Noise Spread Spectrum with Adjustable Notch Frequency in Complex Pulse Coding Controlled DC–DC Converters

Yasunori Kobori *, Nobukazu Tsukiji, Yifei Sun, Nobukazu Takai and Haruo Kobayashi

Gunma University, Japan
Outline

1. Background
   1-1 Switching Converter
   1-2 EMI Reduction with clock modulation

2. Pulse Coding and Notch Characteristics
   2-1 Pulse coding control
   2-2 Simulation result with PWC control
   2-3 Experimental results of PWC control

3. Automatic PWC Control for Radio Receivers
   3-1 Generating the clock using PLL circuit
   3-2 Adjustable direct generation from input frequency

4. Conclusion

EMI: Electro-Magnetic Interference  PWC: Pulse Width Coding
1. Background

Our Research about DC-DC converters

- **Buck/Boost Converters** (Standard type)
  - SIMO (Parallel/Serial)
  - Multi-Phase [Easy (Clock)]
  - [Reduce L]
  - [Multi Output]

- **Hysteretic Converters** (High Speed)
  - SIMO (Synchronizing)
  - Multi-Phase
  - Synchronized CK
  - [Multi Output]
  - [Reduce L]

- **Resonant Converter** (High Efficiency)
  - SIMO (Soft SW/ZVS)
  - Multi-Phase
  - Synchronized CK
  - [Reduce L]

- **EMI Reduction** (Spread Spectrum)
  - Clock Modul. (Random/Linear)
  - Notch Chara. Auto. Generation

**Functions**

- Low Cost
- High Power
- Low ripple

**Fig.0** Our Research for Switching Converters

**SIMO**: Single-Inductor Multi-Output
Switching noise and EMI trouble

Switching Converters

Supply many kinds of Voltage by switching converters

Switching Noise

EMI

Conductive Noise

Important to reduce SW noise by decreasing clock spectrum level

Fig.1-1 background (EMI)

EMI: Electro-Magnetic Interference
● Reduce clock noise spectrum level below the Standard Level

▲ By shaking the clock phase/frequency, spread the clock noise around clock frequency and harmonics.

◆ Radio receivers would not like to be affected by spread noise.

※ Our Objective

★ Develop Spread Spectrum Method both to reduce the EMI noise and
research process

- Reduce clock noise spectrum level below the Standard Level
- By shaking the clock phase/frequency, spread the clock noise around clock frequency and harmonics.
- Radio receivers would not like to be affected by spread noise.

※ Our Objective

★ Develop Spread Spectrum Method both to reduce the EMI noise and to reject noise at desired frequency with Notch Characteristics.
1-1 Switching Converter (Buck type)

* Output Voltage $V_o$ is compared with $V_{ref}$ and amplified.
* Amplified voltage $\Delta V_o$ is compared with SAW-tooth signal. ⇒Generate the Pulse Width Modulation (PWM) pulse.
* Power SW is controlled by the PWM pulse.
* Inductor Current changes Up/Down to control $V_o$ stable.

Fig. 1-2 Circuit of the Buck converter

Fig. 1-3 Waveforms
● Spectrum of PWM pulse
* Electro-Magnetic Interference (EMI) Noise [from Circuit]
* Conductive Current Noise [Input Current]
* Noise Spectrum (PWM pulse)
  ⇒ High Level spectrum at Fck (=200 kHz) & harmonics.
★ Reduce clock frequency spectrum
1–2 EMI reduction with clock modulation

* To reduce EMI noise, clock pulse is modulated.

⇒ Clock spectrum is spread and reduced.

* Clock to SAW generator is modulated by shaking phase or frequency.

* PWM pulse is modulated and the clock frequency is spread.

Fig. 1-5 Converter with EMI reduction

Fig. 1-6 Waveforms
* Clock modulation methods:
   (1) Random Digital, (2) Linear sweep, (3) Random Analog

1) Random Digital phase modulation:
   ・Using many shift resistors (> 1,000)
   ・Need same number of selectors
   ・Using M-sequence for random signal

\[ F_s > 200\text{MHz} \]

Fig. 1-7  Digital EMI reduction

Fig. 1-8  Timing chart
2) **Linear sweep modulation:**

- Clock pulse is generated using VCO.
  - VCO is modulated by Triangular signal with.
- Spectrum of modulated PWM pulse
  - Peak level is reduced and the top shape is flat.

![Circuit of Linear Sweep](image)

![Spectrum with Linear Sweep](image)
(3) Random Analog noise modulation:
* Pseudo Random Noise + PLL Circuit

- Random pattern is generated from M-sequence (3 bit) through LPF ⇒ pseudo random analog noise (Fig.1-12)
- Output of PLL circuit is the clock with random frequency.

![Diagram of pseudo random noise generation](image1)

Fig. 1-11 Spectrum with Linear Sweep

Fig. 1-12 pseudo random noise

Fig. 1-13 PLL characteristics
- Simulated noise spectrum with EMI reduction
- Peak level is reduced to 2.0V (−4.9 dB)
- Harmonics are much reduced. (ex. −20 dB at 1.0 MHz)
- Output Voltage Ripple $V_o$ is about 13 mVpp. (=0.3%)

**Bottom levels increase high!**

**Fig.1-14** Comparison of Spectrum

**Fig.1-15** Output Voltage Ripple
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PWC: Pulse Width Coding
2. Pulse Coding and Notch Characteristics

2-1 Pulse coding control

★ Switching Converter with Pulse Coding

* Make SEL signal by comparing $\Delta V_o$ vs. $V_r$
  - Select Pulse-H or Pulse-L.
    - Pulse-H: with H-Duty ratio

* In order to control $V_o$, duty ratios of coding pulses are very important.

★ $D_H > D_o > D_L \cdots (1)$
  $D_o = \frac{V_o}{V_in}$

Fig.2-1 Switching Converter with Pulse Coding
★ Pulse Coding control

1) Pulse Width Coding (PWC)
   - Pulse width is different.
   - Notch frequency: $F_n$
     \[ F_n = \frac{N}{(W_H - W_L)} \cdots (2) \]

2) Pulse Phase Coding (PPC)
   - Pulse phase is different.
     \[ F_n = \frac{N}{(2 \cdot \tau)} \cdots (3) \]

3) Pulse Cycle Coding (PCC)
   - Pulse cycle (period) is different.
     \[ F_n = \frac{N}{(T_L - T_S)} \cdots (4) \]

Fig.2-2  Pulse Coding control
★ Complex Pulse Coding control

1) Pulse Width & Phase Coding (PWPC)
   - Pulse width & phase are different.
   - Notch frequency: \(F_n\)
     \[F_{n1} = \frac{N}{2 \cdot \tau}\]
     \[F_{n2} = \frac{M}{(T_L - T_S)}\]

2) Double notch characteristics
   When set \(\tau = \frac{(T_L - T_S)}{2} \cdots (5)\)
   then \(F_{n1} = F_{n2}\). : Double Notch

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Fig.2-3  PWPC control
Simulation results with PWC control

- Condition: $V_i=10\text{V}$, $V_o=5\text{V}$, $F_{ck}=500\text{kHz}$
- Pulses: 
  - H-Pulse $W_H=1.7\text{us}$, $D_H=0.85$
  - L-Pulse $W_L=0.4\text{us}$, $D_L=0.2$
- Static Ripple: $A_{V_o}<2\text{mV}$ @ $I_o=0.25\text{A}$
- Overshoot = 2.5 mV @ $A_{I_o}=0.125\text{A}$

Fig. 2-4 PWC Pulses
Fig. 2-5 Signals with PWC control
Fig. 2-6 Output ripple with PWC control
Noise Spectrum with PWC control of PWM pulse

* Notch Freq. : \( F_N = \frac{N}{(W_H - W_L)} = \frac{N}{1.3\text{us}} = 0.77, 1.5 \text{ MHz} \)

Peak Level Reduction: 3.5V \( \Rightarrow \) 0.9V (\(-11.8 \text{ dB}\))

* Frequency relation : \( F_{ck} < F_n < 2F_{ck} \)

Fig. 2-7 Noise Spread Spectrum with PWC control
Noise Spectrum with PWPC control:

* Conditions: $V_i=10V$, $V_o=5.0V$, $F_{ck}=1.4$ MHz ($T_{ck}=714$ ns)
  
  $W_H=480$ ns, $W_L=320$ ns, $\tau = (W_H - W_L)/2 = 80$ ns

* Notch Frequency: $F_N = 1/160$ns = 6.25 MHz

Bottom Level: $V_B : -65$dB $\Rightarrow -75$ dB ($-10$dB )
2-3 Experimental result with PWC control

* Conditions: \( W_H = 5.0 \text{ ns}, \ W_L = 1.0 \text{ ns}, \ Tck = 160 \text{ kHz} \)
* Notch Frequency: \( F_n = \frac{1}{(5.0 - 1.0) \text{ us}} = 250 \text{ kHz} \)
* Relation: \( F_{ck} < F_n = 274 \text{ kHz} < 2 \cdot F_{ck} \)

Fig.2-9 Noise spectrum & major signals with PWC
Experimental result 2 with PWC

* Conditions 2: \( W_H = 2.0 \text{ ns} \), \( W_L = 1.0 \text{ ns} \), \( F_{ck} = 420 \text{ kHz} \)

* Notch Freq.: \( F_N = \frac{1}{(2.0 - 1.0) \text{ us}} = 1.0 \text{ MHz} \)

* Relation: \( 2 \cdot F_{ck} < F_n = 1.05 \text{ MHz} < 3 \cdot F_{ck} \)

Fig. 2-10 Another noise spectrum with PWC 2
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3. Automatic PWC Control for Radio Receiver

3-1 Generating clock pulse & coding pulses

● Relations among \( \text{Fin}, \ Fck, \ Fn \) and \( W_H, \ W_L \)

* Better to generate \( Fn \) at middle of \( Fck \):

\[
\begin{align*}
\cdot & \ N=1: \quad Fck < Fn < 2 \cdot Fck \\
\cdot & \ N=2: \quad 2 \cdot Fck < Fn < 3 \cdot Fck \\
\therefore & \quad Fn = (N+0.5) \cdot Fck \Rightarrow Tck = Tn \cdot (N+0.5) \quad \cdots (7)
\end{align*}
\]

* Static duty ratio \( Do \) and Coding pulses

\[
\begin{align*}
\cdot & \quad Do = \frac{Vo}{Vin}, \quad Tn = W_H - W_L = Tin \quad \cdots (8) \\
\cdot & \quad W_H = Do \cdot Tck + \frac{Tin}{2}, \quad W_L = Do \cdot Tck - \frac{Tin}{2} \quad \cdots (9)
\end{align*}
\]

★ After generating \( Tck \) from \( Tin \),

\( W_H \) & \( W_L \) are set with Eq. (9).
Case: \( N=1, \, Do=0.5 \)
\[
Tck = Tin \cdot (N+0.5) = 1.5 \cdot Tin \implies 2 \cdot Tck = 3 \cdot Tin \quad \cdots (10)
\]

How to generate Fck from Fin
(A) using **PLL circuit**  (B) Using **Direct calculation**

(A) Generating Tck using **PLL circuit** : (Presentation IPS01-03 [Sun])
* Use VCO and generate \( Fck = (2/3) \cdot Fin \)
* Generate coding pulses \( W_H, W_L \) from Tin & Tck

\[
W_H = \frac{Tin}{2} + \frac{Tck}{2}, \quad W_L = \frac{Tin}{2} - \frac{Tck}{2} \quad \cdots (9')
\]

P.C : Phase Comparator  
VCO: Voltage Controlled Oscillator

![Fig. 3-1 PLL circuit with VCO](image1)

![Fig. 3-2 Generating \( W_H & W_L \)](image2)
* Simulation result: \( \text{Fin} = 500 \text{ kHz} \)

- Noise spectrum: \( \text{Fck}= 330 \text{ kHz, Fn}=520 \text{ kHz} \)
- Step Response with Fin change: @ \( \text{Fin}=0.5\text{MHz} \leftrightarrow 1.0\text{MHz} \)
  Ripple=15mVpp, Undershoot=\(-15\text{mV}\)
  Settling time (recovery time): \( T_s = 0.15 \text{ ms} \)

Fig. 3-3 Noise spectrum with auto generated coding pulses

Fig. 3-4 Transient response with Fin change
(B) Generating Tck using Direct calculation

* Generate Tck from Tin using Eq. 10: \( Tck = 1.5 \cdot Tin \) (N=1)
  - Measure Tin and generate Tck using digital/analog circuit.

* Calculate coding pulses \( W_H \) & \( W_L \) from Tin & Tck
  \[ W_H = \frac{Tin}{2} + \frac{Tck}{2}, \quad W_L = \frac{Tin}{2} - \frac{Tck}{2} \]  

Simulation result: Fin=750 kHz
  - Static voltage ripple: \( \triangle Vo = 3mV \) @ Fin= 750kHz
  - Step Response: when Fin = 1.25M ⇔ 1.0M ⇔ 0.75MHz
    \( \triangle Vo = \) Over/Undershoot = 4mV, Settling time ≈ 0 ms

Fig. 3-5 Direct generation of Tck

Fig. 3-6 Transient response with Fin change
● Noise spectrum with Linier sweep EMI reduction

* Case 1: Fin = 750 kHz, N = 1
  - Fn = 750 kHz, Fck = 500 kHz, Fck < Fn < 2Fck

* Case 2: Fin = 1.25 MHz, N = 2
  - Fn = 1.27 MHz, Fck = 500 kHz, 2Fck < Fn < 3Fck

● There appears the large notch at 4·Fn

Fig. 3-7 Noise spectrum (N=1)  Fig. 3-8 Noise spectrum (N=2)
Conclusion

★ Developed Pulse Coding Control in order to generate notch characteristics at desired frequency.

1. Theoretical Notch Frequency:
   - **PWC**: \( F_N = \frac{N}{(W_H - W_L)} \)
   - **PPC**: \( F_N = \frac{N}{(2 \tau)} \)
   - **PCC**: \( F_N = \frac{N}{(T_L - T_S)} \)

2. Experimental Noise Spectrum with **PWC**:
   - Notch appears at \( F_n = (N+0.5) \cdot F_{ck} \)

3. Automatic notch generating method:
   1) Generate \( F_{ck} \) from \( F_{in} \):
      - \( F_{ck} = \frac{2}{3} \cdot F_{in} \) (or \( F_{ck} = 1.5 \cdot T_{in} \))
      - (A) using PLL circuit     (B) using Direct Calculation
   2) Make \( W_H \) & \( W_L \) from \( T_{in} \) & \( T_{ck} \) and set \( F_n \):
      \[ W_H = T_{in}/2 + T_{ck}/2, \quad W_L = T_{in}/2 - T_{ck}/2 \]

● Future Work:
   Investigate why the large notch at \( 4 \cdot F_n \) appear.
Thank you for your kind attention!

Is there any question?