第8回 電気学東京支部会栃木・群馬支所合同研究発表会
群馬大学　桐生キャンパス

Mar. 1　2018 (Thu)

# Automatic High Frequency Notch Generation in Noise Spectrum of Switching Converters with Pulse Coding Method

Yifei Sun, Yi Xiong, Nobukazu Tsukiji, Yasunori Kobori, Haruo Kobayashi
Gunma University
Kobayashi Laboratory
t172d004@gunma-u.ac.jp

群馬大学
GUNMA UNIVERSITY

Kobayashi Laboratory

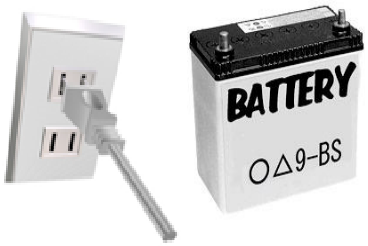
# OUTLINE

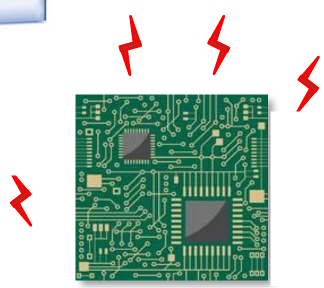
- Introduction & Objective
- Conventional Switching Converters
- Pulse Coding Method in Switching Converter
- Automatic PWC Control
    - Relationship with the Clock frequency and the Notch frequency
    - Direct generation of clock pulse from input frequency
    - Simulated Noise Spectrum of PWM Signal
- Conclusion and future work

# OUTLINE

- Introduction & Objective
- Conventional Switching Converters
- Pulse Coding Method in Switching Converter
- Automatic PWC Control
  - Relationship with the Clock frequency and the Notch frequency
  - Direct generation of clock pulse from input frequency
  - Simulated Noise Spectrum of PWM Signal
- Conclusion and future work

# Research Background



EMI

Switching converters

Supply many kinds of voltage by switching power

Power of switching converter
has become large

Switching noise has strongly spread
in wide frequency range

Important to reduce switching noise
by decreasing main spectrum level

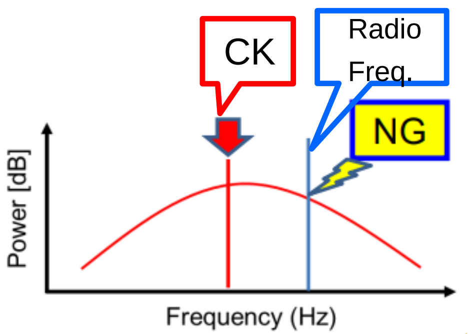
EMI:Electro-Magnetic Interference

# Research Objective

Reduce clock noise by spread spectrum
with shaking clock phase

Trouble

Noise of clock frequency is spread




Some electronic devices would not like to be affected at special frequency noise

Radio receiver

Research Objective

Spread spectrum with both EMI[1] reduction and control the diffusion of noise

[1]EMI: Electro-Magnetic Interference

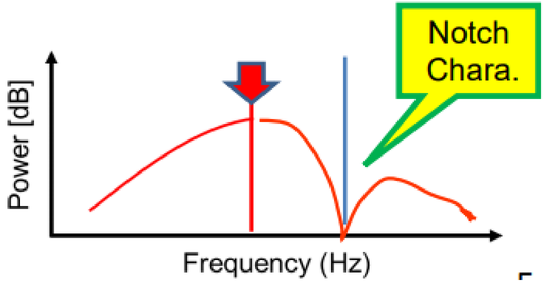
# Research Summary

## Proposed method

Spread spectrum method using pulse coding

Design modulation circuit
in order to generate notch frequency automatically

## Achievement




①Reduction of EMI generated from clock
②Noise removal at specific frequency
③Automatic generation of notch frequency

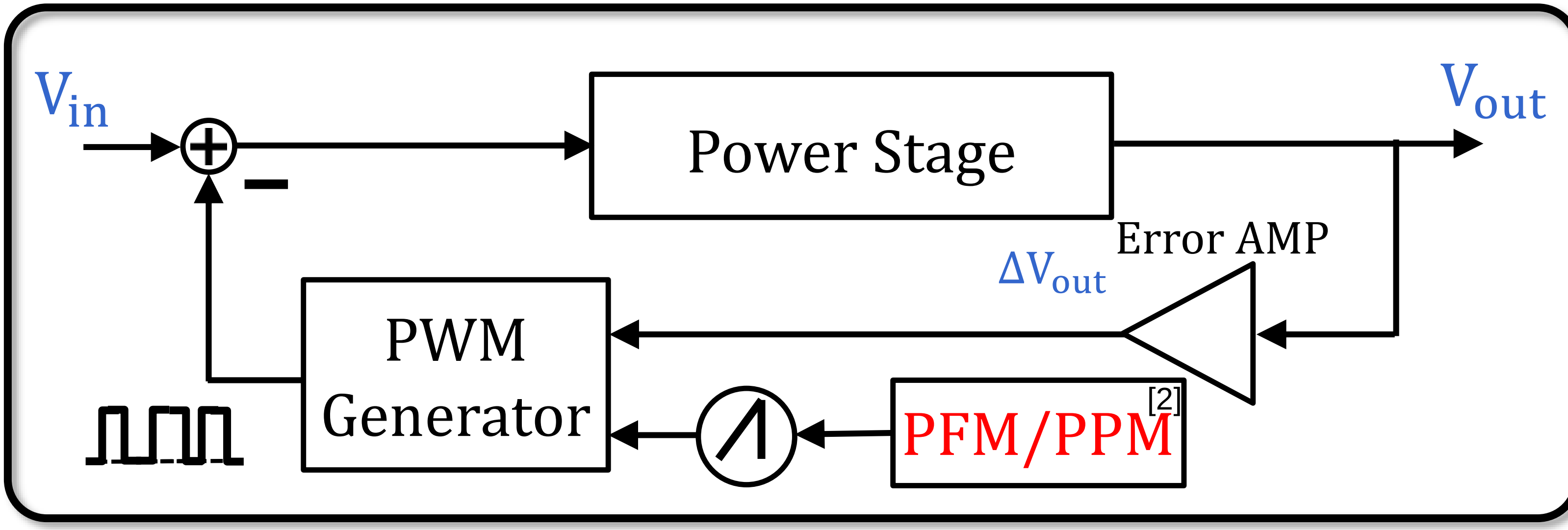
# OUTLINE

- Introduction & Objective
- Conventional Switching Converters
- Pulse Coding Method in Switching Converter
- Automatic PWC Control
  - Relationship with the Clock frequency and the Notch frequency
  - Direct generation of clock pulse from input frequency
  - Simulated Noise Spectrum of PWM Signal
- Conclusion and future work

# Conventional Switching Converter with Spread Spectrum

## Spread Spectrum

Continuous modulation of periodic clock
⇒Reduction of EMI concentrating on fundamental frequency

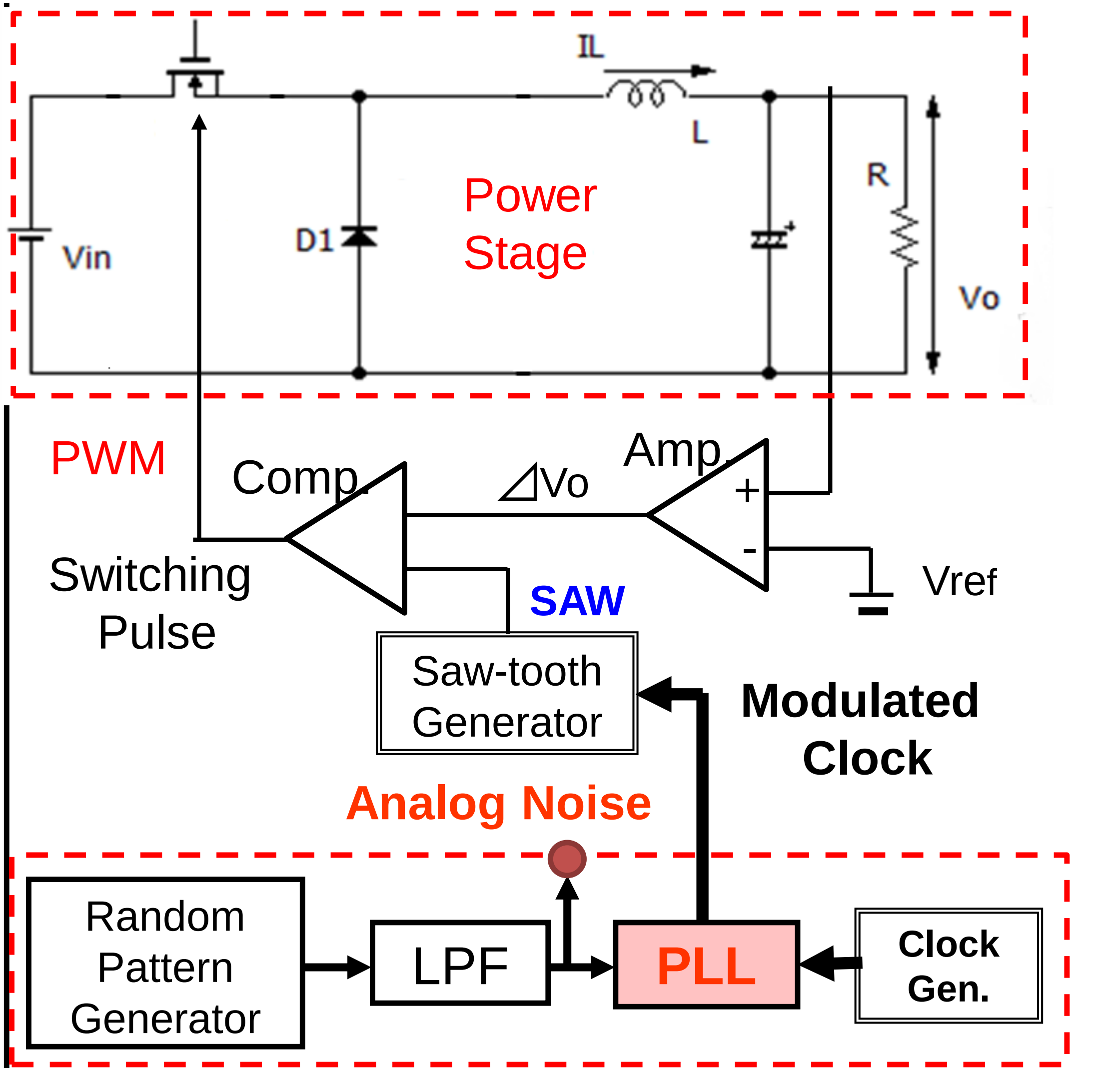



Switching Power

[2] PFM: Pulse Frequency Modulation PPM: Pulse Phase Modulation

# Spread Spectrum for EMI Reduction

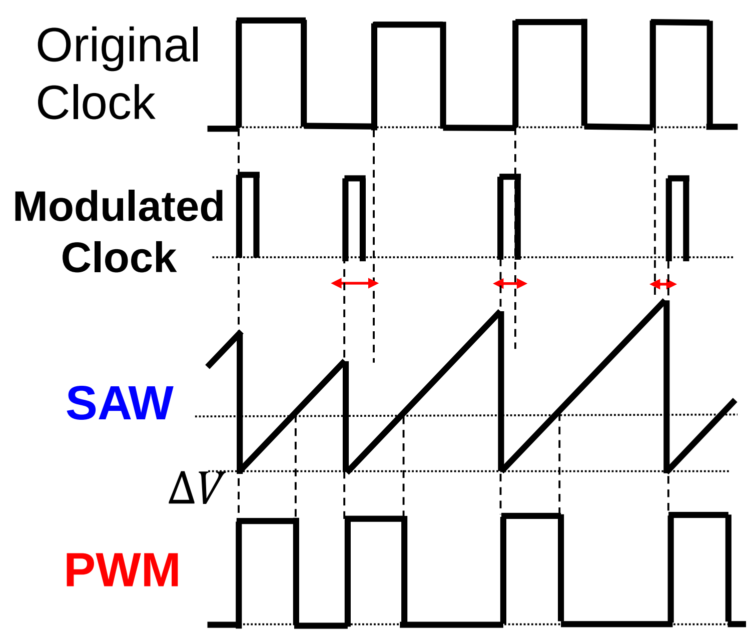
Spread spectrum using pseudo analog noise




Buck converter with modulated clock

To reduce EMI noise, clock pulse is modulated

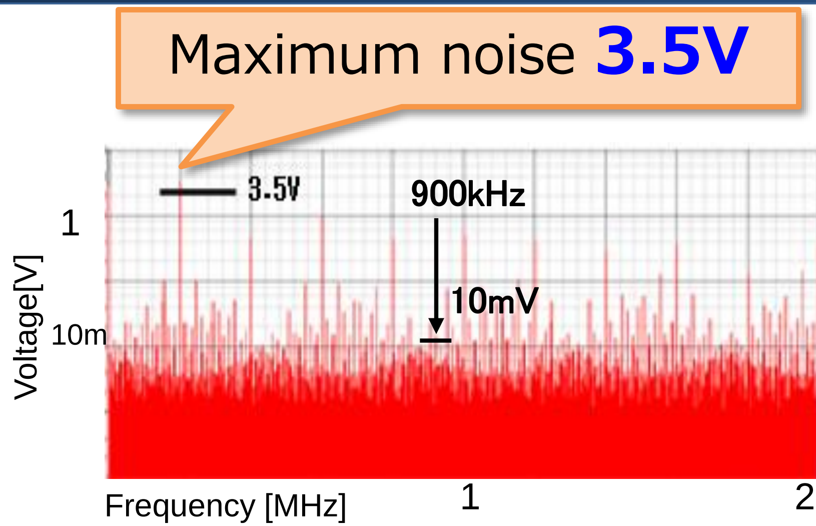
＊ SAW is modulated by shaking phase using analog noise & PLL[3]



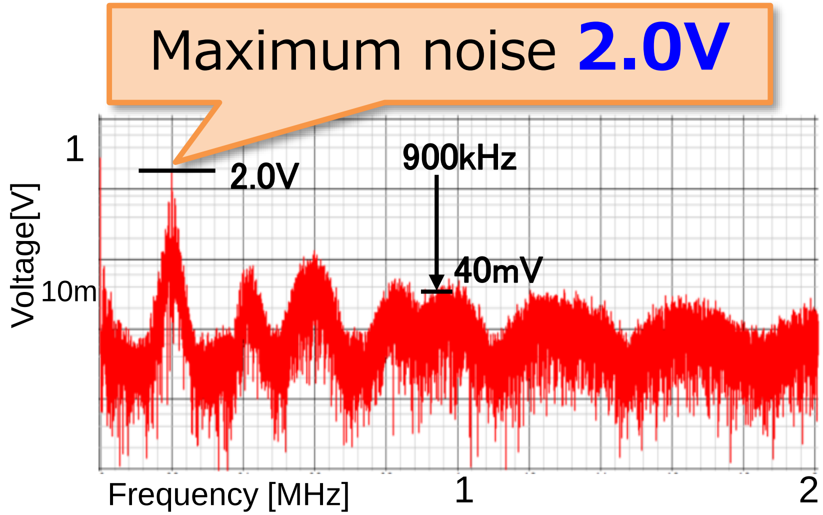

Timing Chart

[3] PLL: Phase Locked Loop

# Spread spectrum for EMI Reduction




PWM signal spectrum without EMI reduction




PWM signal spectrum with EMI reduction

◎Simulation conditions

Input : 12V
Output : 6V
Clock frequency : 200kHz

Without EMI reduction

- Noise is concentrated in basic and harmonic frequencies

With EMI reduction

- Peak level of clock frequency is reduced a lot

⇩

Noise is concentrated by diffusion

⇩

Bottom levels are increased NG

# OUTLINE

- Introduction & Objective
- Conventional Switching Converters
- Pulse Coding Method in Switching Converter
- Automatic PWC Control
  - Relationship with the Clock frequency and the Notch frequency
  - Direct generation of clock pulse from input frequency
  - Simulated Noise Spectrum of PWM Signal
- Conclusion and future work

# Coding Method

## Single coding method

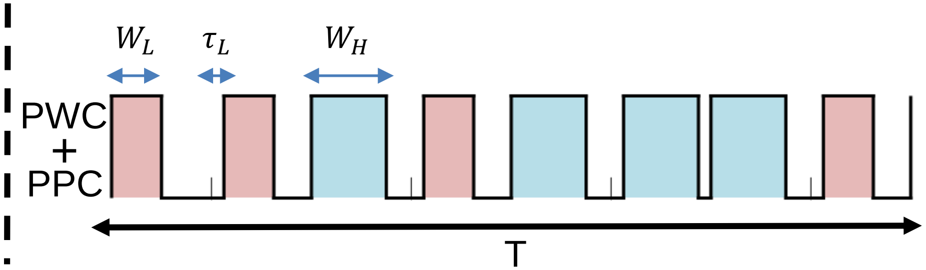
Pulse width · period · position
select one to modulation

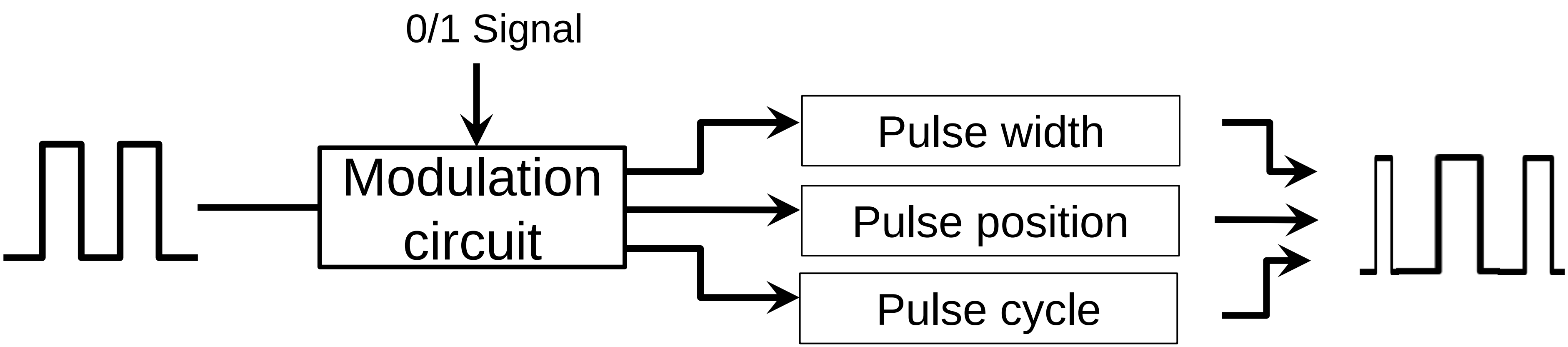
- PWC(Pulse Width coding)method
- PCC(Pulse Cycle coding) method
- PPC(Pulse Phase coding) method

## Complex coding method

Pulse width · period · position
select two to modulation

- PWPC（PWC+PPC） method



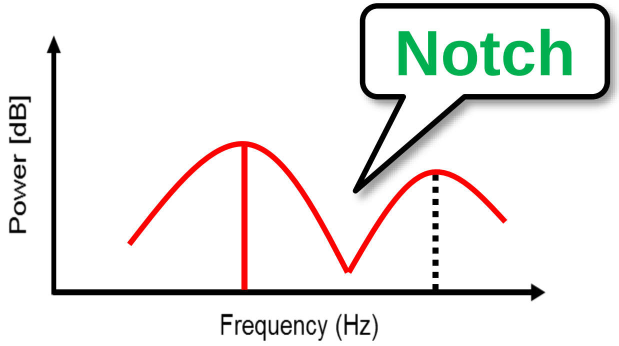




Complex coding method

# Diffuse Noise to Specific Frequency

**Problem**

Noise diffusing uniformly
(using analog modulation)




Using digital modulation

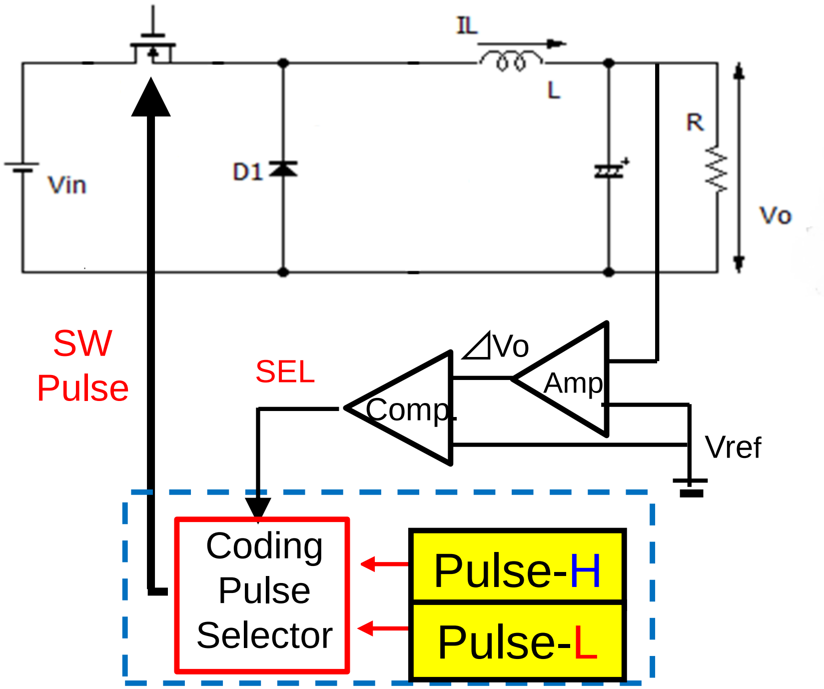
Noise diffuses to specific frequency

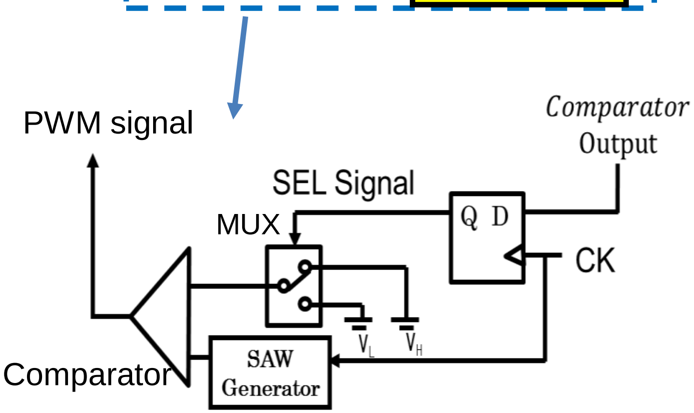
Frequency band where noise does not spread

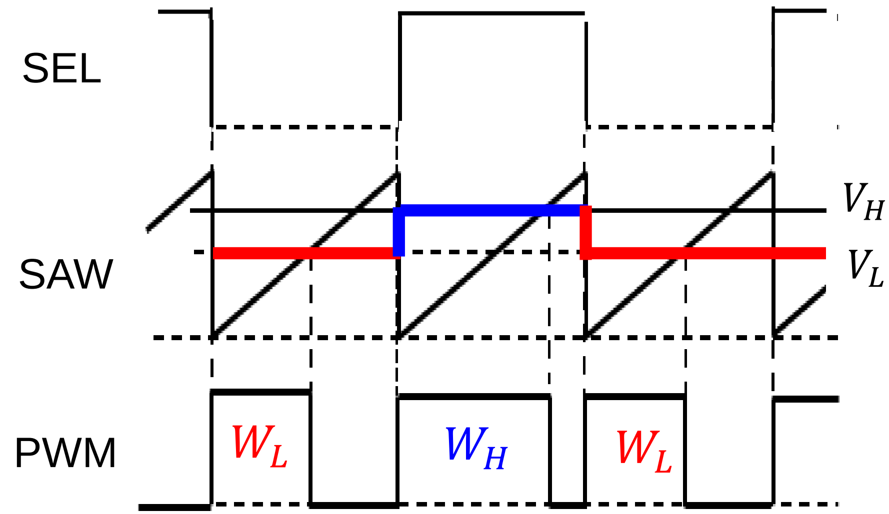
Notch band created in important frequency band

- EMI Reduction
- Control of diffused noise

# Pulse Width Modulation in Switching Converter




## Input High

①SEL: High
②MUX select $V_H$
③Generate pulse with long width in comparator

## Input Low

①SEL: Low
②MUX select $V_L$
③Generate pulse with short width in comparator

★ $D_H > D_o > D_L$

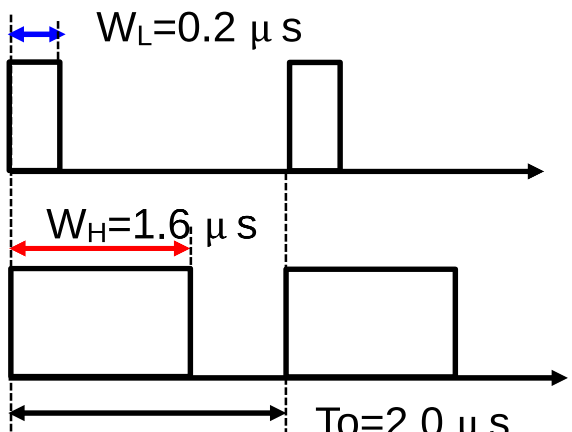
$$D_o = V_o / V_{in}$$

★manually set $W_L$ and $W_H$

# Simulation Result with PWC Control

## ◎ Condition

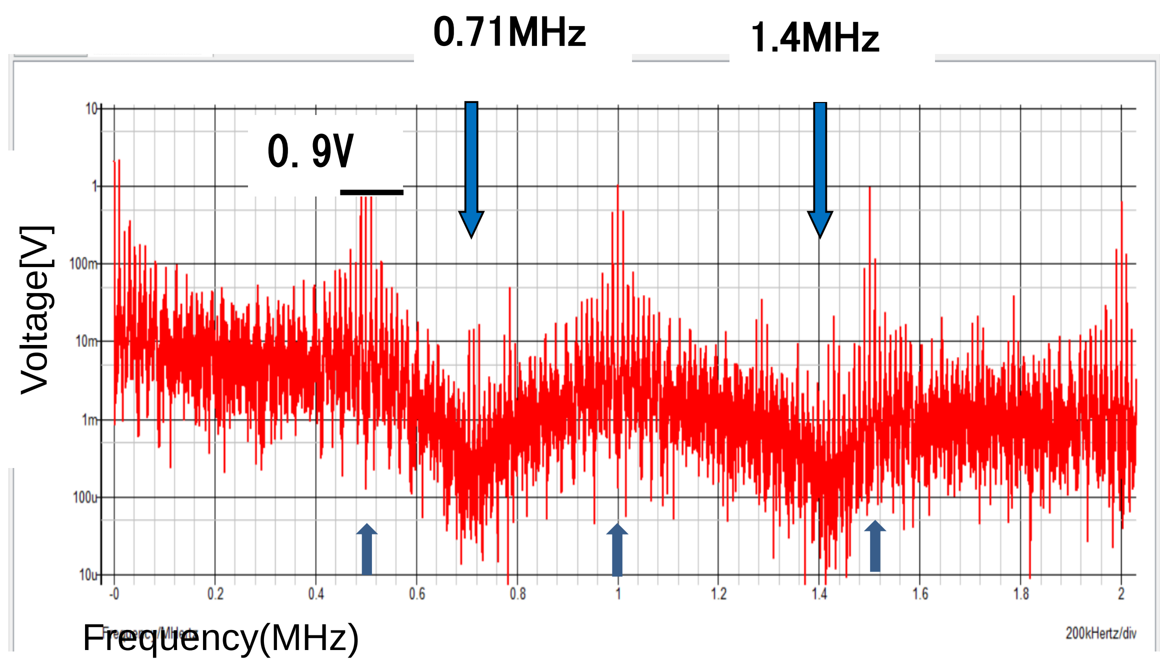
Buck DC-DC converter
$V_{in}$ : 10V
$V_{out}$ : 5V
L : 200 μ H
C : 470 μ F
$I_{out}$ : 0.25A
$f_{ck}$ : 500kHz



Pulse widths of the coding pulses

Design clock pulse to determine the notch frequency

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



PWM signal spectrum using PWC control

# OUTLINE

- Introduction & Objective
- Conventional Switching Converters
- Pulse Coding Method in Switching Converter
- Automatic PWC Control
  - Relationship with the Clock frequency and the Notch frequency
  - Direct generation of clock pulse from input frequency
  - Simulated Noise Spectrum of PWM Signal
- Conclusion and future work

# Automatic PWC Control

Set frequency of radio reception

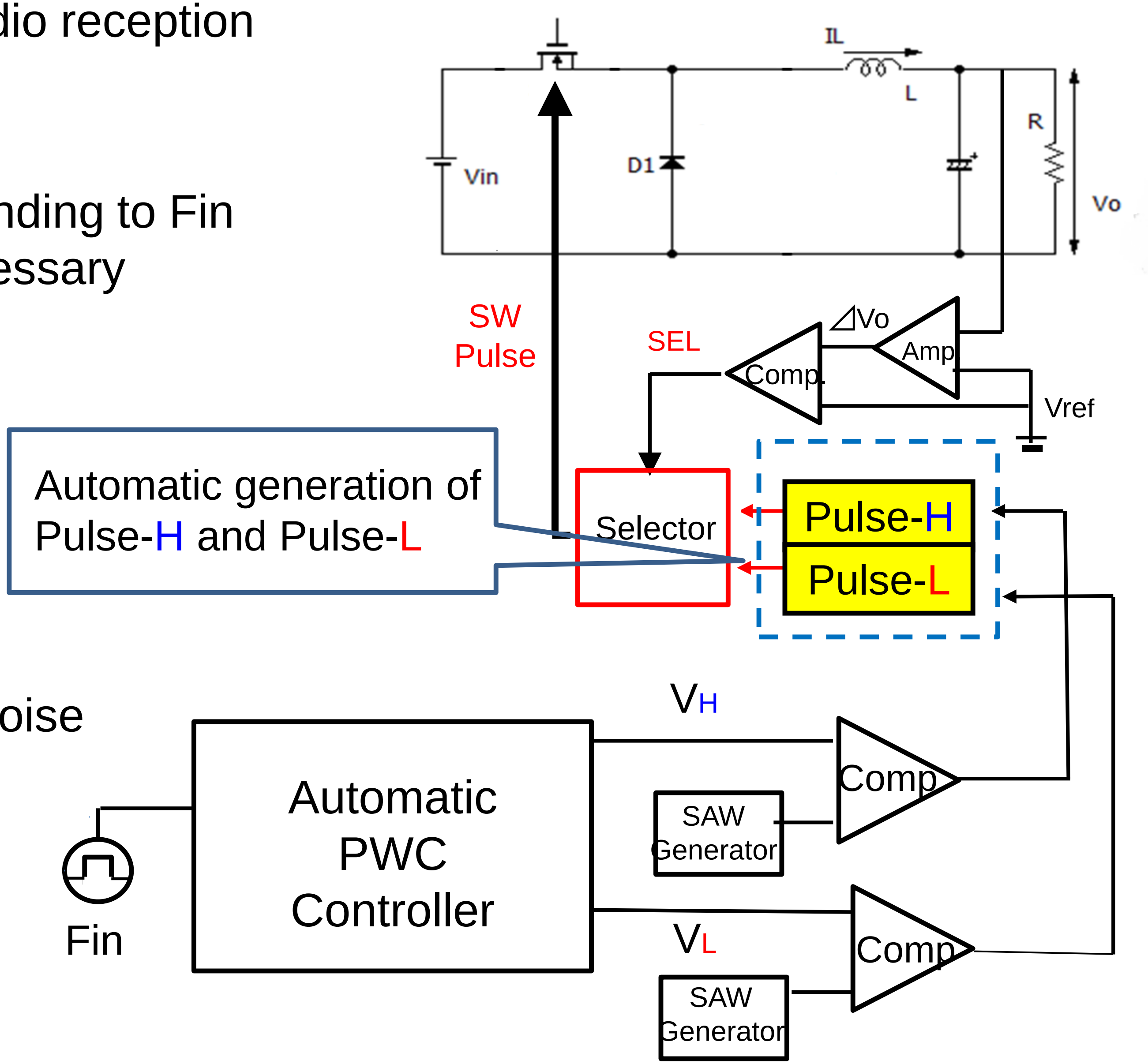
Auto corresponding to Fin change is necessary

Notch frequency

Research object

Control of diffused noise

Radio receiver

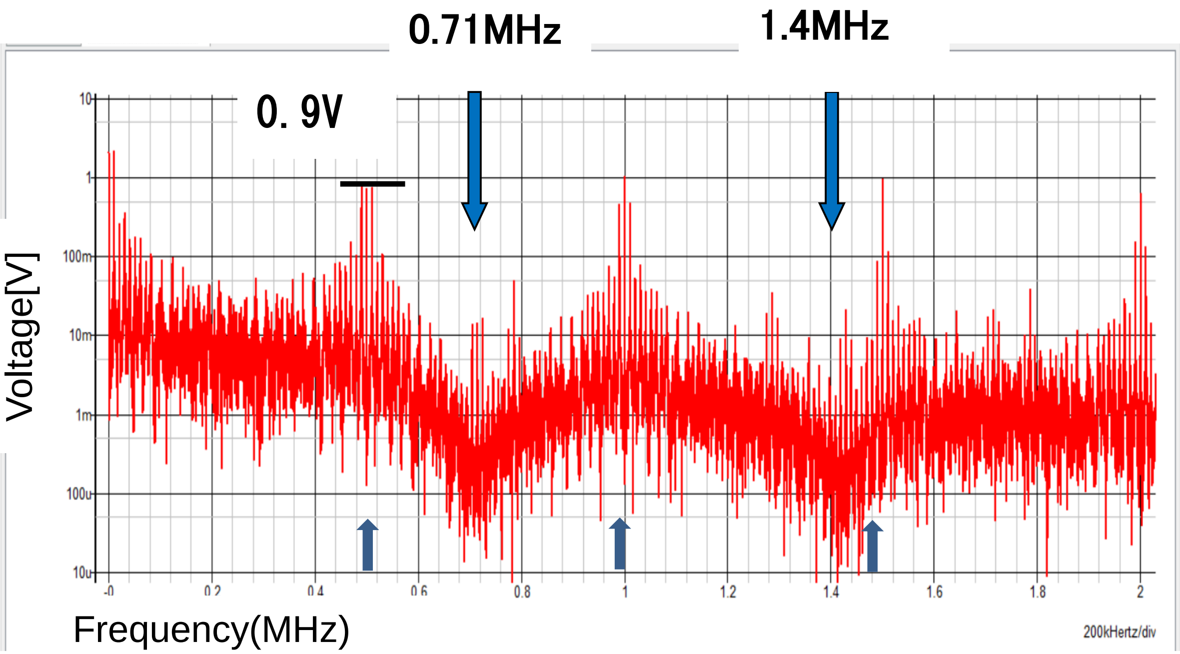


# OUTLINE

- Introduction & Objective
- Conventional Switching Converters
- Pulse Coding Method in Switching Converter
- Automatic PWC Control
  - Relationship between Clock frequency and Notch frequency
  - Direct generation of clock pulse from input frequency
  - Simulated Noise Spectrum of PWM Signal
- Conclusion and future work

# Relationship with Clock and Notch

$F_{ck}$ : 500kHz




PWM signal spectrum using PWC control

Better to generate Fn at middle of Fck

$$F_{ck} < F_n < 2F_{ck}$$

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

Optimal

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

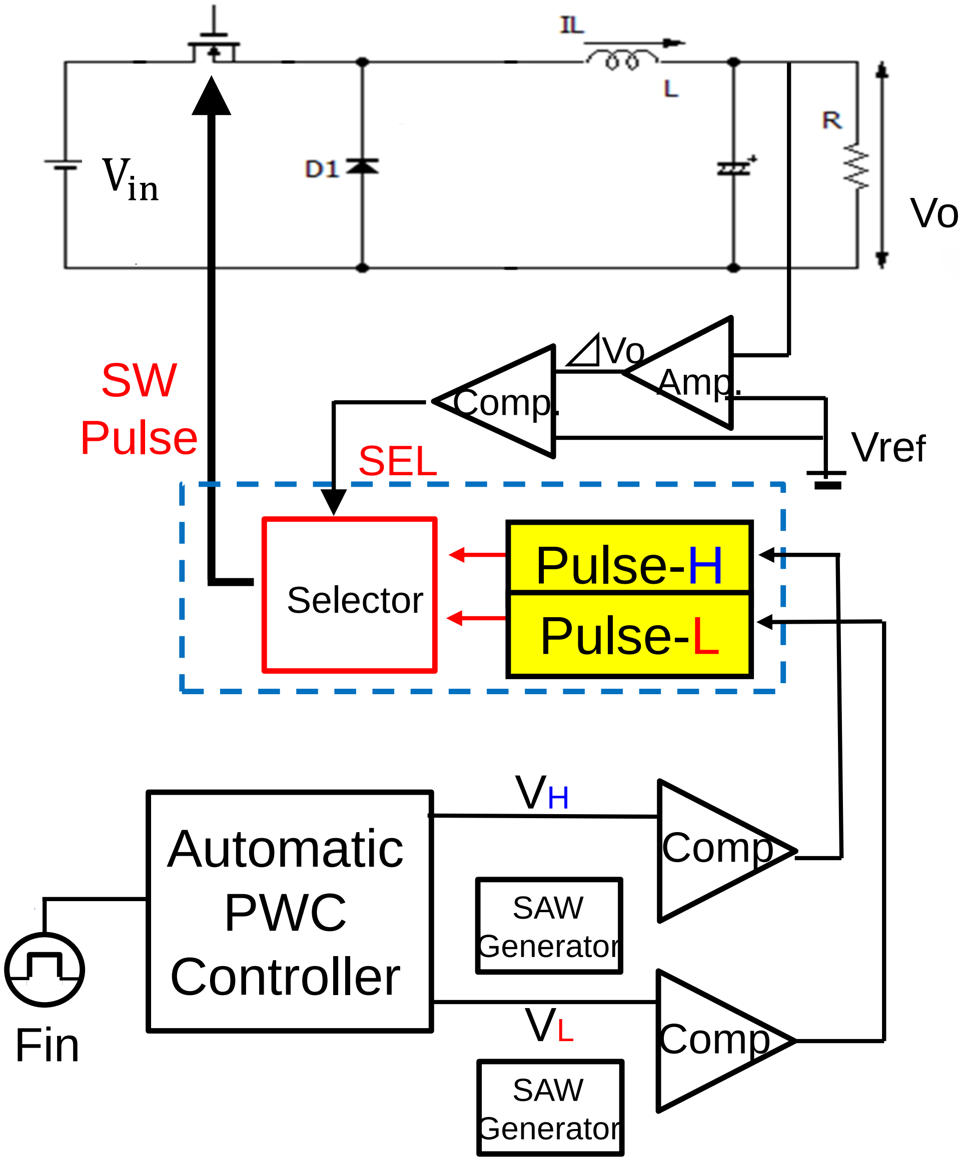
When N=1

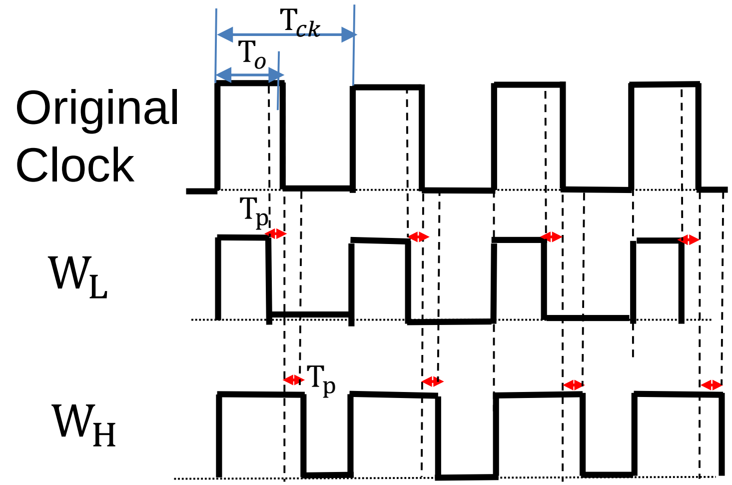
Optimal

$$F_n = 1.5F_{ck}$$

$$\frac{F_n}{3} = \frac{F_{ck}}{2}$$

# Relationship between Pulse-H and Pusle-L




Timing Chart

$$W_L = T_o - T_p$$

$$W_H = T_o + T_p$$

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

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

# OUTLINE

- Introduction & Objective
- Conventional Switching Converters
- Pulse Coding Method in Switching Converter
- Automatic PWC Control
  - Relationship with the Clock frequency and the Notch frequency
  - Direct generation of clock pulse from input frequency
  - Simulated Noise Spectrum of PWM Signal
- Conclusion and future work

# Generating Tck using Direct Calculation

Generate Tck from Tin using:

$F_{in}$=(N+0.5) ・ $F_{ck}$

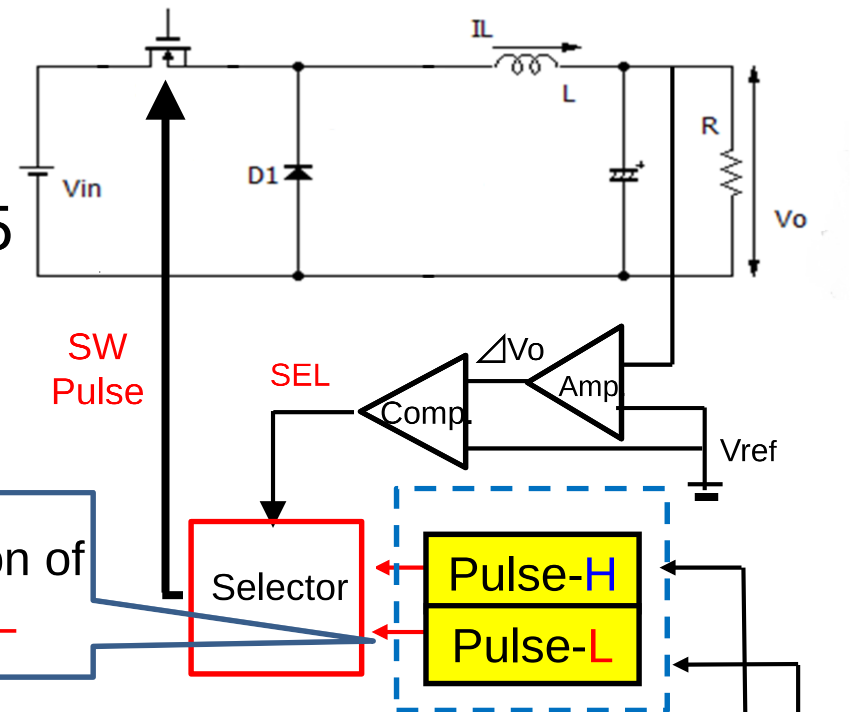
$T_{ck}$=(N+0.5) ・ $T_{in}$   N=1  $D_o$=0.5

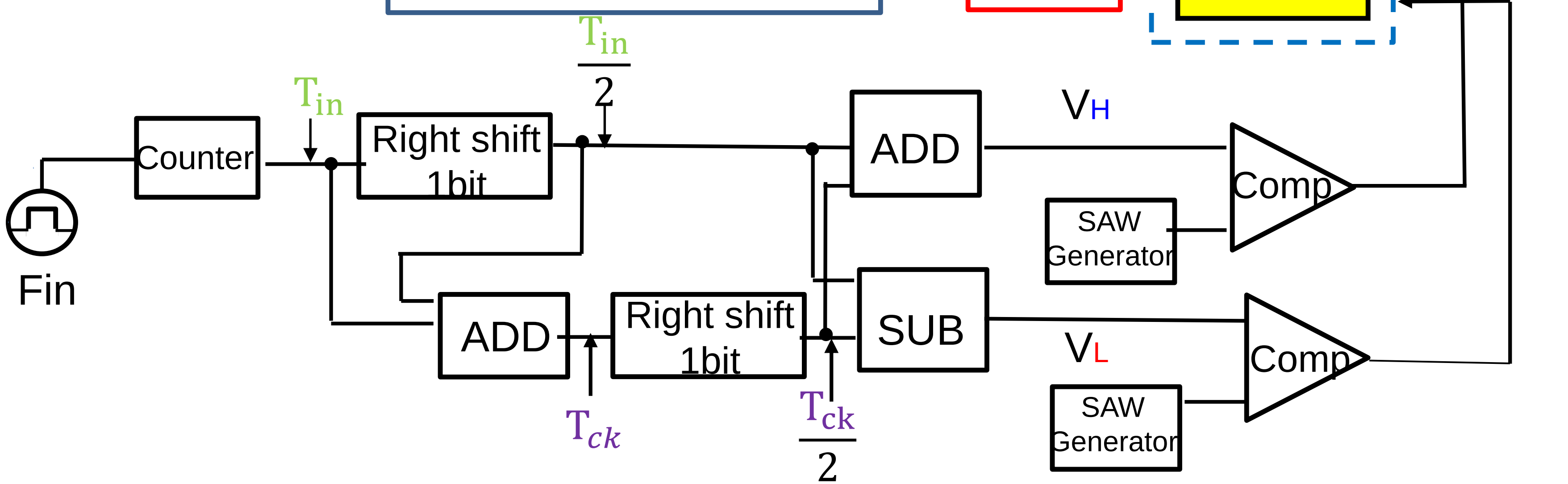
$$W_L = T_o - T_p = D_o \times T_{ck} + \frac{1}{2} T_{in}$$

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

$$T_n = 2 \times T_p$$

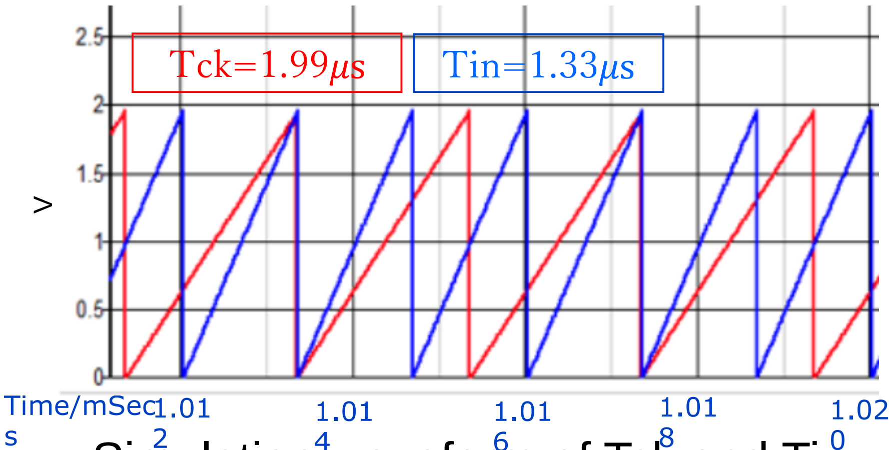
Automatic generation of Pulse-H and Pulse-L



# Simulation Waveforms of $W_H$, $W_L$ Generation

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




Simulation waveform of Tck and Tin

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

Theoretical formula

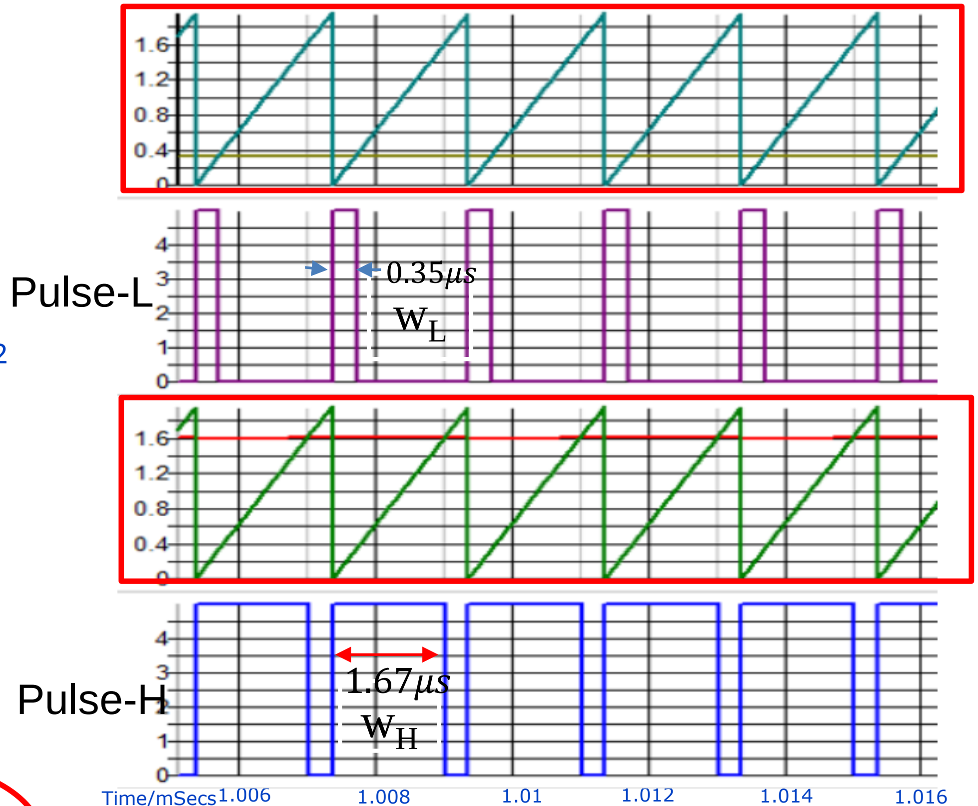
$W_H = 1.66\mu s$
$W_L = 0.33\mu s$

Simulation result

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

Well matched

Tck compare with VL or VH




Simulation waveform of $W_H$ and $W_L$

# OUTLINE

- Introduction & Objective
- Conventional Switching Converters
- Pulse Coding Method in Switching Converter
- Automatic PWC Control
  - Relationship with the Clock frequency and the Notch frequency
  - Direct generation of clock pulse from input frequency
  - Simulated Noise Spectrum of PWM Signal
- Conclusion and future work

# Simulated Noise Spectrum of PWM Signal Case 1

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

● Case 1 : Fin=750kHz , N=1 ・・・ Fin=1.5・Fck

Fn=750 kHz, Fck=500 kHz, Fck ＜ Fn ＜ 2Fck

## ◎ Condition

Buck DC-DC converter

$V_{in}$ ： 10V

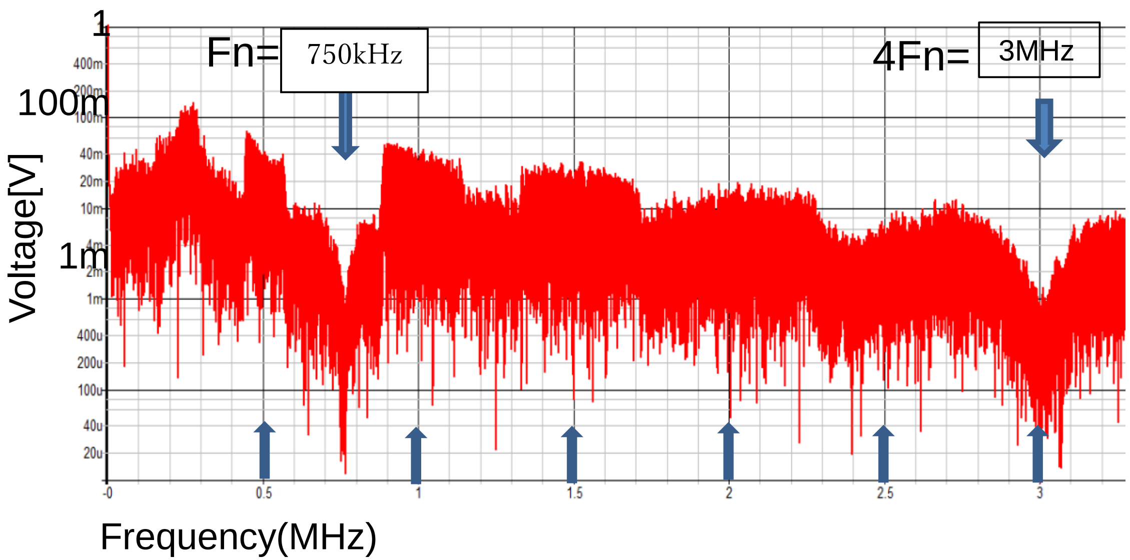
$V_{out}$ ： 5V

L ： 200 μ H

C ： 470 μ F

$I_{out}$ ： 0.25A

$F_{in}$ ： 750kHz




Simulated spectrum with EMI reduction

Assume to suppress influence on AM radio in 750kHz
⇒A notch was generated around 750kHz

# Simulated Noise Spectrum of PWM Signal Case 2

- Case 2 : Fin=1.25MHz , N=2 ・・・ Fin=2.5·Fck

  Fn=1.27 MHz, Fck=500 kHz, 2Fck < Fn < 3Fck

## ◎ Condition

Buck DC-DC converter

$V_{in}$ : 10V

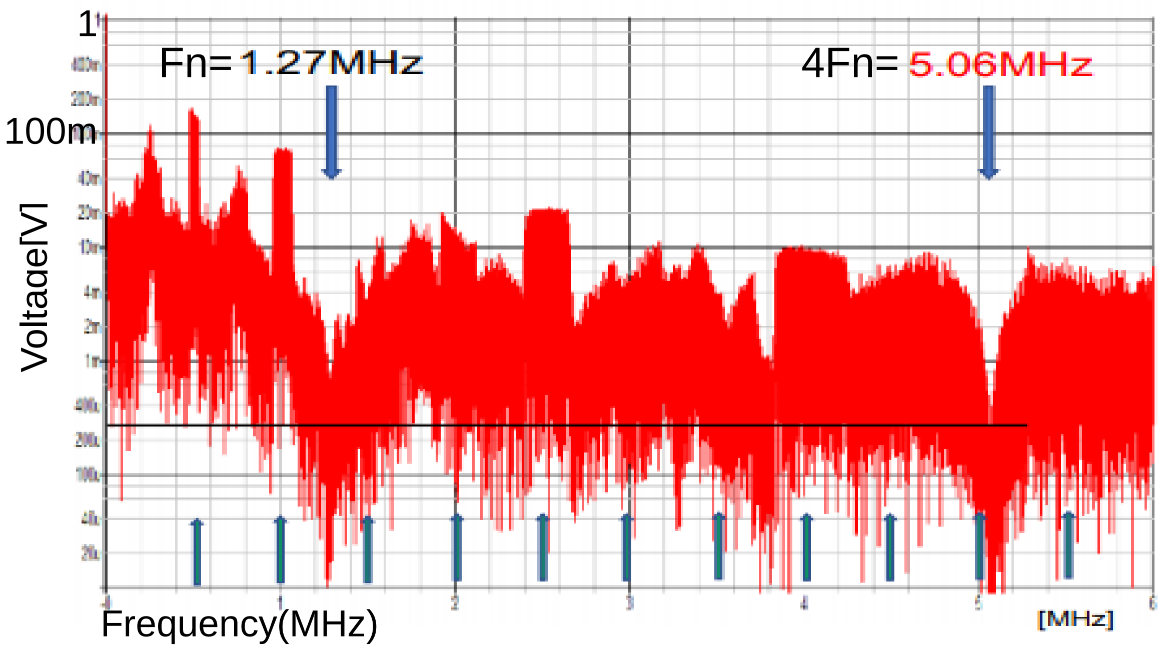
$V_{out}$ : 5V

L : 200 μ H

C : 470 μ F

$I_{out}$ : 0.25A

$F_{in}$ : 1.25MHz




Simulated spectrum with EMI reduction

# Transient Response with $F_{in}$ Change in Case 2

## ◎ Condition

$F_{in} = 1.25\text{MHz} \Rightarrow F_{in} = 1\ MHz$

$F_{in} = 1.25\text{MHz} \Rightarrow F_{in} = 750kHz$

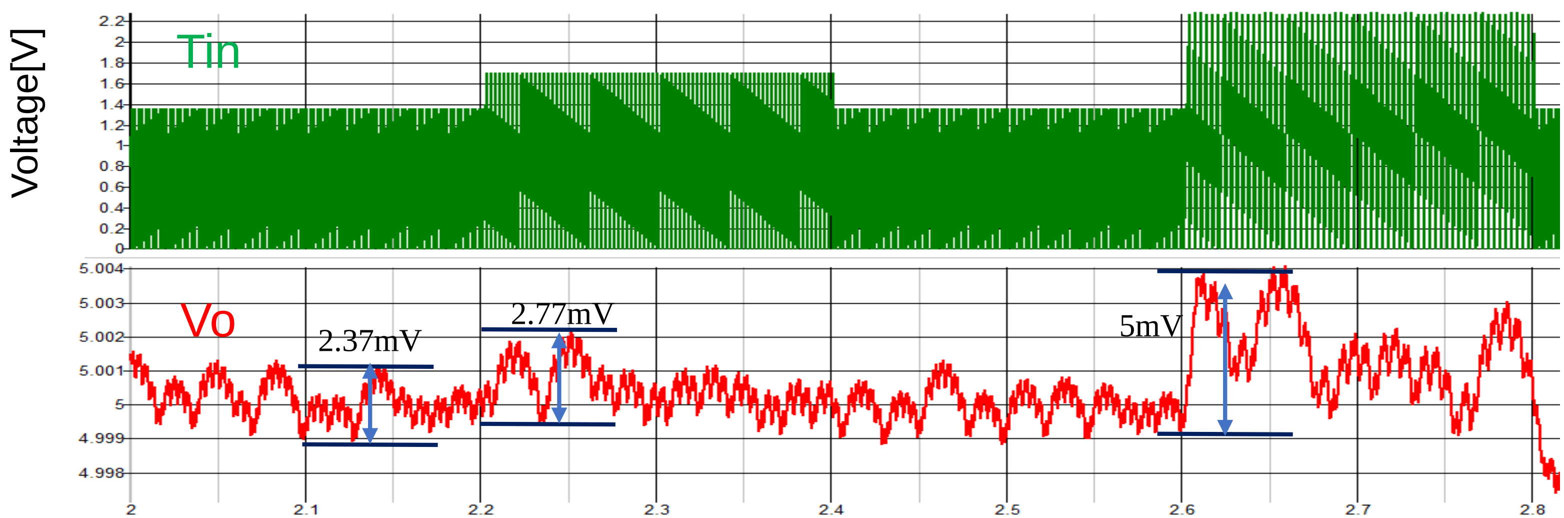
Settling Time≈ $0\mu s$

## ◎ Output stability

Ripple: $2.37mV_{pp}$ at $F_{in} = 1.25MHz$
$2.77mV_{pp}$ at $F_{in} = 1MHz$
$5mV_{pp}$ at $F_{in} = 750kHz$

Overshoot : $5mV$

Static ripple is about 0.1% of the output voltage $V_o$
stable




Transient response with Fin change

Response speed is important when tuning or switching communication channels

# Simulated Noise Spectrum of PWM Signal Case 3

● Case 3 : Fin=1.75MHz , N=3 ・・・ Fin=3.5･Fck

Fn=1.8 MHz, Fck=500 kHz, 3Fck ＜ Fn ＜ 4Fck

## ◎ Condition

Buck DC-DC converter

$V_{in}$ : 10V

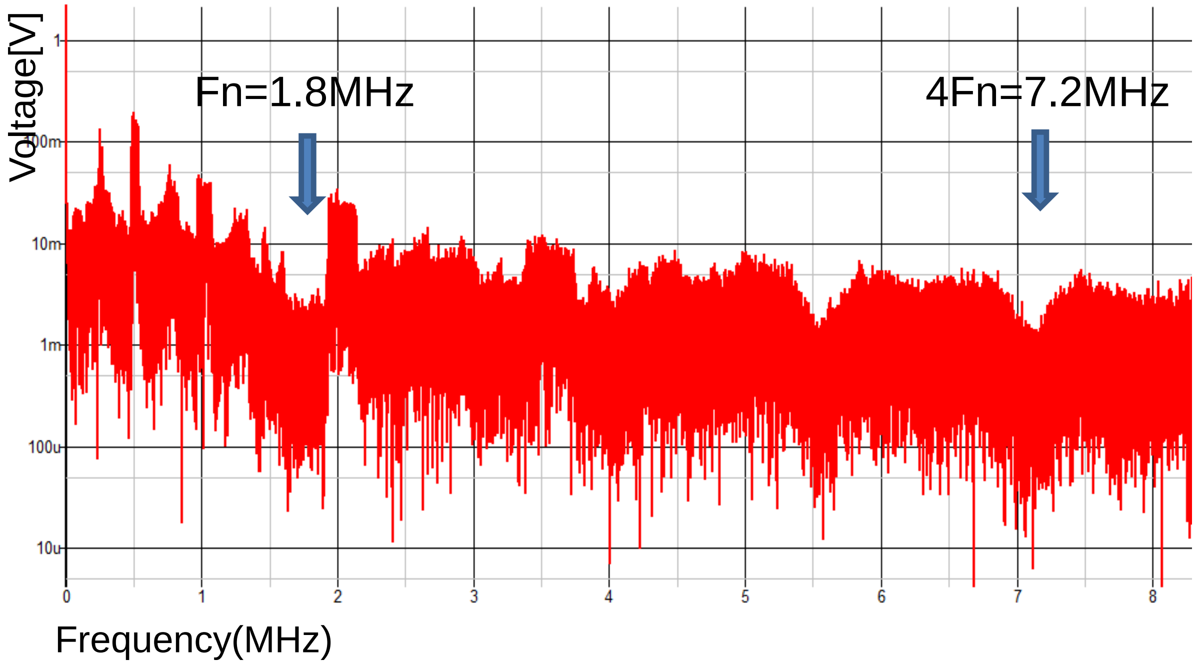
$V_{out}$ : 5V

L : 200 μH

C : 470 μF

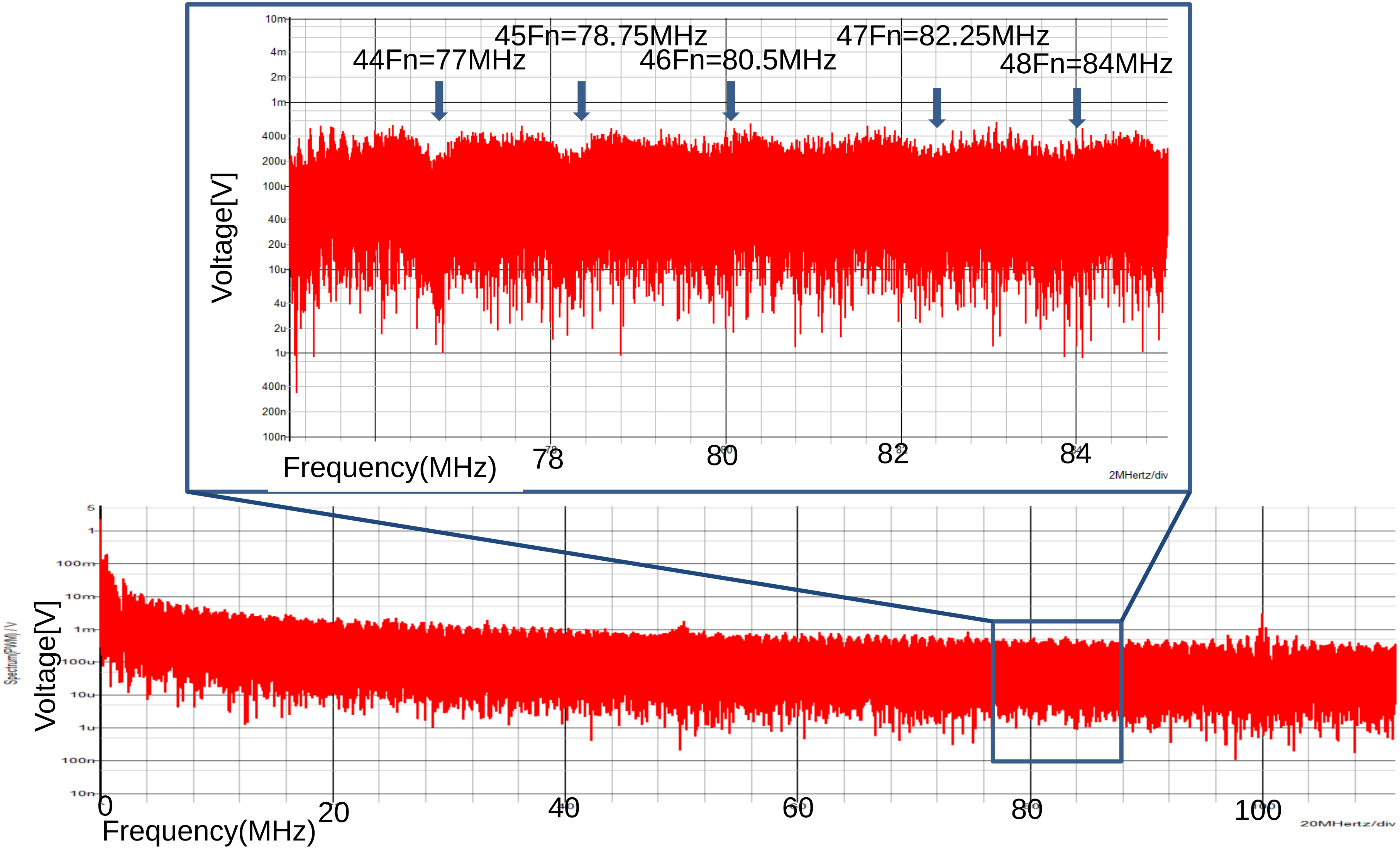
$I_{out}$ : 0.25A

$F_{in}$ : 1.75MHz




Simulated spectrum with EMI reduction

# Simulated Noise Spectrum of PWM Signal Case 3




It is good for radio receiver to receiving high frequency signal without other communication devices interference

# OUTLINE

- Introduction & Objective
- Conventional Switching Converters
- Pulse Coding Method in Switching Converter
- Automatic PWC Control
  - Relationship with the Clock frequency and the Notch frequency
  - Direct generation of clock pulse from input frequency
  - Simulated Noise Spectrum of PWM Signal
- Automatic PWPC Control
- Conclusion and future work

# Conclusion

- Developed pulse coding control in order to generate notch characteristics at desired frequency
- Analyze spread spectrum with notch characteristics
- Automatically generate the notch frequency from Fin

Create notch characteristics occurred around $F_{in}$

Using $F_{\mathrm{in}} = (N + 0.5)F_{\mathrm{ck}}$, discussion on direct generation of notch in N=1,2,3 situation using PWC method

# Future Work

- Notch generation using PCC(Pulse Cycle Coding) method

- Investigate why the large notch at 4Fn appear.

Thank you for Listening

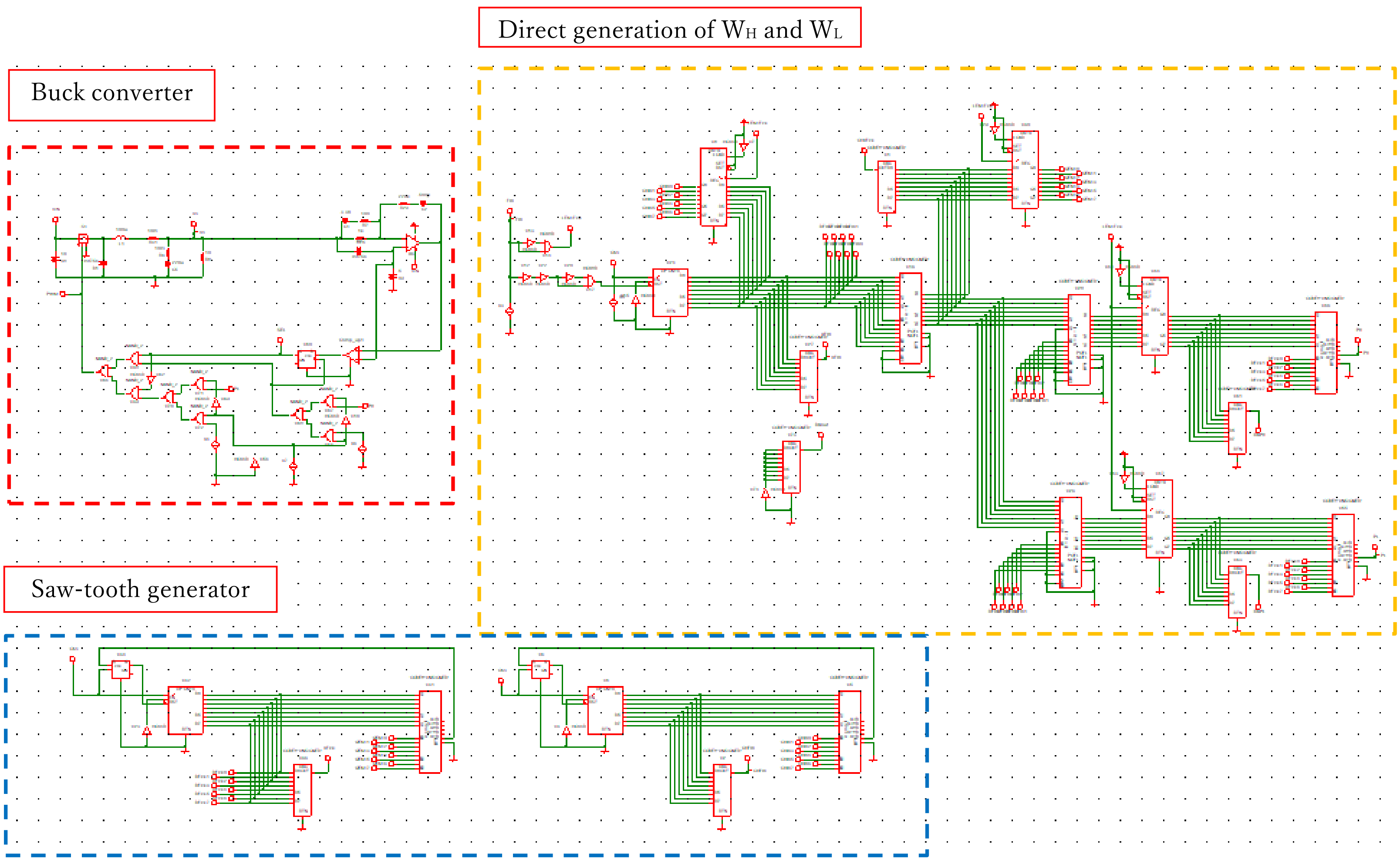
# Q and A

Q1.Is any consider about filter design?
A: filter in this buck converter using RC filter, connect between Vo and diode, can makes the output point becoming the dc voltage that no rush and without ripple .

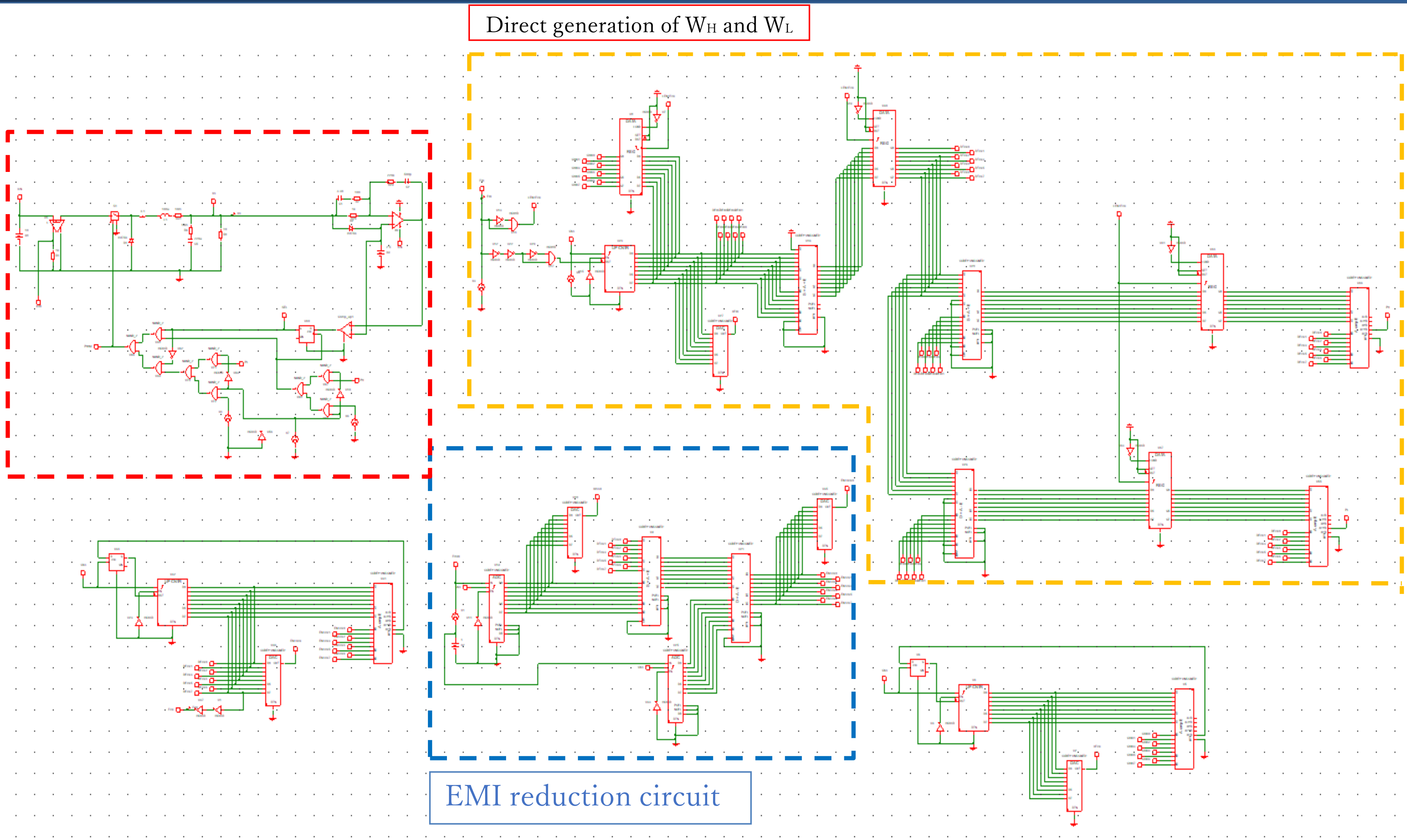
Suggestion:  The transistor respond is important when turn on and off in switching.

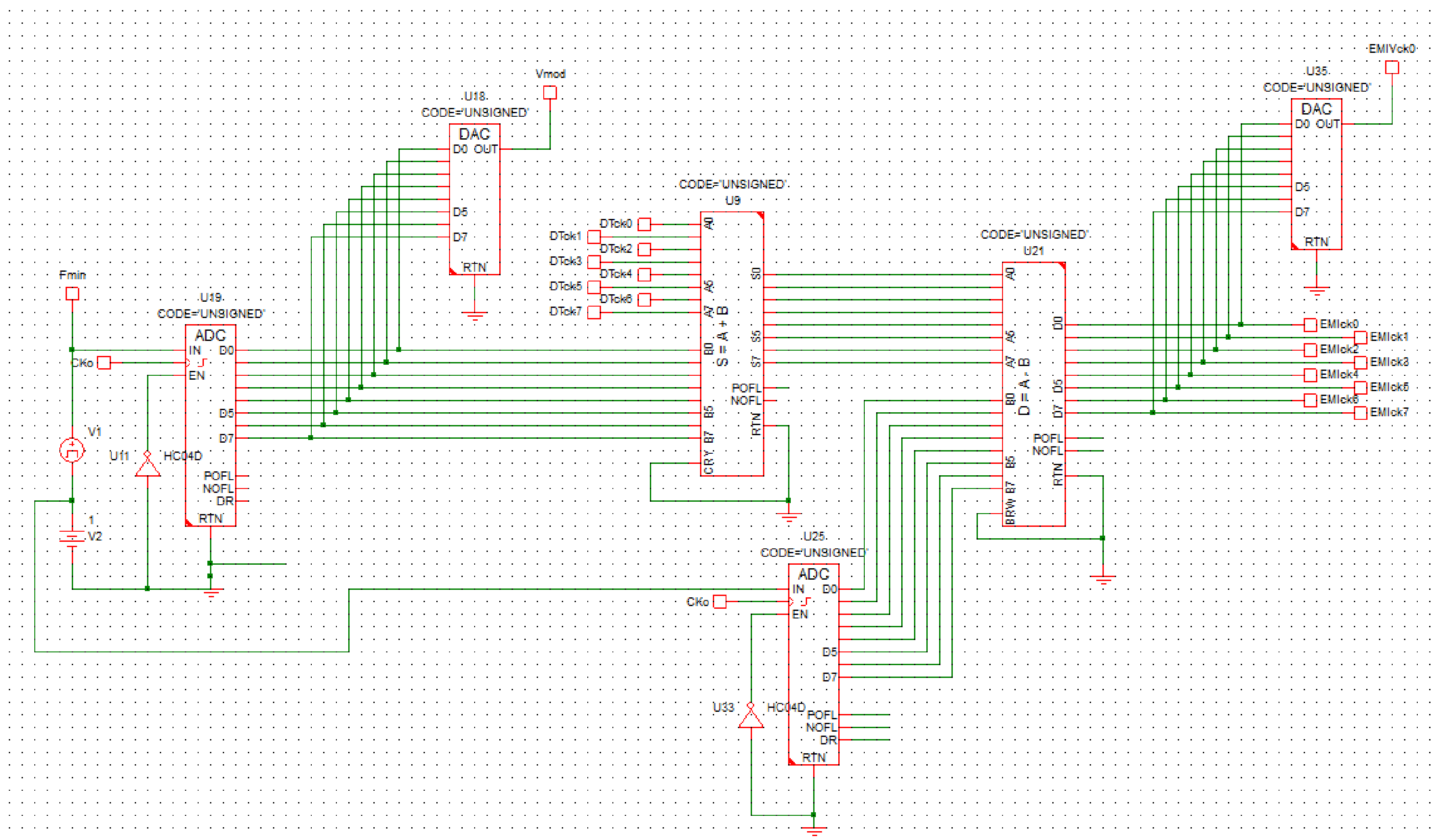
The select of switching frequency is important. The longer the switch time, the greater the loss. Shorting the switching period can reduce the volume of the filter, but it will increase the total loss. So we need to choose between these two evaluation.

# Automatic Notch Generation using Direct method（N=1)



# Automatic Notch Generation using Direct method with EMI Reduction（N=2)




Vmod
U18
CODE='UNSIGNED'
DAC
D0 OUT
D5
D7
RTN
CODE='UNSIGNED'
U9
DTck0
DTck1
DTck2
DTck3
DTck4
DTck5
DTck6
DTck7
S = A + B
POFL
NOFL
RTN
CRY
CODE='UNSIGNED'
U21
D = A - B
POFL
NOFL
RTN
BRW
EMIVck0
U35
CODE='UNSIGNED'
DAC
D0 OUT
D5
D7
RTN
EMIck0
EMIck1
EMIck2
EMIck3
EMIck4
EMIck5
EMIck6
EMIck7
Fmin
U19
CODE='UNSIGNED'
ADC
IN D0
CKo
EN
D5
D7
POFL
NOFL
DR
RTN
V1
U11
HC04D
V2
U25
CODE='UNSIGNED'
ADC
IN D0
CKo
EN
D5
D7
U33
HC04D
POFL
NOFL
DR
RTN

# Application of Automatic Generation of the Notch Frequency

Switching frequency and harmonics used in in-vehicle DC-DC converter must not overlap reception frequency bands of AM, FM of radio

demand

Reception frequency from radio receiver ≈ Notch frequency

Frequency band where noise does not spread

Goal

Automatic generation of notch frequency

DC-DC converter

It is possible to greatly reduce influence on other electronic devices

Radio receiver

Set frequency of radio reception

Auto correspond to Fin change is necessary