Selectable Notch Frequencies of EMI Spread Spectrum Using Pulse Modulation in Switching Converter

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Outline

1. Introduction & Objective

2. Spread Spectrum for EMI Reduction

3. Pulse Coding Method in DTC
   3-1 PWM Pulse Coding with Notch Frequency
   3-2 PCM Pulse Coding with Notch Frequency

4. Spread Spectrum in Switching Converter
   4-1 Spread Spectrum with PWM Coding
   4-2 Spread Spectrum with PCM Coding

5. Conclusion

DTC : Digital to Time Converter
PWM: Pulse Width Modulation
PCM: Pulse Cycle Modulation
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1. Introduction & Objective

Switching Converters

Supply many kinds of Voltage by switching Power

1. Important to reduce SW noise by decreasing main spectrum level

Fig.1-1 background (EMI)

EMI: Electro-Magnetic Interference
1. Introduction & Objective

- We reduce the clock noise by spread spectrum with shaking the clock phase at random.

- Noise of clock frequency is spread to all frequencies around the clock & harmonics.

- Some electronic devices like radio receivers would not like to be affected at special frequency noise.

★ Spread Spectrum Method is required with notch frequency and noise reduction.
Objective:

1) **Clear the relationship** between notch frequencies and parameters of coding pulses.

2) **Simulate the notch frequency** in spread spectrum with PWM and PCM pulse coding.

3) **Check the notch frequencies** in the switching converter with pulse coding and EMI reduction.
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   4-2 Spread Spectrum with PCM Coding
   4-2 Spread Spectrum in Ripple Controlled Converter

5. Conclusion
2. Spread Spectrum for EMI Reduction

★ Developed EMI reduction method as previous presentation.

* Clock to SAW generator is modulated by shaking phase of original clock at random using analog noise & PLL.

* SW pulse frequency is modulated and reduce the EMI noise.

Fig.2-1 Buck converter with modulated clock

Fig.2-2 Timing Chart
Simulation results of spread spectrum with EMI reduction.

- Clock Frequency (200kHz)
  Peak level is reduced from 3.5V to 2.0V (-2.4 dB)

- Harmonic frequency (1 MHz)
  from 500mV to 50mV (-10 dB)

- Peak level of clock frequency is reduced a lot, but other frequency level is increased about 10 mV.

★ No good for radio receivers.

Fig.2-3 Comparison of Spectrum
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DTC: Digital to Time Converter
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3. Pulse Coding Method in DTC

3-1 PWM Pulse Coding with Notch Frequency

- **Pulse Coding** in Digital-to-Time Converter (DTC)
- Digital Signal $\Rightarrow$ 3 Pulse Coding (PWM, PPM, PCM)

**PWM Coding**
- Period is constant: To
- Pulse Width is different.
  - Select “WL pulse” when ‘L’ comes.
  - WL means width of Low-duty pulse.

Fig.3-1 Digital to Time Converter (DTC)

Fig.3-2 PWM Coding Pulse
★ Simulation Result with PWM Coding

* Parameters of coding pulses:
  \[ W_L = 200\text{us} \text{, } W_H = 600\text{us} \text{ (To=1.0 ms) } \]

* Notch Frequency:
  \[ F_N = \frac{k}{(W_H - W_L)} \]

Here, \( F_N \) is independent on the period.

* \( F_N = \frac{k}{400\text{us}} = 2.5, 5.0, 7.5 \cdots \text{[kHz]} \)

Fig.3-3  Notch Frequency with PWM Coding

Fig.3-4  PWM Coding Pulse
Simulation Result (2) with PWM Coding

* $W_H = 800\text{us}$, $W_L = 200\text{us}$ (To=1.0 ms)

$F_N = \frac{k}{600\text{us}} = 1.67, 3.33, 5.0 \cdots \text{[kHz]}$

Set $F_N$ by adjusting pulse width difference with setting the clock frequency not overlapped with $F_N$.

Fig. 3-5 Notch Frequency with PWM Coding

Fig. 3-6 PWM Coding Pulse
3. Pulse Coding Method in DTC

3-2 PCM Pulse Coding with Notch Frequency

★ Parameters of PCM Coding

* Pulse Width is constant. : \( W_0 \)
* Pulse Cycle (Period) \( T \) is different.
  • Select “ \( T_L \) “ when 「L」comes.

● Notch Frequency:

\[
F_N = \frac{k}{(T_L - T_H)} \quad \cdots (2)
\]

It’s derived from pulse cycle difference.

Fig.3-7 PCM Coding Pulse
Simulation results with PCM Coding

- **Parameters:** $T_L = 600\text{us}$, $T_H = 200\text{us}$ (Wo = 100us)
  
  $F_N = k/400\text{us} = 2.5, 5.0, 7.5 \cdots \text{[kHz]}$

- $F_{ckH} = 5.0 \text{kHz}$
- $F_{ckL} = 1.67 \text{kHz}$

Fig. 3-8 PCM Coding Pulse

Fig. 3-9 Input & Output Pulses

Fig. 3-10 Notch Frequency with PCM Coding
simulation result (2) with PCM Coding

- $T_L = 800\text{us}$, $T_H = 200\text{us}$ ($W_o = 100\text{us}$)
- $F_N = k / 600\text{us} = 1.67, 3.33, 5.0, 6.67, 8.33 \cdots [\text{kHz}]$
- $F_{ckH} = 5.0 \text{kHz}$, $F_{ckL} = 1.25\text{kHz}$

★ Set $F_N$ by adjusting pulse period difference
with setting the clock frequency not overlapped with $F_N$.

Fig.3-11 PCM Coding Pulse

Fig.3-12 Notch Frequency with PCM Coding
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PWM: Pulse Width Modulation
PCM: Pulse Cycle Modulation
4. Spread Spectrum in Switching Converter

4-1 Spread Spectrum with Pulse Coding

★ Switching Converter with Pulse Coding

* Make SEL signal by comparing $\Delta V_o$ w $V_r$.
  - 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.

★ $V_H > V_O > V_L \cdots (3)$
  
$V_o = \frac{V_o}{V_{in}}$

Fig.4-1 Switching Converter with Pulse Coding
Simulation results with **PWM Coding** & EMI reduction

* Duty: \( D_H = 0.8, D_L = 0.1 \)

* \( F_N = k/1.4\text{us} = 0.71, 1.43 \text{MHz} \)

* Clock Level: \( 3.5\text{V} \Rightarrow 0.9\text{V} \) (−5.9dB)

**Spectrum of SW pulse**

![Spectrum of SW pulse](image)

**Table 4-1 Parameters of buck converter**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vin</td>
<td>10.0 V</td>
</tr>
<tr>
<td>Vo</td>
<td>5.0 V</td>
</tr>
<tr>
<td>Io</td>
<td>0.25 A</td>
</tr>
<tr>
<td>L</td>
<td>200(\mu\text{H}))</td>
</tr>
<tr>
<td>Co</td>
<td>470(\mu\text{F}))</td>
</tr>
<tr>
<td>Fck</td>
<td>500kHz</td>
</tr>
</tbody>
</table>

**Fig.4-2** PWM Coding Pulse 2

**Fig.4-3** Spread Spectrum with PWM Coding
Two coding pulses supplied from PCM pulse generator.

* Pulse period: $T_H$ or $T_L$.

Pulse width is constant: $W_0$.

**4. Spread Spectrum in Switching Converter**

4-2 Spread Spectrum with **PCM Coding** in SW converter

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**Fig. 4-5** PCM Pulse Generator

**Fig. 4-6** Timing Chart

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SW Pulse

$T_H$

$T_L$

$W_0$

$V_{sw}$

$V_r$

$\Delta V$

Comp.

Q

D

Pulse Length

Pulse Gen.

Edge Det.

$\text{Comp.}$

$\text{V}_{sw}$

$\text{SAW Gen.}$

$\text{SEL}$
Simulation Results with PCM Coding (without EMI rejection)

- Parameters: $T_L = 3.5 \text{us}$, $T_H = 2.0 \text{us}$ (Wo = 1.3us)
- $F_N = N / (3.5 - 2.0) \text{us} = 0.667N \text{ [MHz]}$

* Highest spectrum level: 3.5V $\Rightarrow$ 2.0V ($-2.4 \text{dB}$)
* Simulation Results (PCM Coding)

* Duty Ratios: \( D_H = \frac{1.3}{2.0} = 0.6 \), \( D_L = \frac{1.3}{3.5} = 0.38 \)

* Output Voltage Ripple: 10 mVpp (0.2 % of \( V_o \))

Fig. 4-9 SEL and PWM Pulses

Fig. 4-10 Output Ripple
Conclusion

★ Pulse Coding Method with notch frequencies in the switching converters.

1. Notch Frequencies with pulse coding:
   • \( F_N = \frac{K}{(W_H-W_L)} \) @ PWM coding
   • \( F_N = \frac{K}{(T_L-T_H)} \) @ PCM coding

2. Simulation results with Pulse Coding:
   1) PWM Coding with EMI reduction:
      • Notch Frequency: \( F_N = 0.71 \text{ MHz} \)
      • Peak level of Fck: \(-5.9 \text{ dB (Ripple: 15 mVpp)}\)
   2) PCM Coding without EMI reduction:
      • Notch Frequency: \( F_N = 0.67 \text{ MHz} \)
      • Peak level of Fck: \(-2.4 \text{ dB (Ripple: 10 mVpp)}\)

★ We can set the Notch frequency freely by adjusting the coding pulse parameters.
Future Research

1. Simulation of spread spectrum with PCM pulse coding and EMI rejection.

2. Implementation of the buck converter with notch frequencies and EMI rejection.

3. Applications to another converters which use no clock pulse like ripple controlled converters.
Thank you for your kind attention!

謝謝

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Simulation Results with EMI Reduction

Spread Spectrum (Fo=200kHz)

- Peak level of basic frequency is reduced (-2.4 dB)
- Harmonic frequency is widely spread (-9.0 dB @1MHz).

(a) Without Spread Spectrum
(b) Digital Spread Spectrum
(c) Analog Spread Spectrum

Fig. A-1  Comparison of Spread Spectrum
**Primitive polynomials**

- **3 degree**
  - (a) $G(s) = x^3 + x^2 + 1$
  - (b) $G(s) = x^3 + x + 1$

- **4 degree**
  - (a) $G(s) = x^4 + x^3 + x^2 + x + 1$
  - (b) $G(s) = x^4 + x^3 + 1$
  - (c) $G(s) = x^4 + x + 1$

- **5 degree**
  - (a) $G(s) = x^5 + x^4 + x^3 + x + 1$
  - (b) $G(s) = x^5 + x^4 + x^2 + x + 1$
  - (c) $G(s) = x^5 + x^3 + x^2 + x + 1$
  - (d) $G(s) = x^5 + x^3 + 1$
  - (e) $G(s) = x^5 + x^2 + 1$
PCM Coding

* Ideal coding like Fig. 3-7 is difficult, because of difference of the period.

* Pseudo PCM Coding. Period of the SEL signal is constant.
  - Output $3 \ D_H$ pulses when SEL=H.
  - Output $2 \ D_L$ pulses when SEL=L.
4. Spread Spectrum with Switching Converter

4-2 Spread Spectrum with PCM Coding

★ PCM Coding

* Ideal coding like Fig. 3-7 is difficult, because of difference of the period.

* Pseudo PCM Coding.
  
  Period of SEL signal is constant.
  
  - Output 3 $T_H$ pulses when SEL=H.
  - Output 2 $T_L$ pulses when SEL=L.

![Fig.4-7 Pseudo PCM Coding](image)

![Fig.3-7 Ideal PCM Coding](image)
● Simulation results (Pseudo PCM)

* Parameters: \( T_{SEL} = 6 \cdot T_{ck} = 12\mu s \) (\( F_{ck} = 500\text{kHz}, T_{ck} = 2\mu s \))
  \( T_{H} = 4\mu s, T_{L} = 6\mu s, W_{o} = 2.8\mu s \) (\( D_{H} = 0.7, D_{L} = 0.467 \))

* Spread Spectrum
  - Many line frequencies:
    \( 167\text{kHz}, 333\text{kHz} (= N \cdot 500/3 = 167 \cdot N \text{ kHz}), 500\text{kHz} \pm 55\text{kHz} \)
  - Notch Frequency is not clear.
    \( F_{N} = k/(6-4)\mu s = 0.5 \cdot k \text{ MHz} (= N \cdot F_{ck}) \) : No good!

Fig.4-8 Spread Spectrum (Pseudo PCM)

Fig.4-9 Pseudo PCM Coding
Duty of coding pulses

* Steady state: \( D_0 = \frac{V_o}{V_i} \)

* Duty relation with coding pulses,
  \[ D_H > D_0 > D_L \cdots (4-1) \]

Ex. (PWM Coding, Fig. 3-4)

\( D_H = 0.6 \), \( D_L = 0.2 \)

@ \( V_i = 10V, V_o = 5.0V \): \( D_0 = 0.5 \)

Fig. 4-3 SW Pulses with PWM Coding

Fig. 4-4 PWM Coding Pulse