

Spread Spectrum with Notch Frequency using Pulse Coding Method for Switching Converter of Communication Equipment

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Abstract This paper proposes a novel EMI spread spectrum technique with the selectable notch frequencies using the pulse coding methods for DC-DC switching converters of communication equipment. The notches in the spectrum of the switching pulses appear at the frequencies obtained from empirically derived equations using the pulse coding methods, the PWC (Pulse Width Coding) and the PCC (Pulse Cycle Coding). The notch frequencies are directly inversely proportional to the time difference between two coded pulses. We have investigated these relationships with the experimental result of the PWC method.

Keywords: Switching converter, Buck converter, Spread spectrum, Pulse width coding, Pulse Cycle coding

1. Introduction

In recent years, expansion of the mobile device usage has been accelerated by the progress in an information society. There the switching power converter is well known for its downsizing, light weight and high efficiency. As for the Pulse Width Modulation (PWM) control method is usually used for the switching converters and it is very important to reduce an Electro Magnetic Interference (EMI) problem, mainly by suppressing the peak level of the fundamental frequency and its harmonic frequencies.

On the other hand, for the communication equipment including the radio, it is very important to reduce the radiation noise at the particular frequencies by suppressing diffusion of power supply noise.

This paper proposes a new technique in order to have the notches at the particular frequencies with the EMI reduction in the switching converters using the pulse coding technology. We show the relationships between the notch frequencies and the coded pulses in the simulation. Finally we experiment some notch frequencies in the PWC method by changing the parameters.

2. Switching Converters with Spread Spectrum

2.1 DC-DC switching converters

Figure 1 shows the block diagram of a buck type DC-DC converter and Fig.2 shows its major signals. The converter consists of the power stage and the control part. The power stage contains a main power switch, a free-wheel diode, an inductor and a bulk capacitor. The main switch is controlled by the PWM pulse from the control part. The control part consists of an operational amplifier, a comparator, a saw-tooth generator and a reference voltage source.

The current flows are shown in Fig.1, where the red solid line shows the direction of the current flow when the inductor is charged (the switch is ON), and the blue dashed line shows the current flow when the inductor is discharged (the switch is OFF). The difference between the output voltage and the reference voltage is amplified and compared in order to generate the PWM pulse with the saw-tooth signal.

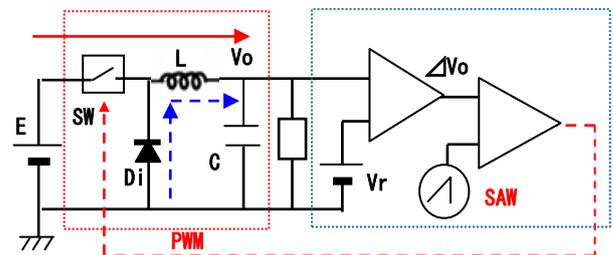


Figure 1. Block diagram of a buck converter.

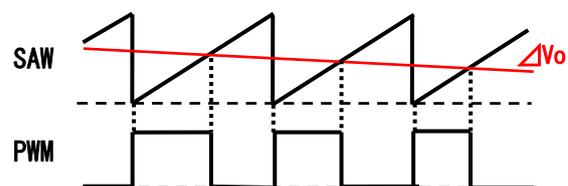


Figure 2. Waveforms of the major signals.

2.2 EMI reduction with spread spectrum

The radiation from the PWM switching pulses is well known as the EMI noises. Fig. 3 shows the spectrum of the PWM pulse of the buck converter shown in Fig.1

without spread spectrum where the peaks at the basic frequency (3.5V at 200 kHz) and its harmonic frequencies are very large. Figure 4 shows the spread spectrum with the EMI reduction which modulates the phase or frequency of the saw-tooth signal [1]. In Fig.4, the peak levels of the line spectrums are reduced and the energy of the basic frequency and its harmonic frequencies are spread to all frequencies, which would not be desired for the communication equipment like the radio.

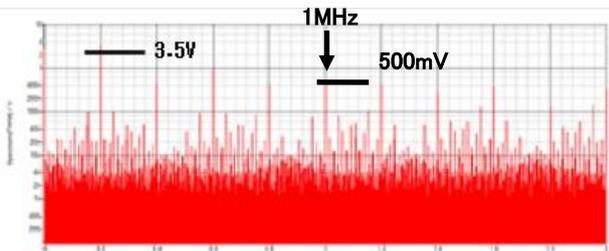


Figure 3. Simulated spectrum of the PWM pulse of the buck converter without pulse modulation.

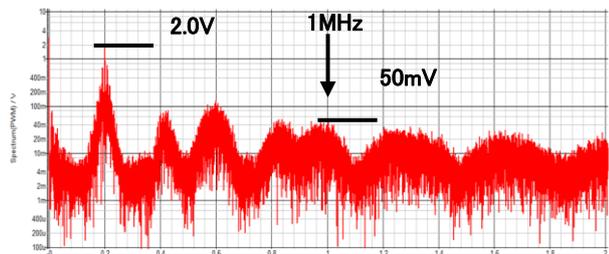


Figure 4. Simulated spread spectrum of the PWM pulse of the buck converter with pulse modulation.

3. Notch Frequency with PWC Method

3.1 Pulse Width Coding : PWC

In the pulse coding control methods, the main switch is controlled by the pulse coded drive signal PCD which are selected from two coded pulses. They are high duty pulse 1 and low duty pulse 2 shown in Fig. 6. These two coded pulses are selected by the select signal SEL supplied from the flip-flop shown in Fig.5. The flip-flop and two pulse generators (pules 1, 2) are trigger d by the internal clock. When the SEL signal is Hi, then the Hi duty pulse is selected.

Here the duty D_H of the pulse 1 is higher than the duty D_L of the pulse 2. In the buck converter, the standard transformed voltage ratio is fundamentally $D_o = V_o/V_i$, then there is the relation with D_H , D_L and D_o as bellow.

$$D_L < D_o < D_H \quad (1)$$

In Fig.6, there shows the example of two pulses. Here the pulse period is 500 kHz (the pulse period is 2.0 us) and the pulse width of the pulse 1 is 1.7 us, then its duty is 0.85. The pulse width of the pulse 2 is 0.3 us so the

duty of the pulse 2 is 0.15. The condition of the converter shown in Fig. 5 are $V_i=10V$ and $V_o=5.0V$, so the transfer duty $D_o=0.5$.

In this case, the equation of the notch frequencies F_{nw} in the spectrum of the PCD signal is represented below. According to this equation, notches do not appear at the clock frequency or its integer-multiple frequencies.

$$F_{nw} = K/(W_H - W_L) = k/1.4 \approx 710 \cdot K \text{ [kHz]} \quad (2)$$

Where $K = 1, 2, 3, \dots$

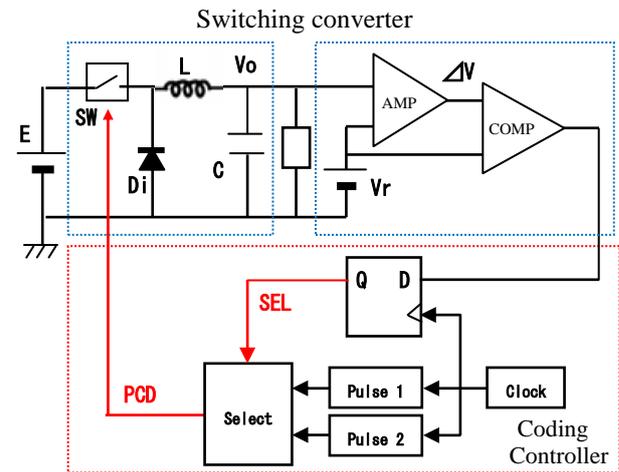


Figure 5. Switching converter with pulse coding

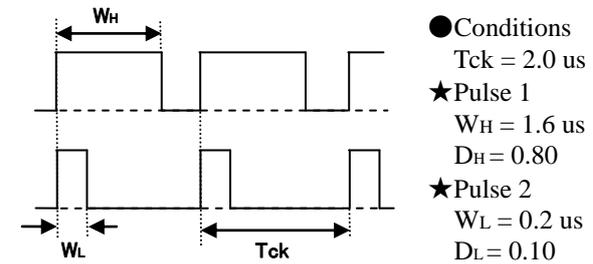


Figure 6. Coded pulses with the PWC method

3.2 Simulation results of the PWC converter

In this pulse coded control, the output voltage is controlled with only two pulses and there is no need of the saw-tooth signal, but in order to control the output voltage precisely, the frequency of the clock is set to be higher 500 kHz. Other parameters of the switching converter with PWC are shown in Table 1.

In Fig. 7, the clock CK, the select signal SEL and the PCD signal are shown in the simulation. The pulse widths are correctly changed according to the SEL signal. In Fig. 8, there shows the output voltage ripples when the output current is changed from 0.125A to 0.25 A. The ripple is less than 2.5 mV_{pp} and it's about 0.05% of the output voltage $V_o=5.0V$. The dynamic load regulation (step response) is about 2 mV at the output current change 0.125A.

The spectrum of the PCD signal is shown in Fig. 9, where the peak level of the basic frequency 500 kHz is 0.9V and the notches appear at around 0.7 MHz and 1.4 MHz which is agreed with the equation (2). These notch frequencies are easily controlled by changing the pulse widths of the PWC pulses shown in Fig. 6.

Table 1. Parameters of the PWC converter

V _{in}	10.0 V
V _o	5.0 V
I _o	0.25/0.125 A
F _{ck}	500kHz

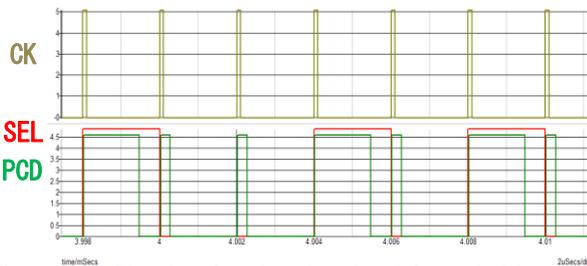


Figure 7. Simulated major signals of the switching converter with the PWC method

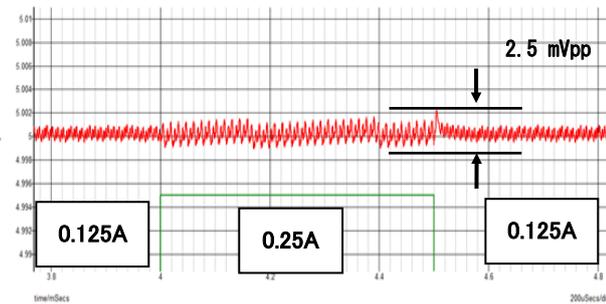


Figure 8. Simulated output voltage ripple and step response of the PWC converter.

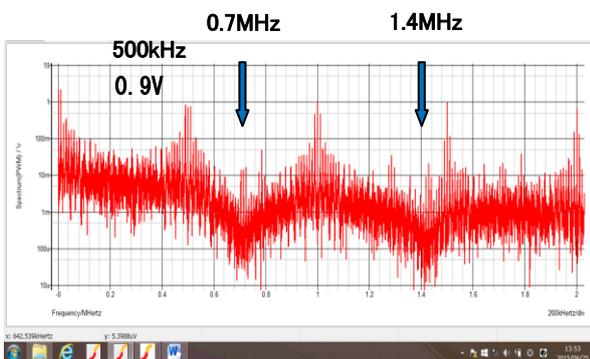


Figure 9. Simulated spread spectrum and the notches of the PCD signal of the PWC converter.

4. Notch Frequency with PCC Method

4.1 Pulse Cycle Coding : PCC

In the switching converter shown in Fig. 5, the duties of two coded pulses are different each other in the relationship with the equation (1). In this case, the duty will be changed by changing the pulse width or the pulse period shown in Fig. 10.

In Fig. 10, there shows the example of two pulses with the PCC method. Here the pulse width W_o is 0.4 us and the pulse periods are $T_S=0.5$ us and $T_L=2.0$ us, then their duties are $D_H=0.8$ and $D_L=0.2$. In this case, the equation of the notch frequencies F_{nc} in the spectrum of the PCD signal is represented below. .

$$F_{nc} = K/(T_L - T_S) = k/1.32 \text{ us} = 0.76 \cdot K \text{ [kHz]} \quad (3)$$

Where $K = 1, 2, 3, \dots$

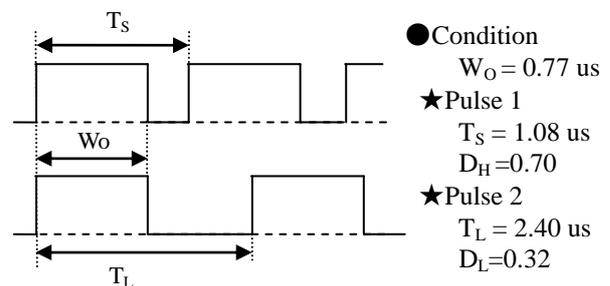


Figure 10. Coded pulses with the PCC method

4.2 Switching converter with PCC method

Operation of the switching converter with the PCC method is difficult because the pulse cycles of the coded pulse are different each other and these PCC pulses are mixed according to the SEL signal shown in Fig. 11. In this case, the clock pulses are occurred at the timing of the end of the SEL signal and the PCC pulse is selected from the coded pulses.

These coded pulses are generated by the analog circuit which includes the saw-tooth generator and three comparators shown in Fig. 12. In this circuit, three pulses, they are pulse 1, pulse 2 and the basic width pulse, are generated by comparing the saw-tooth signal and three reference voltages. The length of the coded pulse is easily changed by adjusting the reference voltage. The length of pulse 2 is longer than that of pulse 1 and the duty of pulse 2 is lower than that of pulse 1.

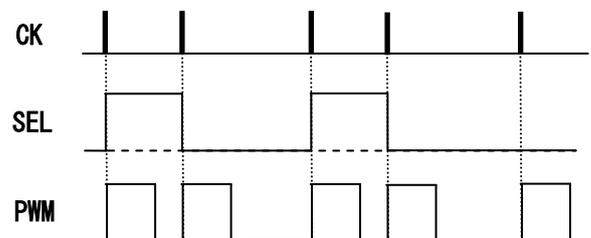


Figure 11. Major signals of the PCC converter

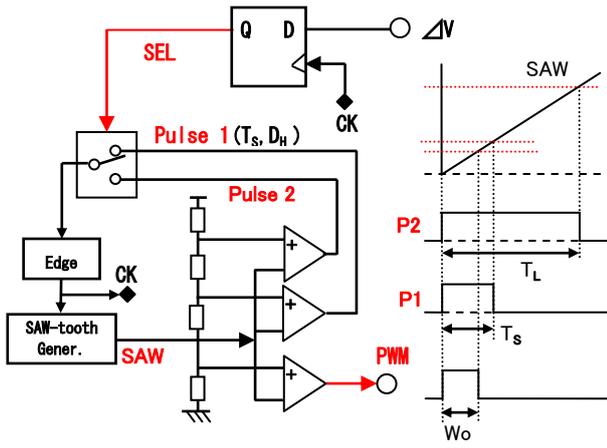


Figure 12. Pulse generator in the PCC converter

4.3 Simulation results of the PCC converter

Figure 13 shows the simulation result of the output voltage ripple and that is about 5 mVpp. The dynamic load regulation is almost 0 mV at the output current change 0.125A. The level of the ripple at $I_o=0.25$ A is a little bit larger than $I_o=0.125$ A.

Figure 14 shows the major signals. The pulse lengths of the PCD signal are changed and its duties are also changed according to the SEL signal. Here, the level of the PCD pulse is intentionally changed in order to be easy to understand.

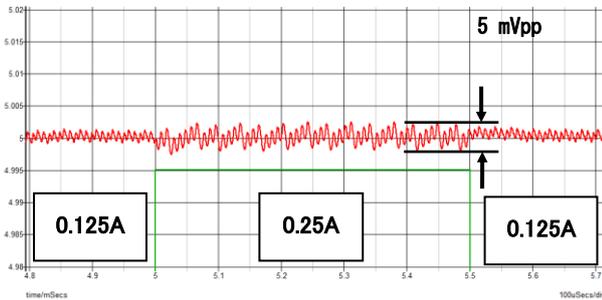


Figure 13. Simulated output voltage ripple of the switching converter with PCC.

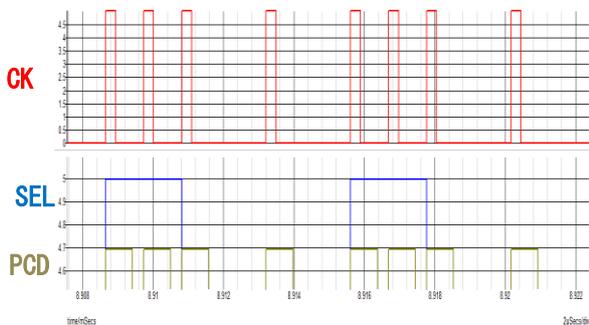


Figure 14. Waveforms of the major signals

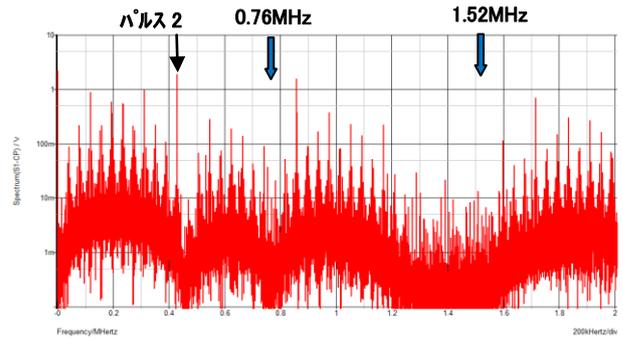


Figure 15. Simulated spread spectrum and the notches of the PCD signal of the PCC converter.

Figure 15 shows the spread spectrum of the PCC converter. In this case, pulse conditions are $T_L=2.4$ us and $T_S=1.08$ us, so the basic notch frequency is calculated $F_n=0.76$ MHz from equation (3). In Fig. 15, there appear the notches at around $F_n=0.76$ M and 1.52 MHz but they are not clear. There are many line spectrum. The spectrum at 420kHz and 940kHz is the frequency of the pulse 2 ($T_L=2.4$ us). Appearances of the notch frequencies or the spectrum are easily changed by the conditions of the coded pulse frequencies or the parameters of the switching converter.

5. Experimental Result of the PWC Converter

5.1 PWM coding in boost converter

Figure 16 shows the experimental results of the PWC converter, which are spread spectrum and the PCD and SEL signals. In this case, the clock frequency is 160 kHz and the pulse conditions are $T_L=5.0$ ns, $T_S=1.0$ ns and the pulse width is 0.2 us. The PCD pulses are changed according to the SEL signal. The calculated notch frequency is 250 kHz and the appeared notch frequency is about 270 kHz, which are almost same. The basic notch appears between the first clock ($f=160$ kHz) and the second clock (which is harmonic frequency: 320 kHz)

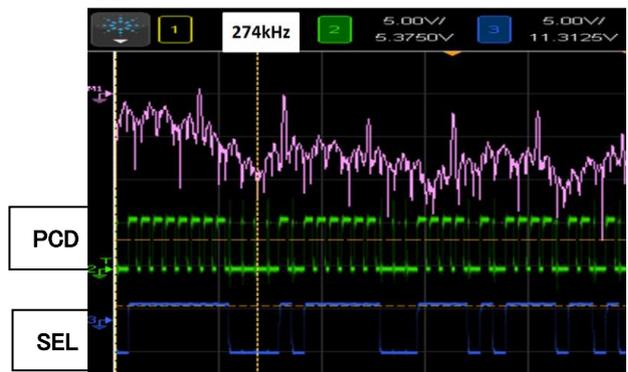


Figure 16 Experimental results of spread spectrum and major signals of the PWC converter

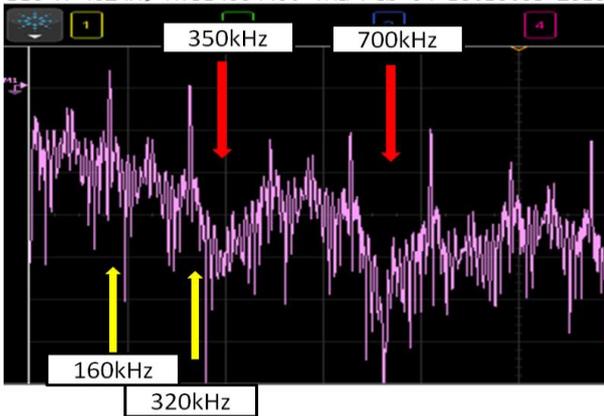


Figure 17 Another experimental spectrum with PWC (Clock frequency is 160 kHz.)

Figure 17 shows the another spread spectrum of the experimental PWC converter, whose conditions are $T_L=4.0$ ns, $T_S=1.1$ ns and others are same. In this case, the calculated notch frequencies are 345 k , 790 kHz. The experimental notch frequencies are almost same. Here, the basic notch appears between the second and third clock frequencies.

In these two experimental results, the notch frequencies are clear and appear between the clocks, but the clock frequency is a little bit low for the switching converters. So we show the last experimental result in Fig 18. In this converter, the clock frequency is 420 kHz. The pulse conditions are $T_L=2.0$ ns, $T_S=1.0$ ns and the pulse width is 0.2 us. In this case, the calculated notch frequencies are 1.0 MHz and the experimental notch frequency is almost same. Here, the basic notch appears between the second and third clock frequencies.

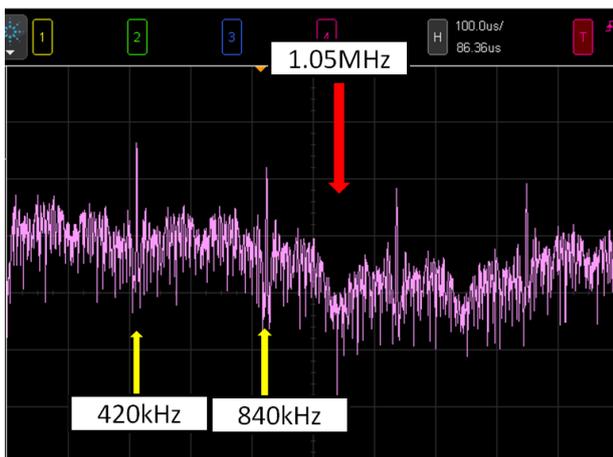


Figure 18 Another experimental spectrum with PWC (Clock frequency is 480 kHz.)

6. Summary

In the switching converters for the communication equipment, we have proposed the new spread spectrum technologies to set the notch characteristics at the desired frequency by the pulse coding, which is the PWC method or the PCC method. The equations of the notch frequencies are derived from the difference between the pulse period or the pulse width of the two coded pulses. For the PWC method, the notch frequency is derived from the equation $F_n = K/(W_L - W_S)$ which depends on only the pulse width. For the PCC method, the notch frequency is represented by the equation $F_n = K/(T_L - T_S)$ which depends on only the pulse period. The simulation results have validated these relationships.

We have shown some experimental spread spectrum of the switching converters with the PWC method, where notch frequencies have clearly appeared between the clocks and they are in agreement with the frequencies derived from the above equation.

References

- [1]S.Ochiai, Y.Kobori, "EMI Reduction by Spread Spectrum with Pseudo Analog Noise in DC-DC Converters," International Simposume on Technology for Sustainability, A3-179, Taipei (Nov. 2014)
- [2]R. Khatami, H. Kobayashi, Y. Kobori, "Delta-Sigma Digital-to-Time Converter For Band-Select Spread Spectrum Clock," Key Engineering Materials, Advanced Micro-Device Engineering V, pp.79-92 (Mar. 2015).
- [3]Y. Kobori, N. Tsukiji, N. Takai, H. Kobayashi, "EMI Reduction by Extended Spread Spectrum in Switching Converter," IEICE Technical Report, EMCJ2015-18, pp.1-6, Bangkok, Thailand (Jun. 2015)
- [4] Y. Kobori, T. Arafune, N. Tsukiji, N. Takai, H. Kobayashi, "Selectable Notch Frequencies of EMI Spread Spectrum Using Pulse Modulation in Switching Converter", IEEE ASICON, B8-8,Chengdu, China (Nov. 2015)
- [5] Y. Kobori, T. Wang ,T. Arafune, N. Tsukiji, N. Takai, H. Kobayashi, "EMI Reduction by Analog Noise Spread Spectrum In Ripple Controlled Switching Converter", IEEE ASICON, B8-8,Chengdu, China (Nov. 2015)