電子情報通信学会
電子通信エネルギー技術研究会（EE）

2019年5月19日(木）
於　機械振興会館

Automatic Notch Generation and Conversion Voltage Ratio Analysis in Pulse Coding Control Switching Converter

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OUTLINE

- Introduction & Objective
- Conventional Switching Converter
- Pulse Coding Method in Switching Converter
- Full Automatic PWC[1] Control
- Conversion Voltage Ratio Analysis
- Conclusion and future work

[1] PWC：Pulse Width Coding

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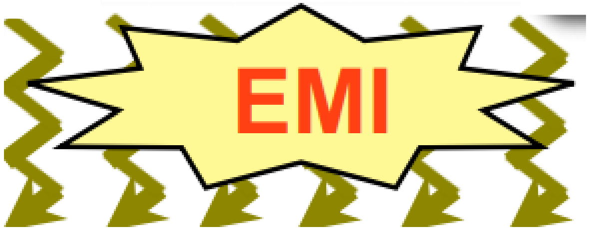
Research Background



Electronic circuits

High density and complication

Problem

Large EMI[2] noise

Focus

EMI reduction ⇒ spread noise spectrum

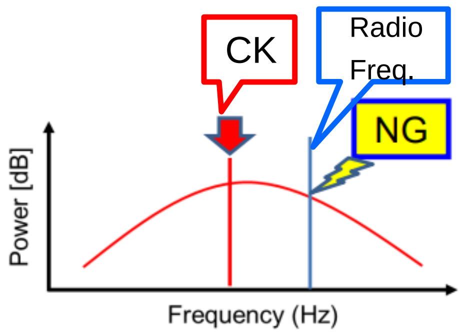
Task

Clock modulation ⇒ diffusion clock noise

[2] EMI: Electro-Magnetic Interference

Research Objective

Problem



Previous Method

Spread spectrum ⇒ shaking clock phase

Problem

F_{ck} noise spread ⇒ Receive frequency

Radio receiver

Research Objective

Spread spectrum :
⇒ EMI reduction & Noise diffusion

Further more

Noise suppression near receive frequency

Research Summary

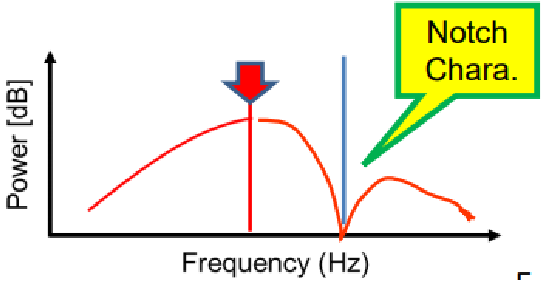
Proposed method

Pulse coding method

↓

Design modulation circuit

⇒ generate notch frequency automatically



Achievement

① EMI reduction

② Noise removal

③ Automatic generation of F_{notch}

④ Conversion voltage ratio analysis

Research Application

Information equipment switching power supply

feature

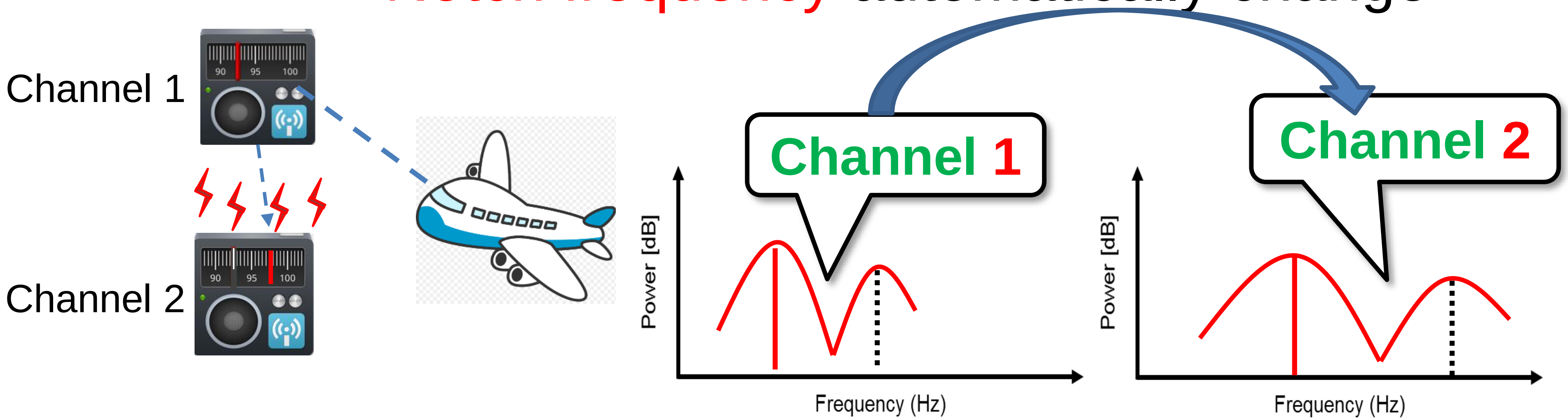
① Receiving weak radio waves

② Noise near receive frequency

⇒ automatically removed

③ Receive frequency change

⇒ Notch frequency automatically change



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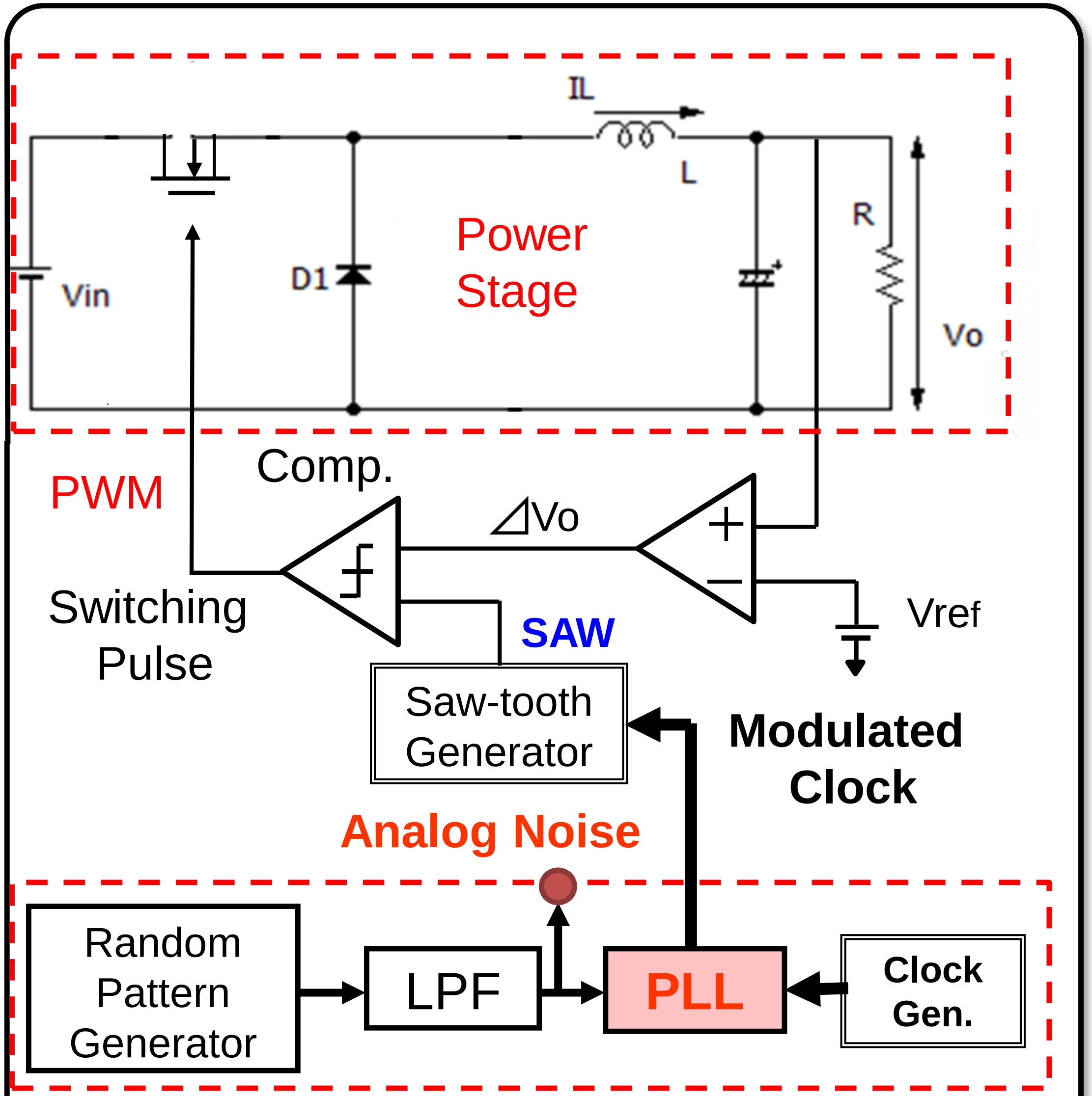
Spread Spectrum Using Pseudo Analog Noise

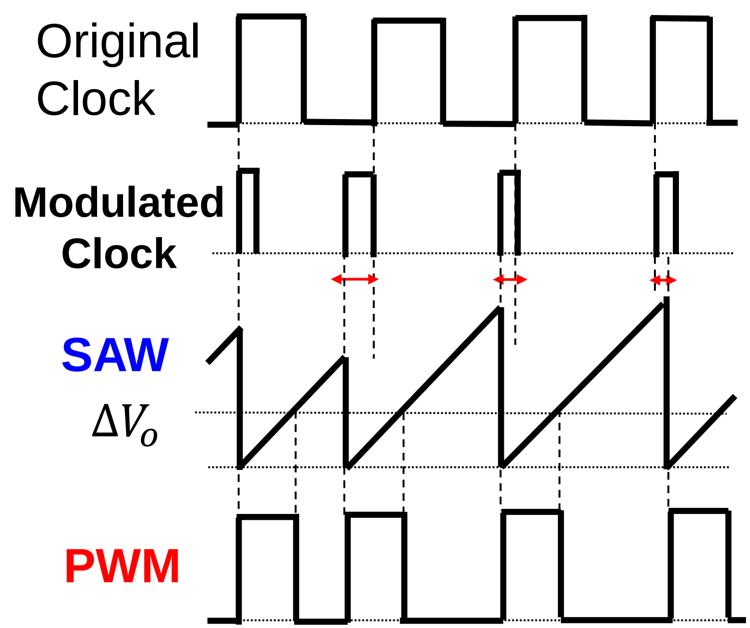


Buck converter with modulated clock

Reduce EMI noise

modulation clock to control SAW

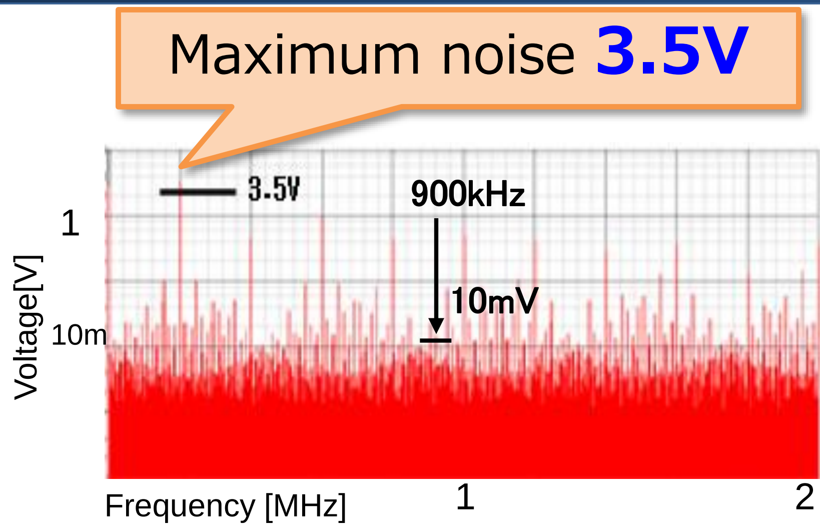
shaking phase using analog noise & PLL[3]



Timing Chart

[3] PLL: Phase Locked Loop

Spread Spectrum for EMI Reduction



PWM signal spectrum without EMI reduction

◎Simulation conditions

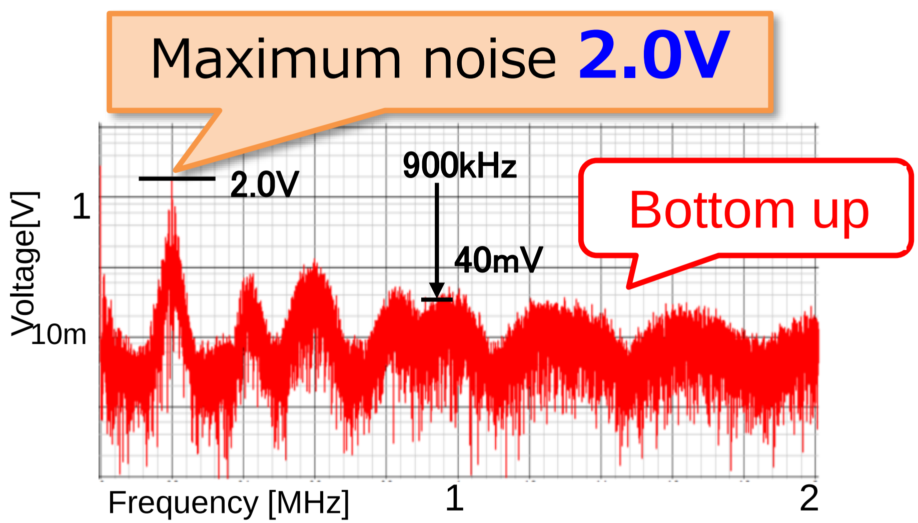
Input : 12V

Output : 6V

Clock frequency : 200kHz

Without EMI reduction

- Noise⇒basic and harmonic frequencies
- Bottom level: 1mV



PWM signal spectrum with EMI reduction

With EMI reduction

- Peak level ⇒ reduced a lot

Noise : concentrated by diffusion

No good

- Bottom level : 10mV around the received frequency

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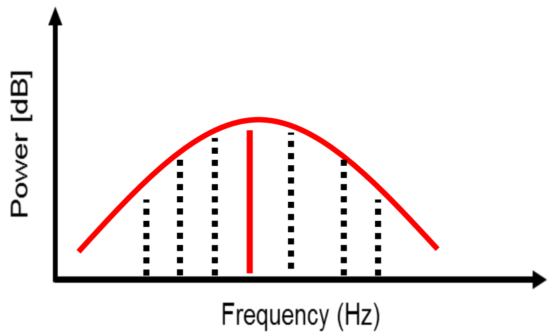
Diffuse Noise to Specific Frequency

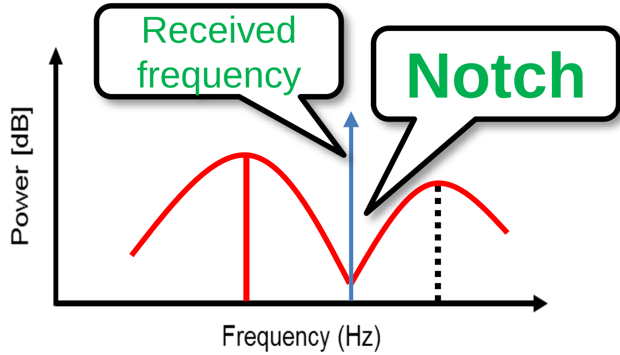
Problem

Noise diffusing uniformly
(analog modulation)



Digital modulation

Noise spread to specific frequency (discrete)

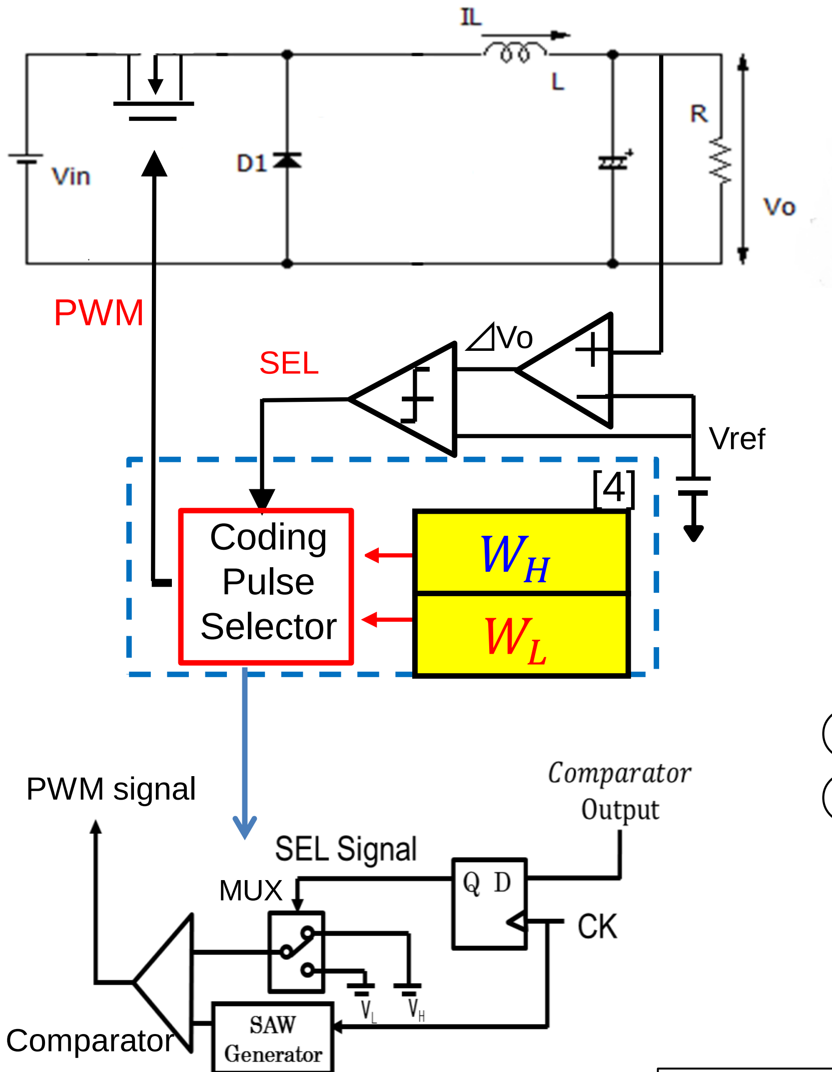


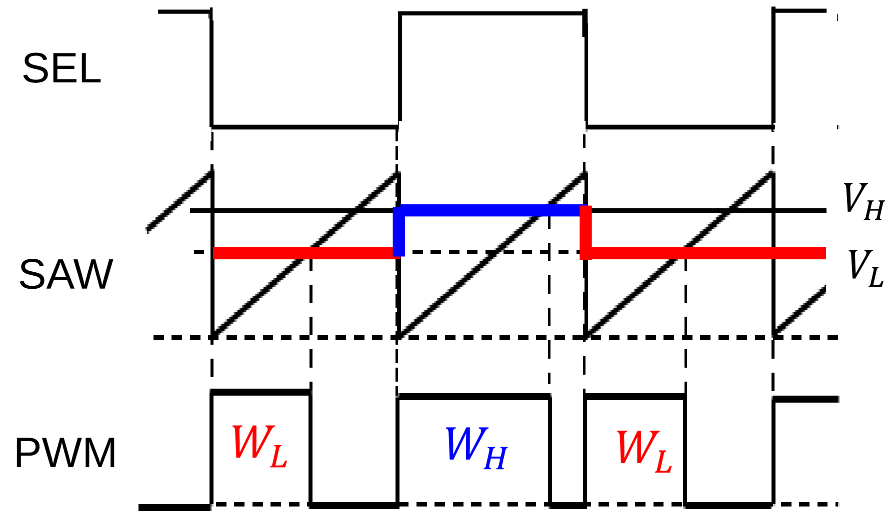
Frequency band where noise does not spread

Notch band created in important frequency band

- EMI Reduction
- Control of diffused noise

Pulse Width Coding in Switching Converter





SEL High

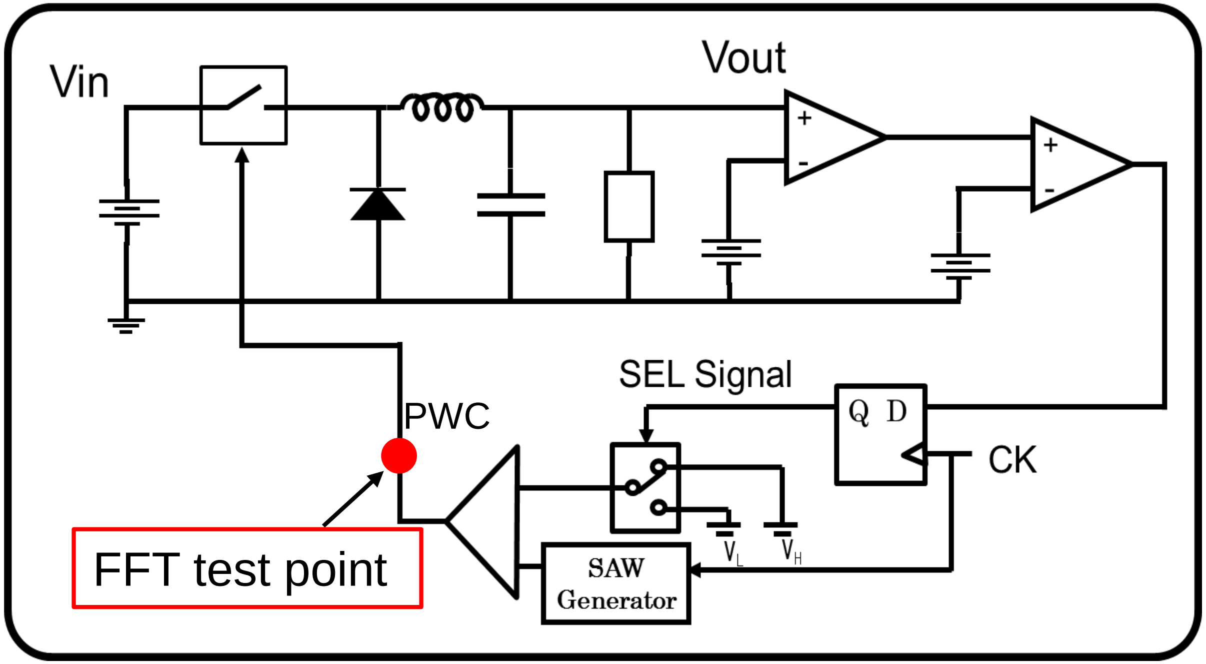
① MUX select V_H
② Generate pulse with wide width in comparator

SEL Low

① MUX select V_L
② Generate pulse with narrow width in comparator

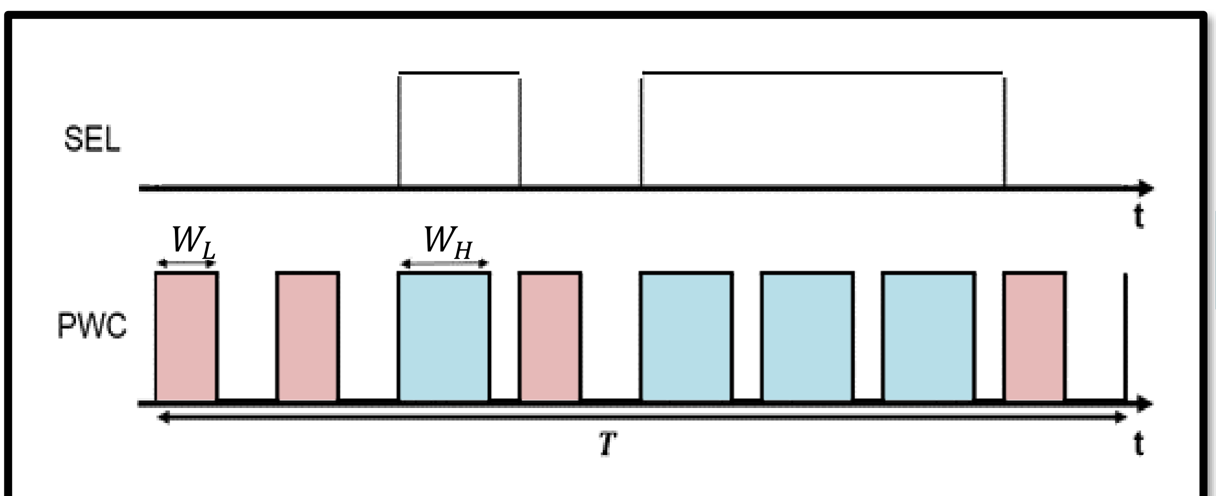
[4] W_H: Wide width of PWM signal (High duty ratio)
W_L: Narrow width of PWM signal (Low duty ratio)

Simulation Condition

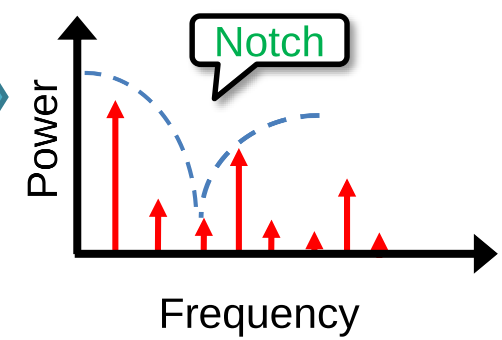


◎ Condition

Buck DC-DC converter
V_{in} : 10V
V_{out} : 5.0V
L : 200 μ H
C : 470 μ F
I_{out} : 0.25A
f_{ck} : 500kHz
W_H : 1.6μs
W_L : 0.2μs

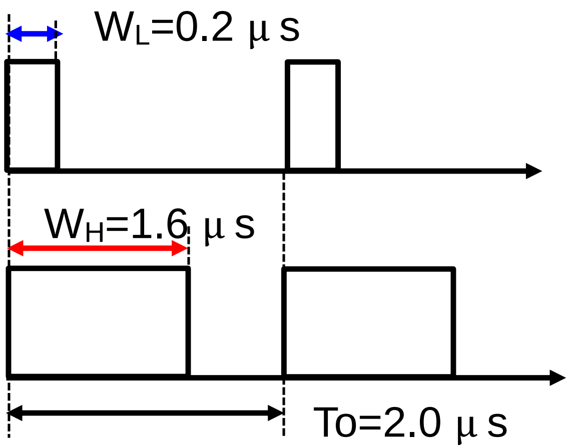


Spectrum of PWC signal



Simulation Result with PWC Control

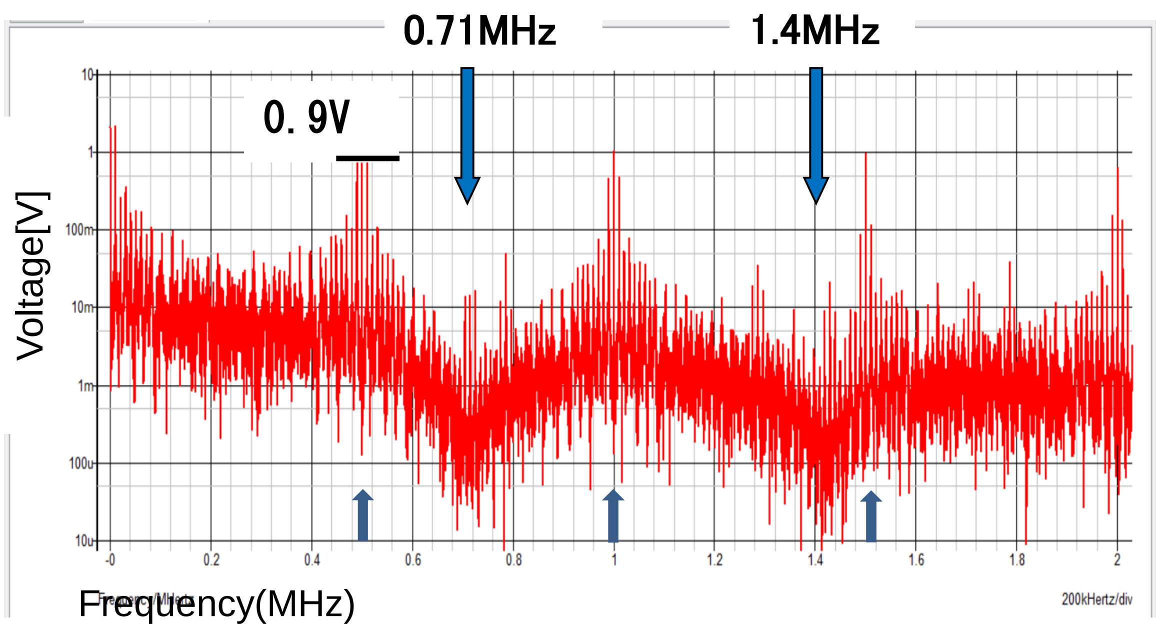
Design clock pulse to determine the notch frequency F_n



Pulse widths of the coding pulses

$$F_n \cong N \times \frac{1}{(W_H - W_L)} \quad [N = 1,2,3,\cdots,n]$$
$$= N \times \frac{1}{1.6\mu s - 0.2\mu s} = 0.71\text{MHz}$$

★manually set W_L and W_H (without feedback)



PWM signal spectrum using PWC control

OUTLINE

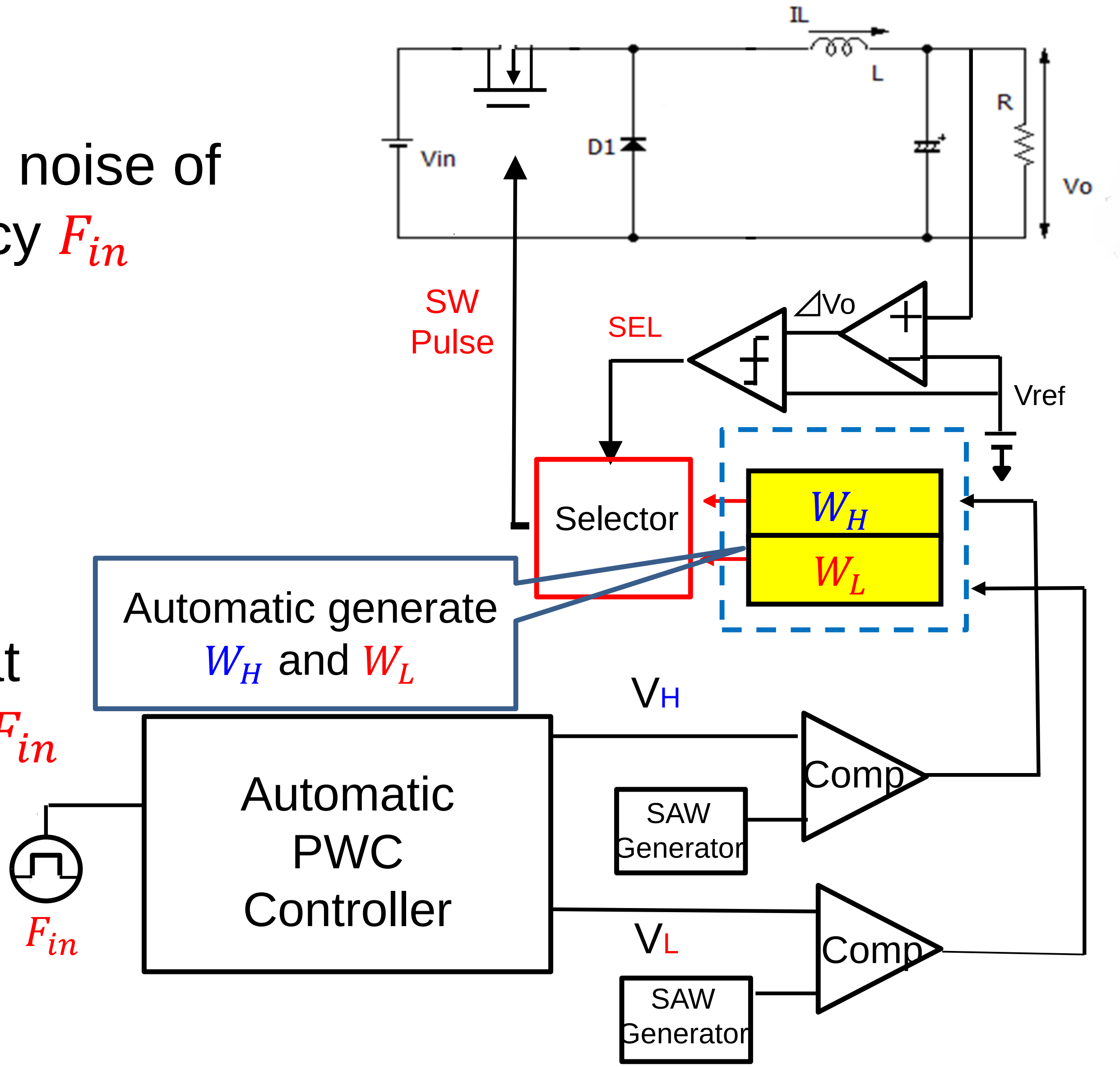
Automatic PWC Controller

Objective

Reduction generate noise of receive frequency F_{in}

Method

PWC control generate notch at receive frequency F_{in}



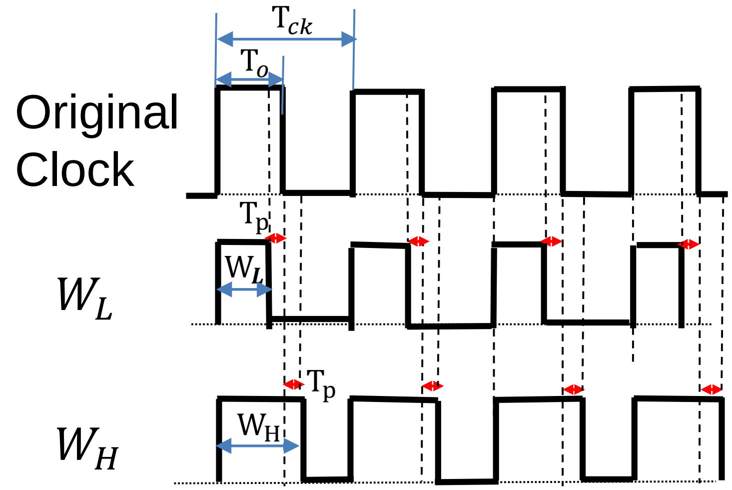
PWC Pulse with Clock Frequency F_{ck} and Notch Frequency F_n

The relationship between F_n and F_{ck}

$$NF_{ck} < F_n < (N+1)F_{ck}$$

Optimal

$$F_n = (N + 0.5)F_{ck}$$



Timing Chart

The relationship between F_n and PWC

$$F_n \cong N \times \frac{1}{(W_H - W_L)}$$

When N =1

$$T_n \cong (W_H - W_L)$$

W_H and W_L

Generated at the center of the original clock

$$T_o = D_o \times T_{ck} = \frac{V_o}{V_{in}} \times T_{ck}$$

$$W_L = T_o - T_p$$

$$W_H = T_o + T_p$$

$$T_n = W_H - W_L = 2 \times T_p$$

Automatic Pulse Generation

Generate T_{ck} from T_{in} using

F_{in}=(N+0.5) · F_{ck}

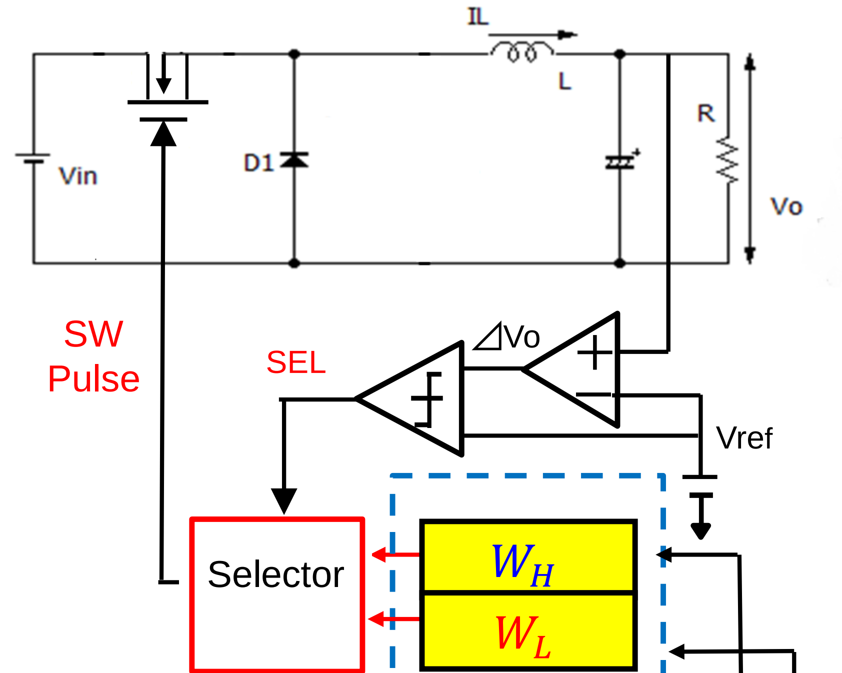
T_{ck}=(N+0.5) · T_{in}

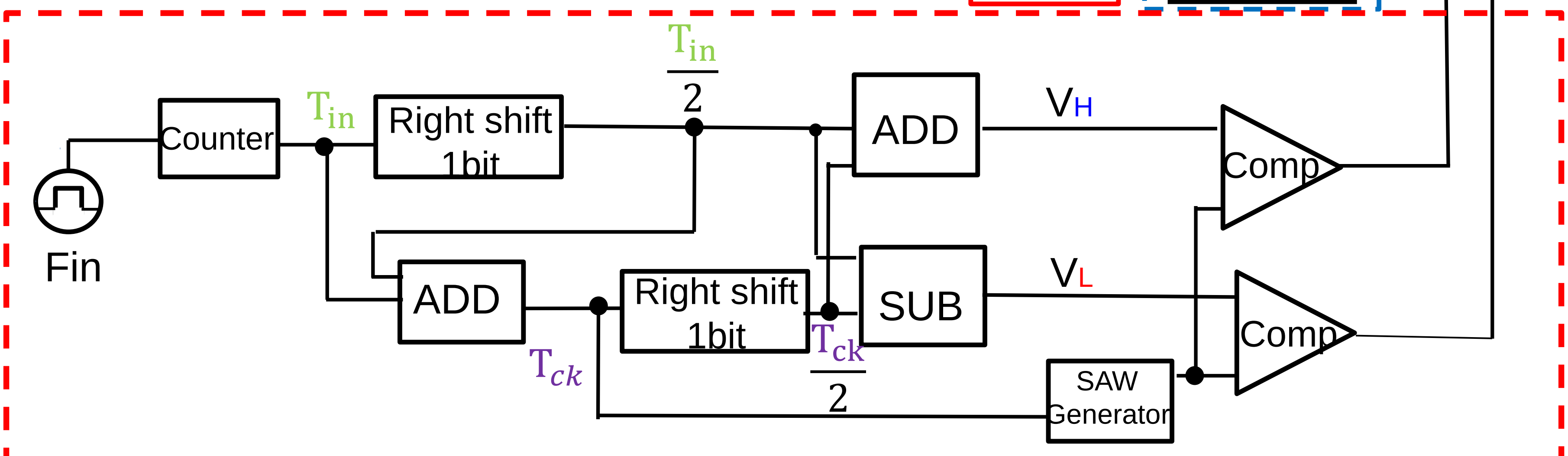
$$W_L = T_o - T_p = D_o \times T_{ck} - \frac{1}{2} T_{in}$$

$$W_H = T_o + T_p = D_o \times T_{ck} + \frac{1}{2} T_{in}$$

$$T_n = 2 \times T_p$$

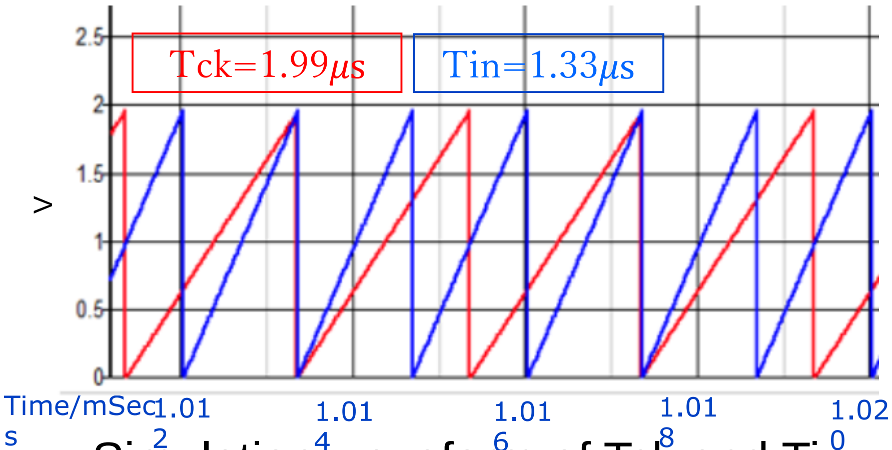
D_o=0.5 N=1 situation



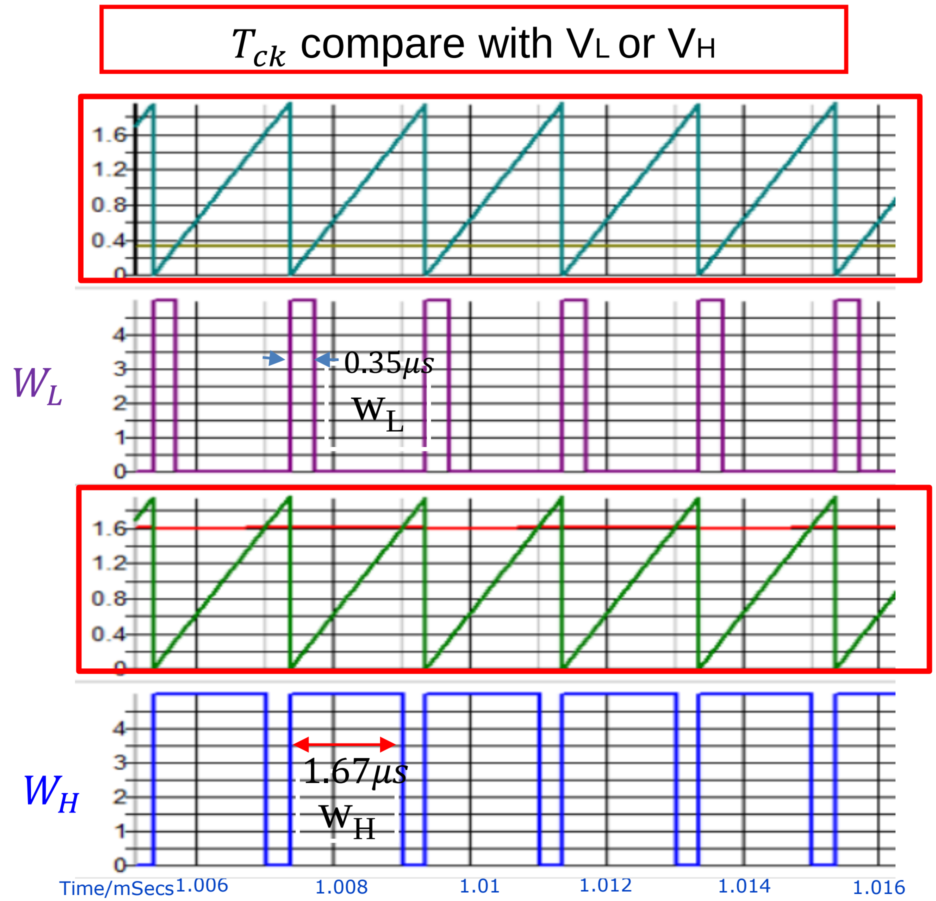


Simulation Waveforms of W_H, W_L Generation

$F_{in} = 750kHz$ ➡ Automatic generated $F_{ck} = 500kHz$



Simulation waveform of Tck and Tin



Simulation waveform of W_H and W_L

Theoretical formula

$W_H = 1.66\mu s$
$W_L = 0.32\mu s$

Experimental result

$W_H = 1.67\mu s$
$W_L = 0.35\mu s$

Well matched

Noise Spectrum of PWC Signal

$$F_{in} = (N + 0.5)F_{ck}$$

N=1 Best position : Fck ＜ Fn ＜ 2Fck

Fin=750kHz ⇒Fck=500kHz （ W_H=1.66μs, W_L=0.32μs）

◎Condition

Buck DC-DC converter

V_{in} ：10V

V_{out} ：5.0V

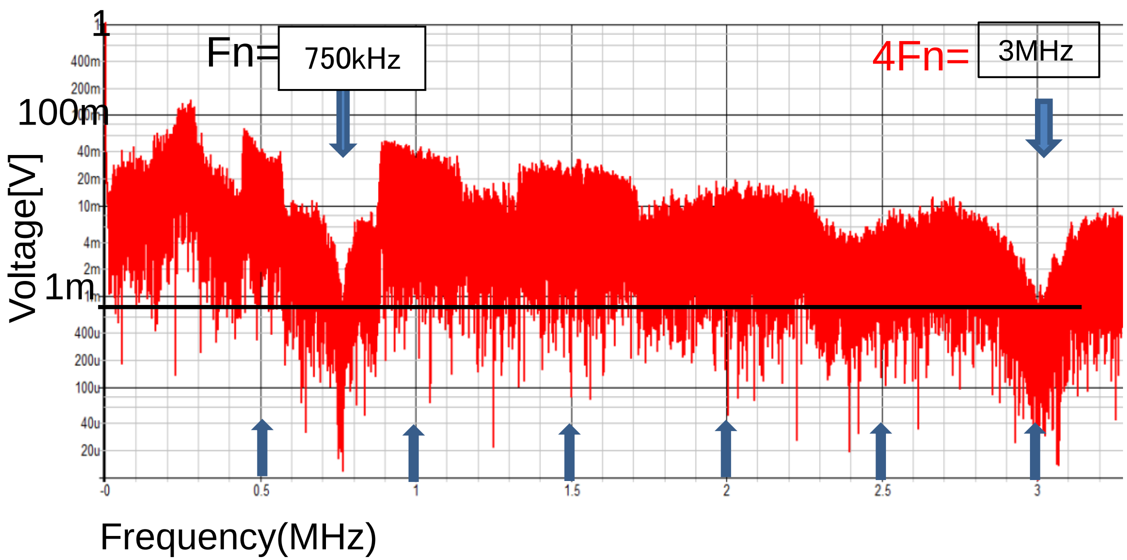
L ：200 μ H

C ：470 μ F

I_{out} ：0.25A

◎Result

Fn=750kHz

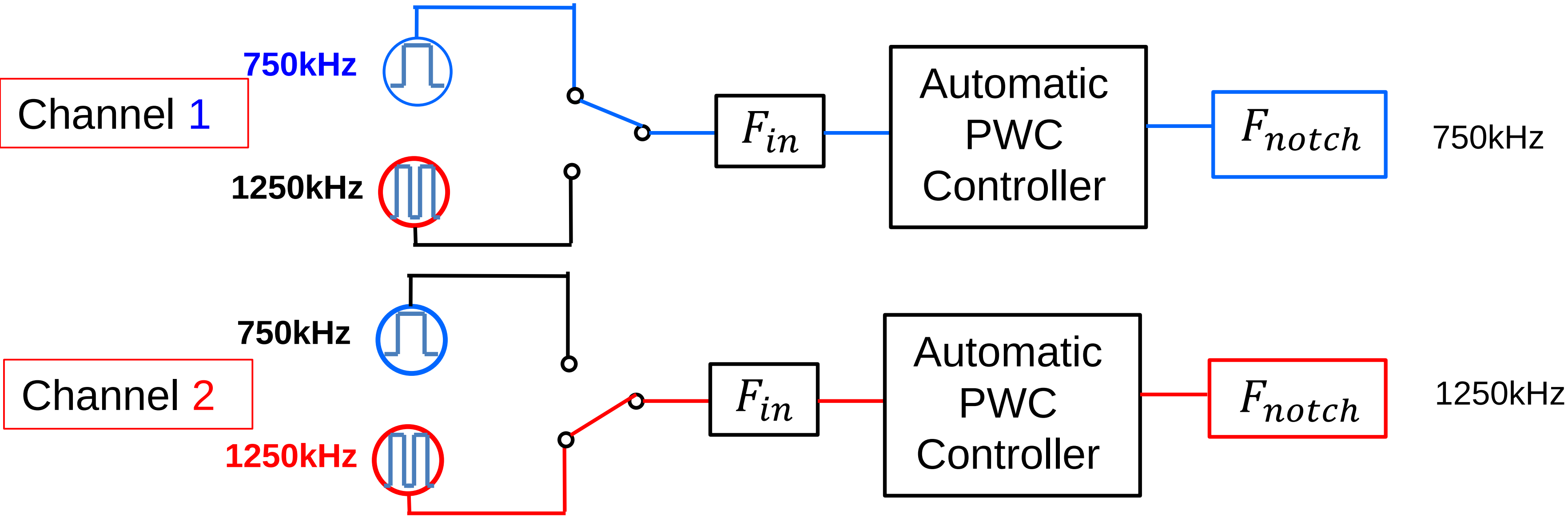


Simulated spectrum with EMI reduction

Assume to suppress influence on AM in 750kHz

$F_{in} = 750kHz \Rightarrow F_{notch} = 750kHz$

Automatic PWC Controller



★ When F_{in} change, F_{ck}, W_H & W_L automatically change

Fck=Fin･(2/3), W_H, W_L = Do･Tck±Tin/2 (when Do=0.5)

Fin1=750kHz ⇒ Fck=Fin･(2/3)=500kHz
Tck= 2.0 us, W_H, W_L = 1.00us ± 0.67us

Fin2=1,250kHz ⇒ Fck=Fin･(2/3)=833kHz
Tck= 1.2 us, W_H, W_L = 0.60us ± 0.40us

Automatic Notch Frequency Shift

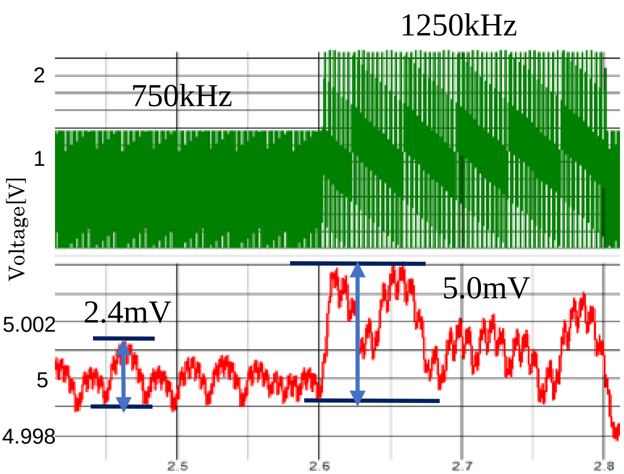
- Step response with input frequency change
  Change F_{in} to $750kHz$ and $1250kHz$ at every 1 sec

∗ Output voltage ripple:

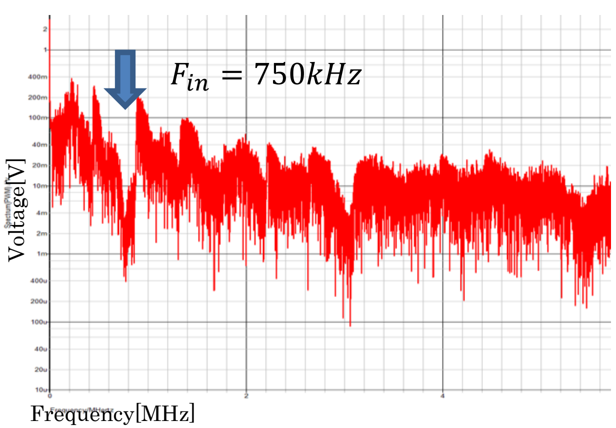
・Stable output voltage ripple: ⊿Vo=2.4mVpp@Io=0.5A

・Overshoot/undershoot : ⊿Vs=5.0mV @Fin=*750k⇔1,250kHz*

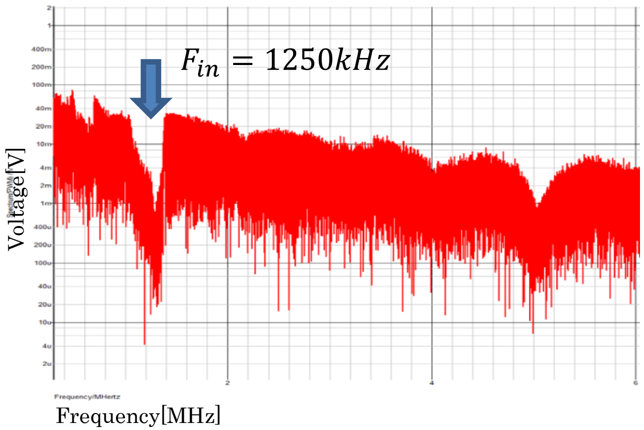
∗ Simulated Spectrum of PWC signal:
(Left) Fin =750kHz, (Right) Fin =1,250kHz



Transient response with F_{in} change



Spectrum in $F_{in} = 750kHz$ situation



Spectrum in $F_{in} = 1250kHz$ situation

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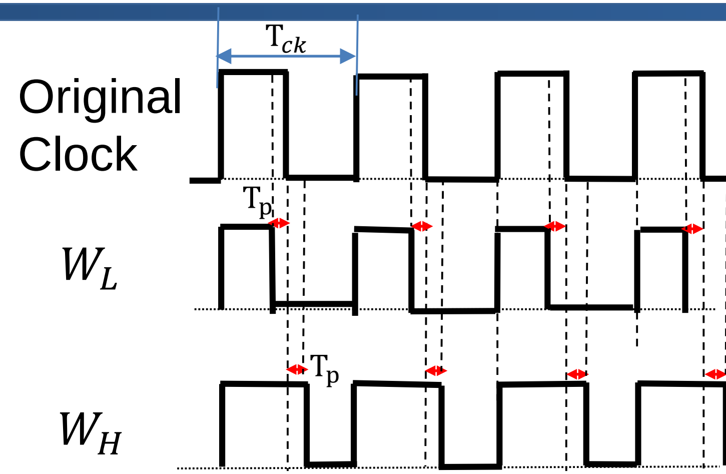
Necessity of Conversion Voltage Ratio Analysis

Conversion voltage ratio : $D_o = \frac{V_o}{V_i}$

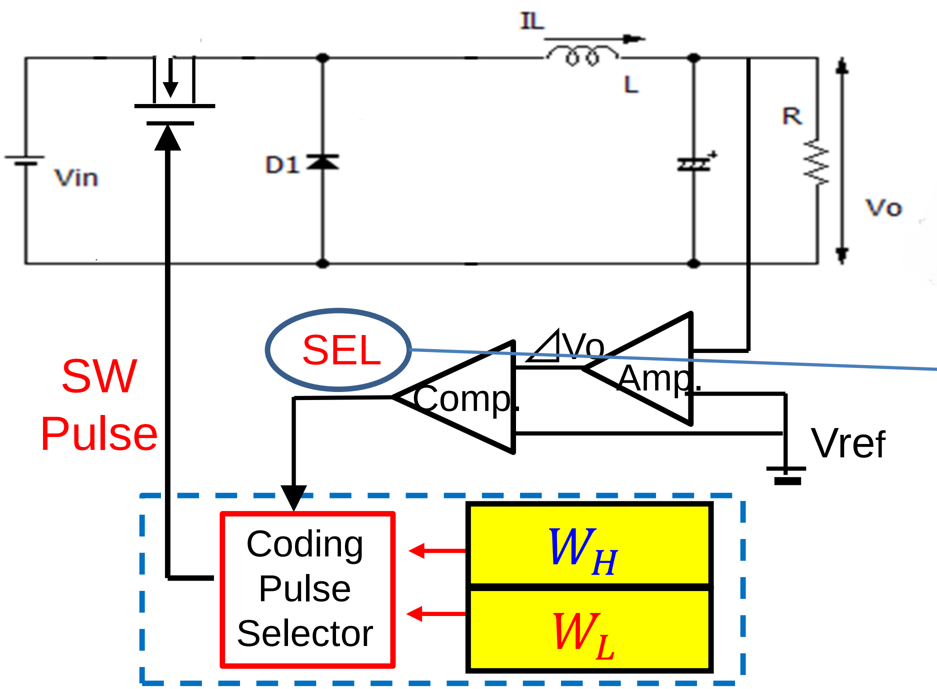
Duty of SEL signal (high and low ratio) : D_s

The duty of W_H: $D_H = \frac{W_H}{T_{ck}}$

The duty of W_L: $D_L = \frac{W_L}{T_{ck}}$



Timing Chart



Cause of D_o shift

① D_o shift $\Rightarrow D_o' = D_o + \Delta D$

② $\Delta D_H = D_H - D_o \neq D_o - D_L = \Delta D_L$

When D_o is accurate

Duty of SEL signal D_s will be balance ⇒0.5

Average voltage of SEL signal will be $\frac{V_{cc}}{2}$

When D_o shift

Duty of SEL signal D_s will be affected

Influence: output voltage ripple

Conversion Voltage Ratio Shift Situation

Cause of D_o shift

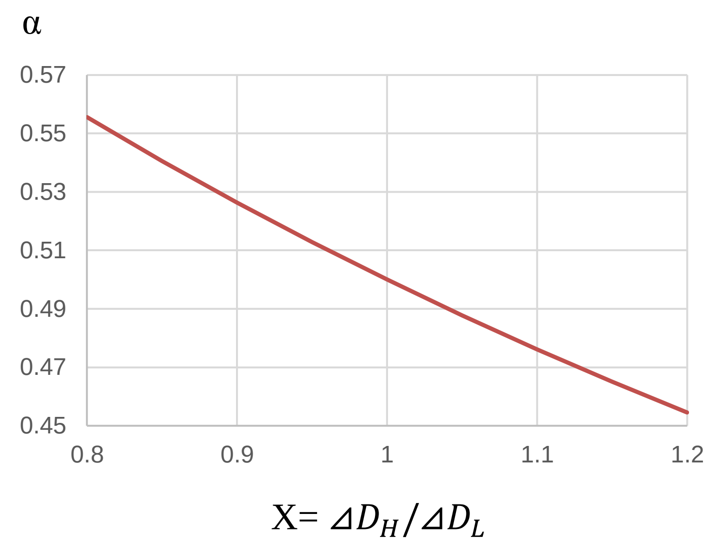
① D_o shift $\Rightarrow D_o' = D_o + \Delta D$

② $\Delta D_H = D_H - D_o \neq D_o - D_L = \Delta D_L$

$$W_H = D_o T_{ck} + \frac{T_{in}}{2} \Rightarrow D_H = (Do + \varDelta Do) + \varDelta D_H$$

$$W_L = D_o T_{ck} - \frac{T_{in}}{2} \Rightarrow D_L = (Do + \varDelta Do) - \varDelta D_L$$

Here $\varDelta D_H = \varDelta D_L = (\mathrm{Tin}/2)/\mathrm{Tck} = 1/3$



Relationship between $\varDelta D_H/\varDelta D_L$ and α

∗ Average of SEL Duty :

$$D_A(\alpha) = \alpha\, D_H + (1-\alpha)\, D_L$$
$$= \alpha\,(\mathrm{Do} + \varDelta Do + \varDelta D_H) + (1-\alpha)(Do + \varDelta Do - \varDelta D_L)$$
$$= (Do + \varDelta Do) + \alpha \varDelta D_H - (1-\alpha)\, \varDelta D_L$$

∗ According above equation, Let SEL duty: $D_A(\alpha)$ =0.5

$\varDelta Do = 0$ & $\alpha \varDelta D_H - (1-\alpha)\, \varDelta D_L = 0$

$\Longrightarrow \varDelta D_H = \varDelta D_L$ & α =0.5

Cause of D_o shift

① D_o shift $\Rightarrow D_o' = D_o + \Delta D$

② $\Delta D_H = D_H - D_o \neq D_o - D_L = \Delta D_L$

⇩

A little affected

∗ In $\Delta D_H \neq \Delta D_L$ situation

To be $\alpha \varDelta D_H - (1-\alpha)\, \varDelta D_L = 0$

α=1/(1+x) Here $x = \varDelta D_H/\varDelta D_L$

Only in this ratio, SEL duty changes, like the right graph

Relationship between Average of SEL Duty D_A (α) and Output Ripple

∗ Cause of D_o shift

① D_o shift ⇒ $D_o' = D_o + \Delta D$

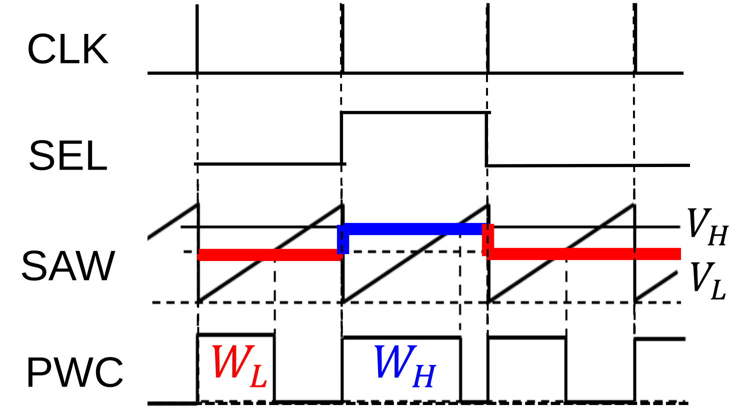
② $\Delta D_H = D_H - D_o \neq D_o - D_L = \Delta D_L$

∗ Automatic generation of W_H and W_L

$$W_H = D_o T_{ck} + \frac{T_{in}}{2} \Rightarrow D_H = Do + 1/3$$

$$W_L = D_o T_{ck} - \frac{T_{in}}{2} \Rightarrow D_L = Do - 1/3$$

$$\because \quad (\mathrm{Tin}/2)/\mathrm{Tck} = 1/3$$



Timing Chart

∗ Duty of SEL signal : $D_S = \alpha$

∗ Average of SEL Duty :

$$D_A(\alpha) = \alpha D_H + (1-\alpha) D_L$$
$$= \alpha (Do + 1/3) + (1-\alpha)(Do - 1/3)$$
$$= Do + (2\alpha - 1)/3$$

∗ To set $D_A(\alpha) = Do$, α should be 0.5.

Then, average voltage of SEL signal will be $\frac{V_{cc}}{2}$.

◆ When Vin changes, actually D'_o shifts after the circuit has been designed

⇓

$$D'_o = V_o/V_i(1+\beta) \fallingdotseq (1-\beta) \cdot V_o/V_i = (1-\beta) \cdot D_o$$

⇓

Influence: output voltage ripple

Influence of Input Voltage Change

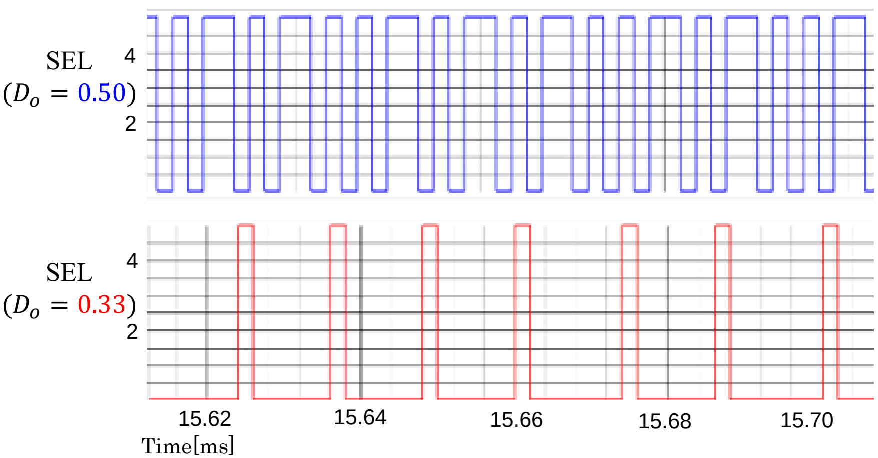
$$D_o = \frac{V_o}{V_i}$$ ⇒ Change Vi = 10V / 15V / 18V ⇒

$$D_{o1} = \frac{V_o}{V_i} = \frac{5}{10} = 0.5$$

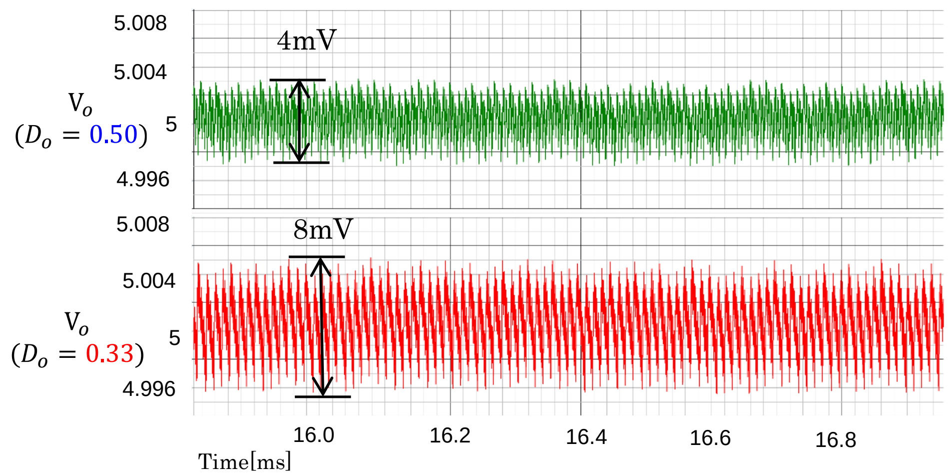
$$D_{o2} = \frac{V_o}{V_i} = \frac{5}{15} = 0.33$$

⇒

$$D_{o3} = \frac{V_o}{V_i} = \frac{5}{18} = 0.28$$



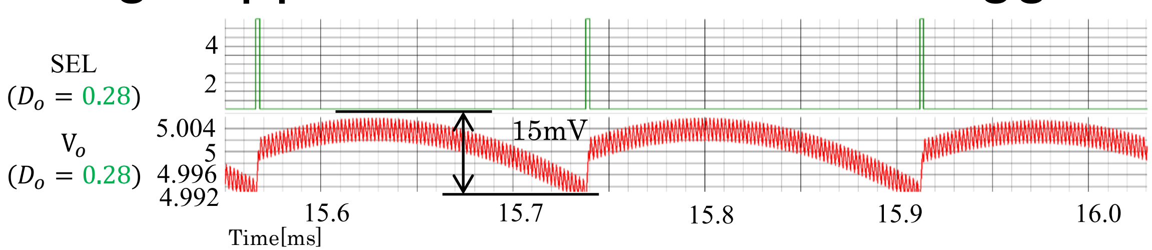
Waveforms of select signal



Change of output ripple

★ D_o shift⇒output voltage ripple effected & become bigger

Ex. D_{o3}=0.28
⊿Vo= 15mVpp



D_o Setting Method

The relationship between T_{in} and D_o （N=1 ）

$$D_oT_{ck} + \frac{T_{in}}{2} < T_{ck}$$

$$D_oT_{ck} - \frac{T_{in}}{2} > 0$$

$$T_{ck} = 1.5T_{in}$$

$$\Rightarrow \quad 0.33 < D_o < 0.67$$

Consider about:

$$D_{o3} = \frac{V_o}{V_i} = \frac{5}{18} = 0.28 \Rightarrow \begin{cases} D_H = D_{o3} + \varDelta D \\ D_L = D_{o3} - \varDelta D < 0 \\ \Rightarrow D_L = 0 \end{cases}$$

$$D_{o4} = \frac{V_o}{V_i} = \frac{5}{7} = 0.71 \Rightarrow \begin{cases} D_H = D_{o4} + \varDelta D > 1 \\ \Rightarrow D_H = 1 \\ D_L = D_{o4} - \varDelta D \end{cases}$$

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Conclusion and Future Work

Conclusion

For EMI problem handling in switching power converter

- Developed pulse coding control in order to generate notch characteristics at desired frequency
- Automatic generate the F_{notch} from F_{in}
- Conversion voltage ratio D_o between 0.33 and 0.67 can let the select signal keep in balance

Future work

- Implementation of automatic PWC control switching converter

Thank you for Listening

Q&A

Q: According to the spectrum of PWC signal, the frequency of F_n and $4F_n$ can generate notch, why does $2F_n$ and $3F_n$ not generate notch?

A: I do not know the reason yet. I am thinking about this question.

Q: In your research, you change frequency from F_{in1} to F_{in2}, in this time, it will create notch?

A: The notch was created at input frequency. If we input F_{in1}, the notch will create at F_{in1}, if the input is F_{in2}, the notch will create at F_{in2}. If the communication of channel 1 is not good, the frequency of channel 2 is switched. At this time, the clock frequency and the coding pulse width are switched so that the notch frequency is automatically switched to the reception frequency. An indication of frequency switching and output ripple was displayed to indicate transient response.