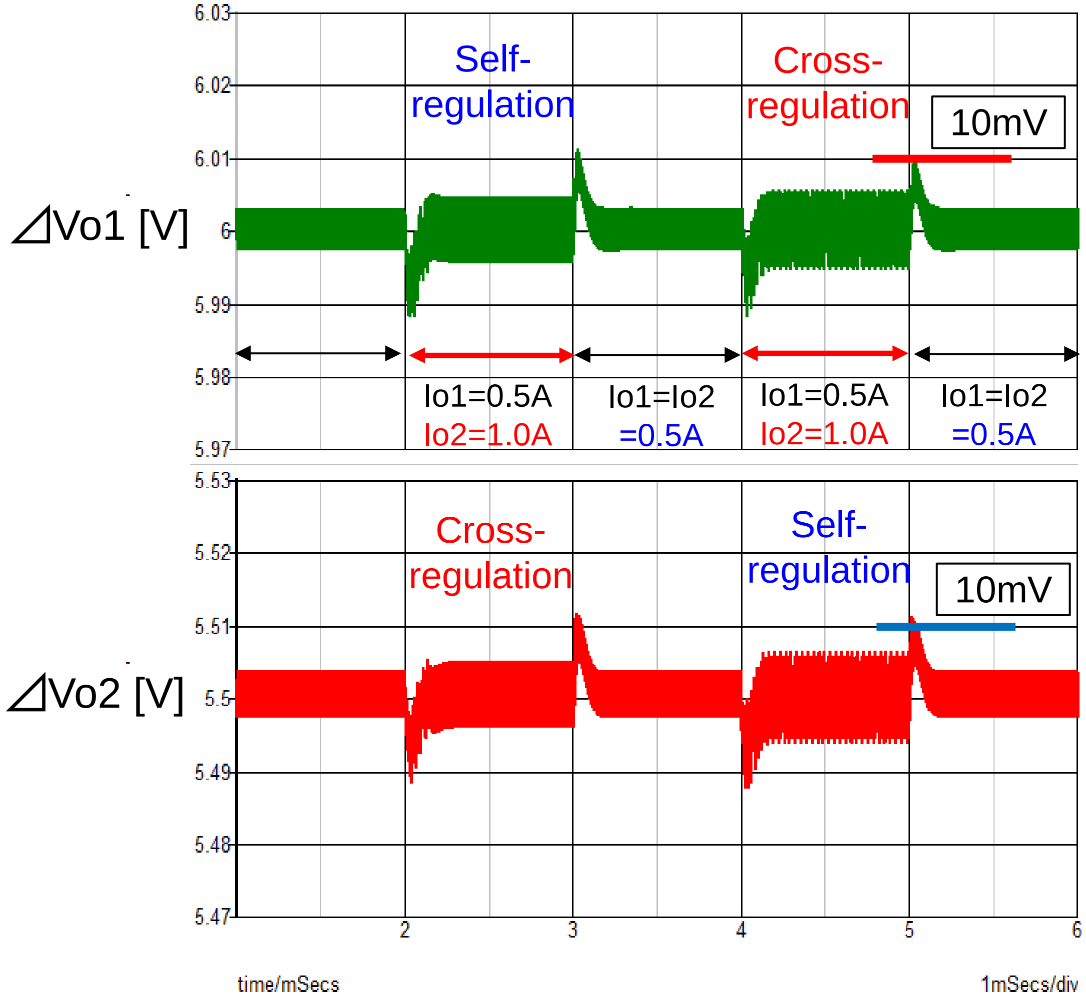


Fig.13 Simulation Results (Ripples)

Proposed SIDO Converter with ZVS-PWM Control

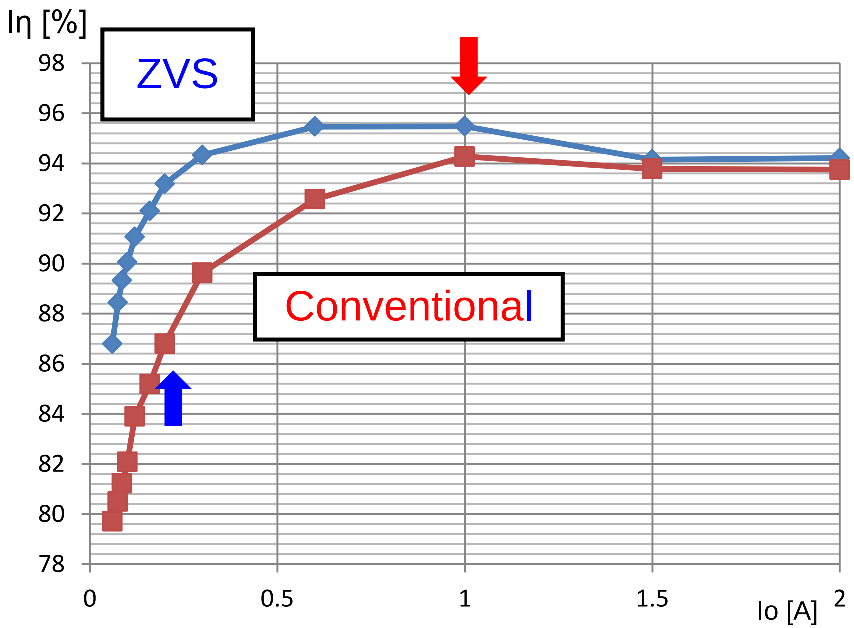
● Efficiency vs. Io of Converters

＊ SISO Converter : MAX 95.5% (Conventional : MAX 94.3%) @ Io=1.0A

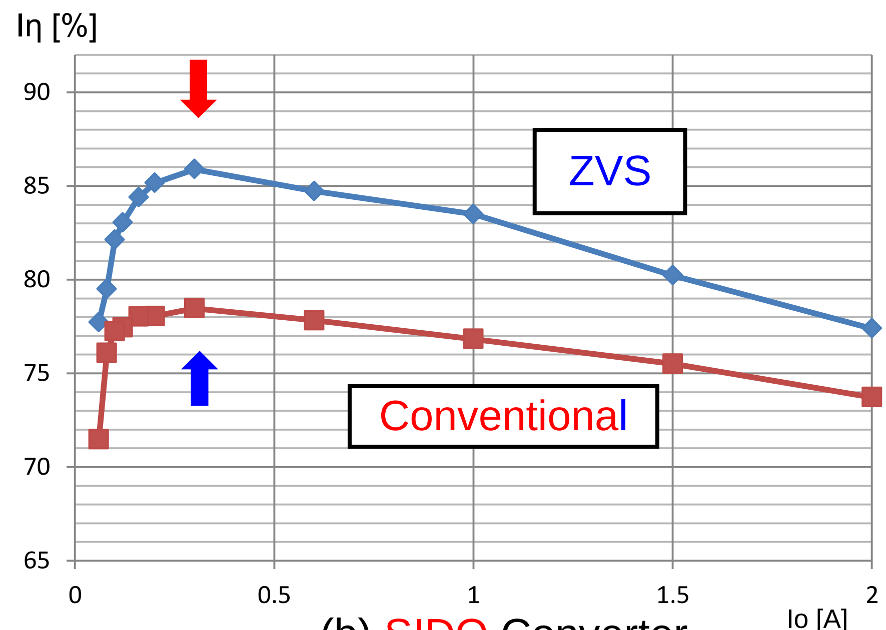
$\Delta\eta$ = 1.2% @ Io=1.0A, MAX $\Delta\eta$ = 6.5% @ Io=0.2 A

＊ SIDO Converter : MAX86.0% (Conventional : MAX 78.5%) @ Io=0.3A

$\Delta\eta$ = 7.5% @ Io=0.3 A



(a) SISO Converter



(b) SIDO Converter

Fig.14 Efficiency of ZVS-PWM Converter

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New EMI Reduction Method

1. Spread Spectrum in Switching Converters

●Method: Random Shift of PWM Phase

＊Conventional Method：Digital Spread Spectrum

・Many Shift-registers & Selectors: 10~12bits

＊Our Previous Method: Analog Noise Spread Spectrum

・Only 3-bit Counter + LPF Circuit ⇒ Shift PWM

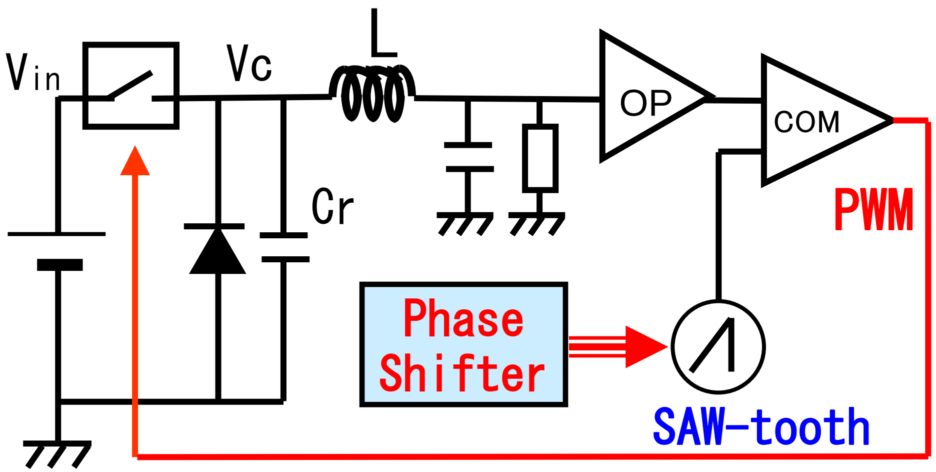


Fig.16 Converter with Spread Spectrum

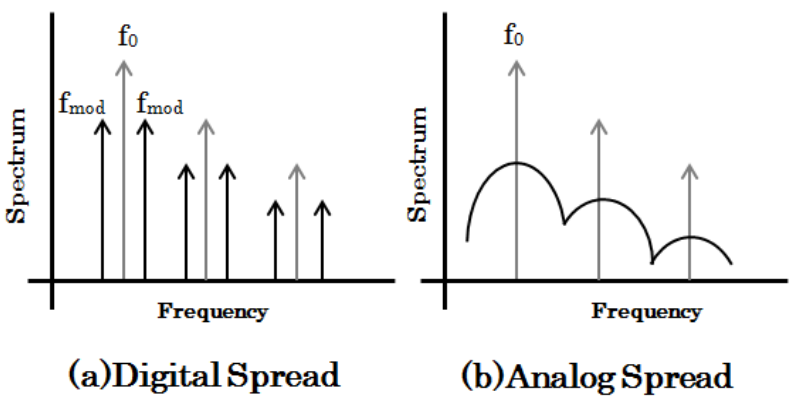


Fig.17 Spread Spectrum

New EMI Reduction Method

2. M-sequence Circuit : Digital Random Noise Generator

●Circuit & Operation

＊Shift−resistors & Ex−OR gate :

＊N=(2^n −1) levels on bit number n of primitive polynomial

$$G(x) = x^3 + x^2 + 1 \quad (\text{3-bit} \Rightarrow \text{7 level})$$

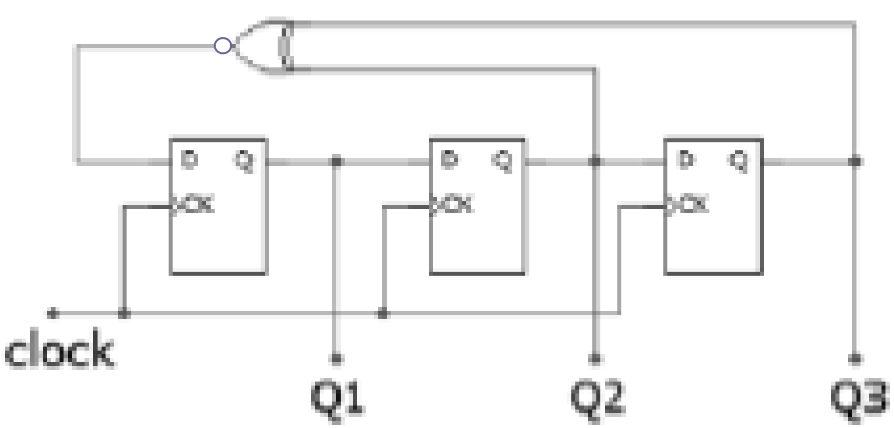


Fig.18 M-sequence Circuit

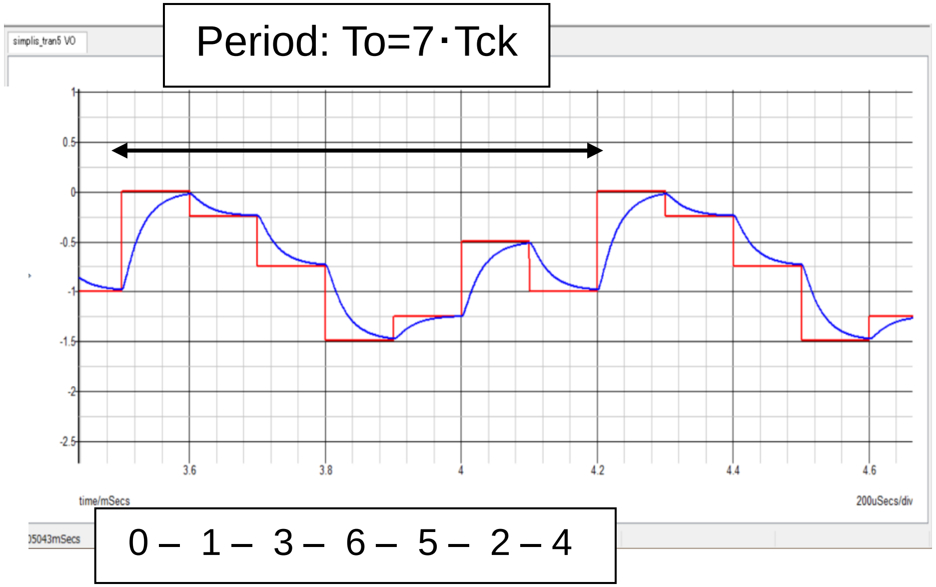


Fig.19 Output Step Pattern

New EMI Reduction Method

3. Proposed Spread Spectrum with New Noise Generator

＊ZVS–PWM Converter is difficult to shift the PWM phase
because of no clock, no synchronized signal.

＊Add analog noise to Voltage Reference

SAW is not constant phase ⟺ Error voltage is dithered

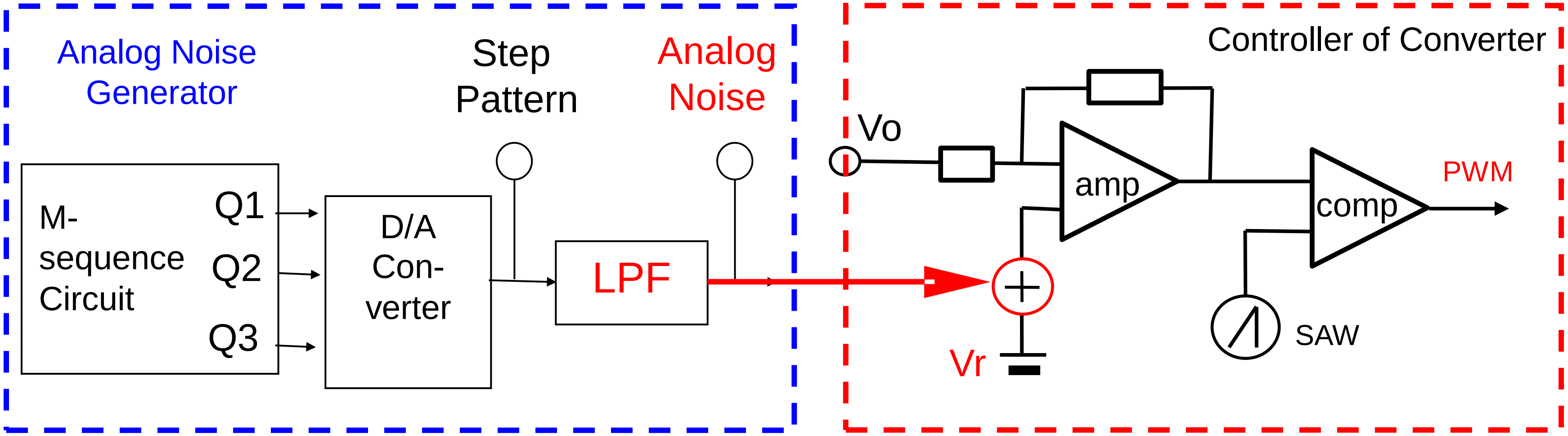


Fig.20 Spread Spectrum by Adding Analog Noise

New EMI Reduction Method

3. Simulation Results

● Output Voltage Ripple

⊿Vo=10mVpp(<0.2% of Vo)

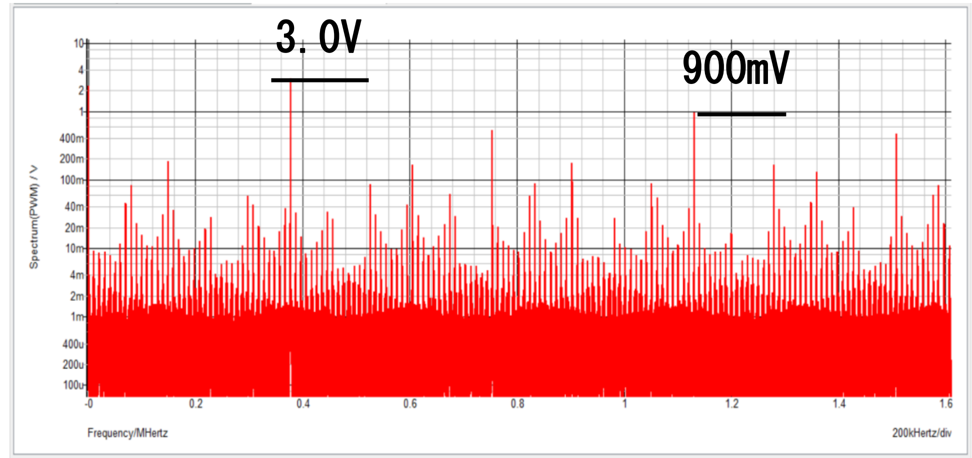
● Effect of Spread Spectrum

＊Peak level : −4.0dB

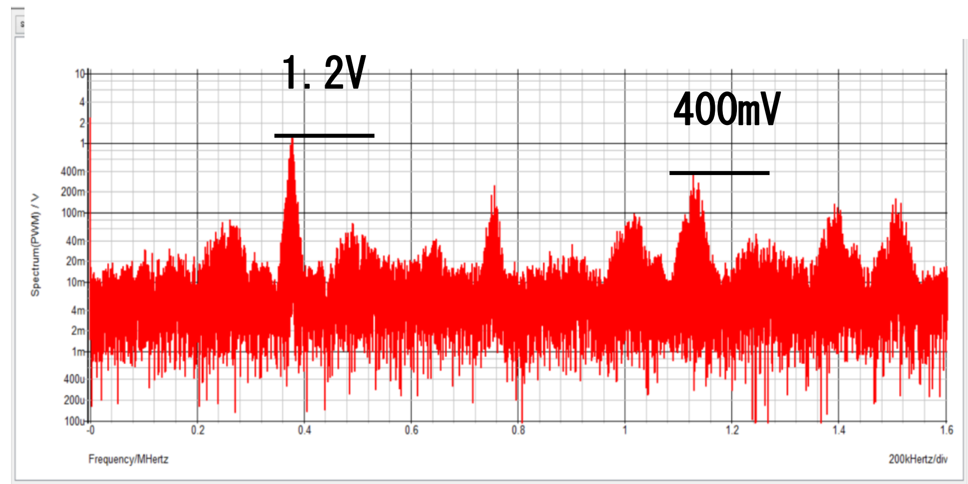
1.2V ⟸ 3.0V (F=377 kHz)

＊Harmonic level : −3.5dB

0.4V ⟸ 0.9V (F=1.13MHz)



(a) Spectrum without Analog Noise



(b) Spectrum with Analog Noise

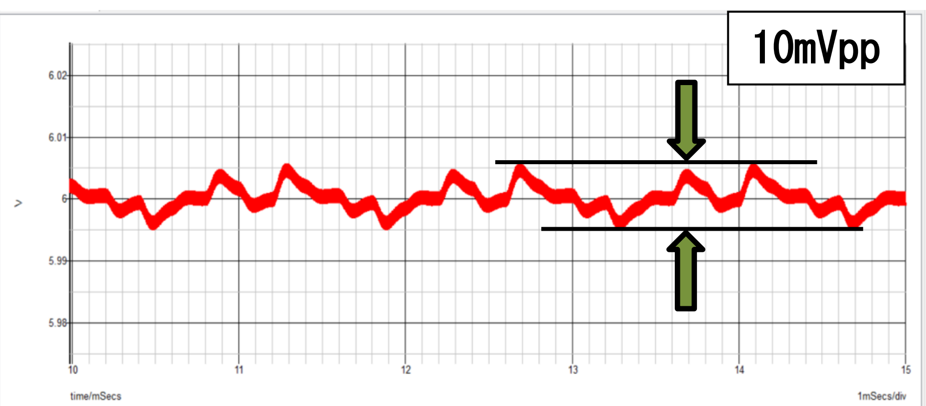


Fig.21 Ripple with Spread Spectrum

Fig.22 Spread Spectrum

Conclusion

1. Buck Converter with ZVS–PWM Control

a) Simulation Result : Efficiency η (%)

＊SISO : η = MAX 95.5 (⊿η =1.2% @Io=1.0A)

MAX⊿η = 6.5% @ Io=0.2 A

＊SIDO : η = MAX 86.0 (⊿η =7.5% @Io=0.3A) = MAX⊿η

b) Simulation Result : SIDO Converter

Output Ripple : ⊿Vo ≒ 10mVpp @ Io =0.5/1.0 A

Over–shoot : ±10mV @⊿Io=±0.5 A

2. Proposed Spread Spectrum

a) New Spread Spectrum with Pseudo Analog Noise

3–bit M–sequence + LPF ⇒ Add to Voltage reference

b) Spectrum Reduction

＊Basic frequency : –4.0dB : 1.2V ← 3.0V (F=377 kHz)

＊Harmonic freq. : –3.5dB : 0.4V ← 0.9V (F=1.13MHz)

Thank you
for your attention.