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Automatic Notch Generation in Noise Spectrum of Switching Converter with Pulse Coding Method

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Abstract This paper proposes a novel EMI spread spectrum technology with the adjustable notch frequencies using the automatic setting the notch frequency with the pulse coding method of the DC-DC switching converter for the communication equipment. In the communication devices, it is desired to be little noise around the frequency of the receiving signal. We have proposed having the notch characteristics in the noise spectrum of the switching pulse using pulse coding method.

In this paper, the notch frequency is automatically set to that of the received signal by adjusting the clock frequency using the equation Fn=(N+0.5)Fck. We have examined the theoretical notch frequency which is adjustable in the PWC controlled converter using the equation Fn=N/(W1-W2). And also investigated the direct generating method of the clock and the coded pulses to automatic generation of the notch frequency.

Keywords Switching Converter, Noise spectrum, Notch frequency, Pulse Coding, Communication Device

1. Introduction

In recent years, the circuit of the communication devices has been accelerated to be higher density packaging. The power of the switching converter has become large and large and the fluctuation of the switching noise has strongly spread in the wide frequency range. So it is very important to reduce an Electro Magnetic Interference (EMI) noise by suppressing the peak levels at the fundamental frequency and its harmonic frequencies.

On the other hand, for the communication equipment including the radio receiver, it is very important to reduce the radiation noise at the specific frequencies, such as the receiving frequency, by suppressing diffusion of power supply noise. We have proposed the pulse coding technique to have the notch characteristics at the random frequency in the noise spectrum of the switching converter[3]~[6].

In this paper, we show the EMI reduction and the notch frequency in the noise spectrum of the switching converter, and show the experiment of the notch characteristics using the PWC method.

2. Switching Converters with Spread Spectrum

2.1. Basic DC-DC switching converters

Fig. 1 shows the basic block diagram of the buck type DC-DC converter[1],[2] with the PWM (Pulse Width Modulation) signal control and Fig.2 shows its main signals. This converter consists of the power stage and the control block. The power stage contains a main power switch, a free-wheel diode, an inductor and an output capacitor. The main switch is controlled by the PWM signal from the control block, which consists of an operational amplifier, a comparator and a reference voltage source. The comparator generates the PWM signal compared a saw-tooth signal and the amplified error voltage.

When the switch is ON, the inductor current flows from the input voltage source E and charges the output capacitance shown as the solid line in Fig. 1. When the switch is OFF, the inductor current flows through the diode shown as the dashed line in Fig.1.In the buck type DC-DC converter, the output voltage Vo can be expressed by the following equation using the input voltage Vi and the ON/OFF ratio D (Duty).

$$V_o = D \times V_i \qquad (1)$$

Here, as the switching signal of high power is increased in speed, large EMI were generated.

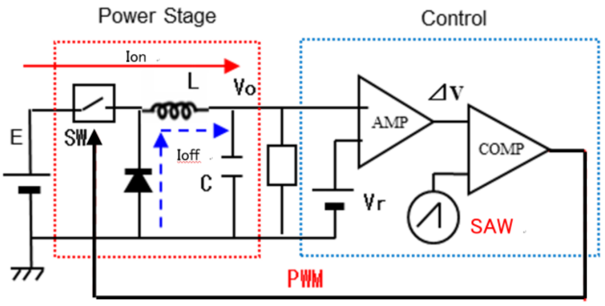


Fig.1 Switching buck converter with PWM signal

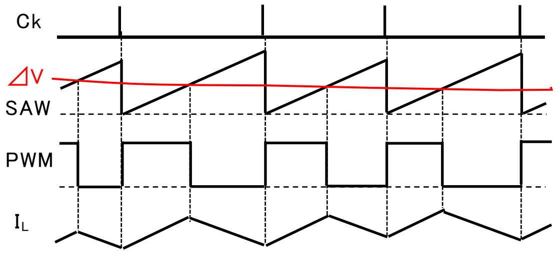


Fig.2 Waveform of switching buck converter

2.2. EMI reduction with clock modulation

In order to reduce the EMI noise, modulation of the clock pulse is usually used by shaking the phase or frequency of the clock in Fig.1. The spectrum of the PWM signal without the clock modulation is shown in Fig.3. There is the line spectrum at the frequency of the clock (0.2MHz) and there appear many harmonic spectra. The level of clock spectrum is 3.5V which is the largest in this figure.

Fig.4 shows the spectrum with the clock modulation. The peak level of the clock spectrum is reduced to 2.0V which is about 4.9dB reduction. There is no line spectrum but the bottom levels of the spectrum are higher than 8mV. That is not so good for the communication devices which receive weak radio waves.

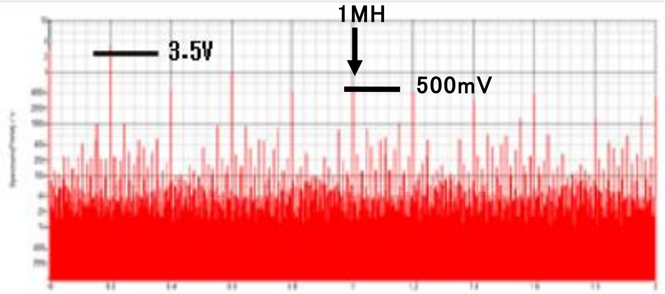


Fig.3 Simulated spectrum without EMI reduction

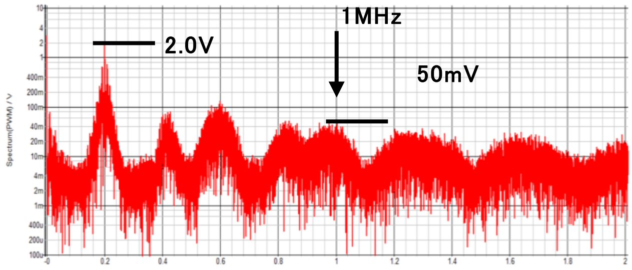


Fig.4 Simulated spectrum with EMI reduction

2.3. Notch frequency with Pulse Coding Control

Fig.5 shows the control circuit for the pulse coding. The amplified error voltage of the output voltage is compared with the reference voltage Vr and its output logic level is kept in the D-type flip-flop FF by the clock for synchronizing with the clock. The output of this FF is called select signal SEL which choices one of the two pulses input to the selector. These two pulses are the coding pulses generated using the modulated clock. We call the selected signal PCD (pulse coded driving) signal.

In this simulation, the pulse width coding PWC pulses are used to generate the notch frequency in the spectrum of the modulate clock. Fig. 6 shows the conditions of the PWC control and the other conditions are Vi=10V, Vo=5.0V, Io=0.2A and Fck=500kHz.

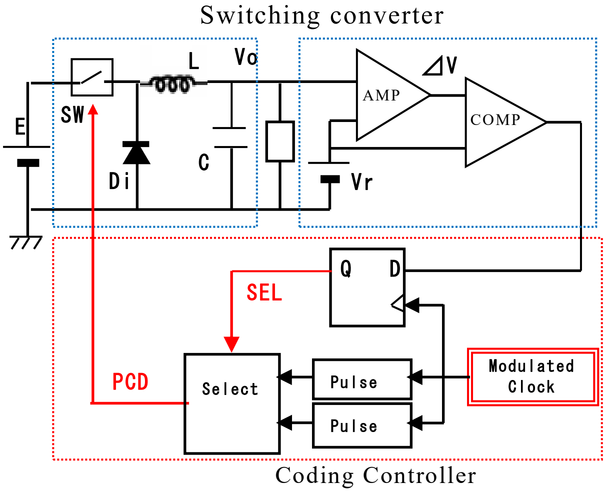
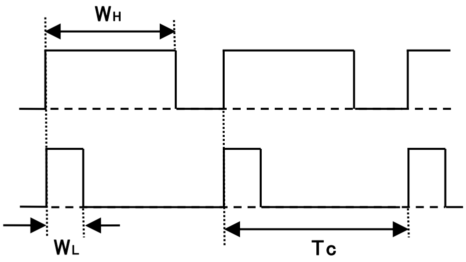


Fig.5Converter with EMI reduction & PWC control



●Conditions	★Pulse 1	★Pulse 2
Tck=2.0μs	W_H=1.6μs	W_L=0.3μs
	$D_H=W_H/T_{ck}=0.80$	$D_L=W_L/T_{ck}=0.15$

Fig.6 Coded pulses of PWC control

2.4. Simulation Results with the PWC control

Fig. 7 shows the spectrum of the coded pulses of the PCD signal. There appear the notch characteristics at the frequency of 770 kHz and 1.5MHz, which are the theoretical frequencies by calculating from the coded pulses shown in Fig. 6.

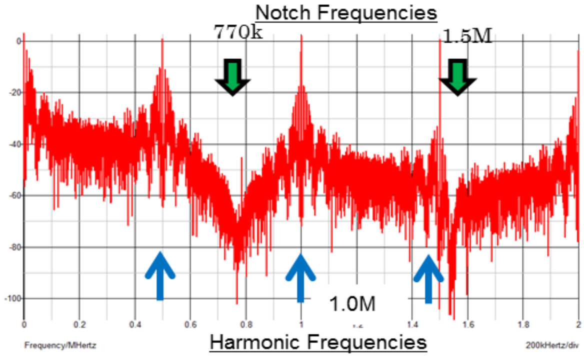


Fig.7 Simulated spectrum with PWC control

2.5. Derivation of theoretical notch frequency

The PWM pulse of the PWC converter is the random series of the two pulses shown in Fig. 4. The theoretical frequency of the PWC control is derived as bellow, performing fast Fourier transform to the pare of the coding pulses.

$$
\begin{aligned}
F(\omega) &= \int_{-\infty}^{\infty} f(t) e^{-j\omega t} dt \\
&= \int_{0}^{t_1} e^{-jwt} dt + \int_{\frac{T}{2}}^{\frac{T}{2}+t_2} e^{-jwt} dt \qquad (2) \\
&= \frac{1}{\omega}\Big(\sin(\omega t_1) - \sin(\omega t_2) \\
&\quad + j\cos(\omega t_1) - j\cos(\omega t_2)\Big) \qquad (3)
\end{aligned}
$$

The absolute value of above complex Eq. (3) is shown in the next sinc function (4).

$$
\begin{aligned}
|F(\omega)| &= \frac{1}{\omega}\sqrt{4\sin^2\left(\frac{\omega t_2 - \omega t_1}{2}\right)} \\
&= (t_2 - t_1)\mathrm{sinc}\left(\frac{t_2 - t_1}{2}\omega\right) \qquad (4)
\end{aligned}
$$

Where ω=2πf, so the notch frequencies are shown in the following equation. Here, N is the natural number. In the Eq. (5), it depends on the difference of the pulse width only, not depends on the period of the control pulse.

$$
f_n = \frac{N}{(t_2 - t_1)} \qquad (5)
$$

2.6. Experimental result of the PWC converter

Fig. 8 shows the experimental noise spectrum of the PWM signal and the SEL signal of the PWC converter. The parameters of this converter are as follow: the clock frequency is about 160kHz (the period Tck=6.25us) and the pulse conditions are W_H=5.0us and W_L=1.3us respectively. In this case, the theoretical notch frequency is 270 kHz and the appeared notch frequency is 274kHz. This experimental notch appears between the clock frequency 160kHz and the twice frequency 320kHz. Another notch at twice frequency (540kHz) does not appear in this figure.

Fig. 9 shows the experimental another spectrum, the notch frequency is 350kHz which appears between the first and second harmonic frequencies (320k and 640kHz) of the clock. Here the conditions of the coded pulses are W_H=4.0μs and W_L=1.1 μs respectively and the theoretical notch frequency is 345kHz. The clock frequency is Fck=160kHz.

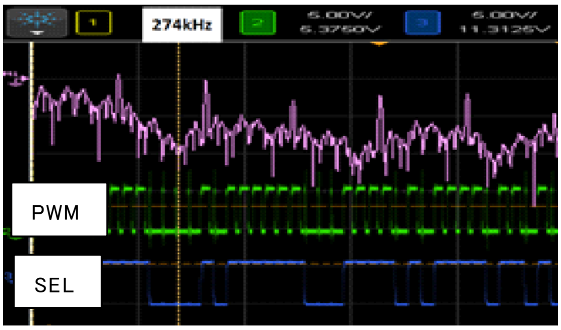


Fig.8 Experimental spectrum of PWC converter1

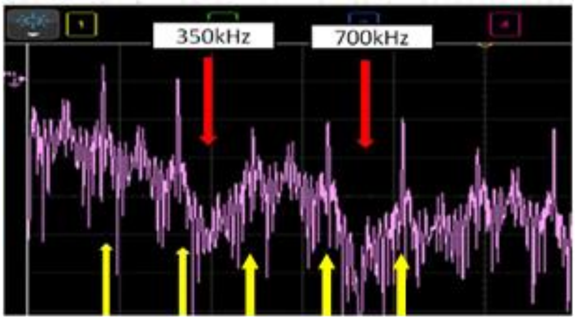


Fig.9 Experimental spectrum of PWC converter 2

3. Automatic Generation of the Notch Frequency

3.1. Analysis of relationship with Fck and Fn

Generally speaking, it is good for the notch frequency Fn to appear at the middle between the clock frequency Fck and its twice frequency 2Fck as shown in Fig. 7, or between its twice frequency and the three times frequency as shown in Fig. 9. Fn is, of course, the frequency of the receiving signal Fin. These relationship is shown as the next equation.

$$\mathrm{Fin} = (N+0.5)\cdot \mathrm{Fck} \qquad [N=\text{natural number}] \qquad (6)$$

$$\text{When } N=1, \quad \mathrm{Fin}/3 = \mathrm{Fck}/2 \qquad (7)$$

$$\text{When } N=2, \quad \mathrm{Fin}/5 = \mathrm{Fck}/2 \qquad (8)$$

On the other hand, the duty Do of the PWM signal in the switching converter is usually represented like Do=Vo/Vin, here Vo is the output DC voltage and Vin is the input DC voltage respectively. Hence the pulse width To of the PWM signal is represented shown in the Eq. (9).

According to the Eq. (5), the period of the notch frequency Tn is derived from the difference between the pulse width of W_H and W_L, here W_H or W_L means t_2 or t_1 in the Eq. (5) respectively. In this case, W_H, W_L and To should have the relation shown in the Eq. (10) in order to control the output voltage Vo stable. Here, Tp is the pulse difference between W_H and To or To and H_L, and 2*Tp is equal to Tn and it means the gain of the pulse coding control.

$$\mathrm{To} = \mathrm{Do}*\mathrm{Tck} = (\mathrm{Vo}/\mathrm{Vin})*\mathrm{Tck} \qquad (9)$$

$$W_H=\mathrm{To}+\mathrm{Tp}, \quad W_L=\mathrm{To}-\mathrm{Tp} \qquad (10)$$

$$\therefore \mathrm{Tn}=W_H-W_L=2*\mathrm{Tp} \qquad (11)$$

3.2. Direct generating the clock pulse (N=1)

In order to make the response quick for changing the input frequency, we have investigated the direct generating method of the clock and the coded pulses. In the Eq. (6), the period of clock Tck is able to be generated by measuring the period of the input pulse Tin like the following Eq. (12). It is easy to make Tck with a shifter and the digital adder in the digital circuit. Fig. 10 shows the block diagram of proposed circuit of the direct method (in the case that N=1).

$$\mathrm{Fin} = (N+0.5)\cdot \mathrm{Fck} \quad \Rightarrow \mathrm{Tck} = (N+0.5)\cdot \mathrm{Tin} \qquad (12)$$

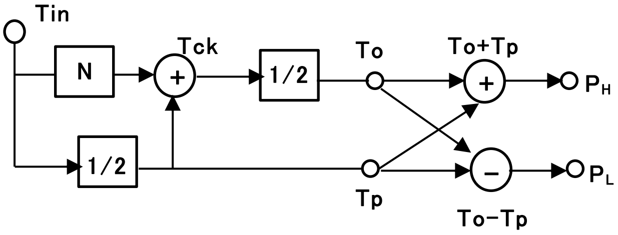


Fig. 10 Block diagram of direct generating the clock pulse and the coding pulses

3.3. Simulated results of the direct method

Fig. 11 shows the simulated pulses directly generated from the input signal. Here, 2·Tck=3·Tin. The conditions of this simulation are Fin=750kHz (Tin=1.33μs) and N=1. Then Fck is set to be 500kHz (Tck=2.0μs).

In the simulated spectrum of the direct method shown in Fig. 12, the generated clock is modulated with EMI reduction like Fig. 4. The notch characteristics clearly appears and its frequency is just 750kHz which is equal to Fin. The bottom level of the notch frequency is about 1mV. There appears another big notch at F=3.0MHz, which is the 4th harmonic of the fundamental notch frequency Fn.

Fig. 13 shows the transient response when the input frequency is changed from 1.25M to 1.0MHz and to 0.75MHz. The clock frequency is changed according to the change of Fin. Fig. 13 shows the change of the peak of the sawtooth signal of Fck. The setting time is only 2 clocks.

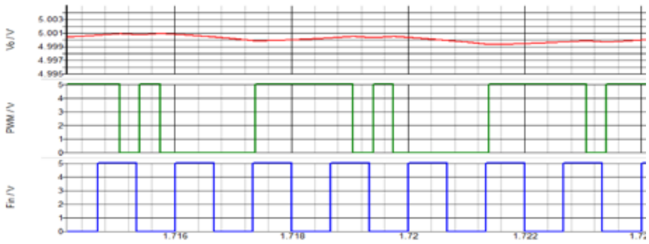


Fig.11 Direct generating the clock pulse

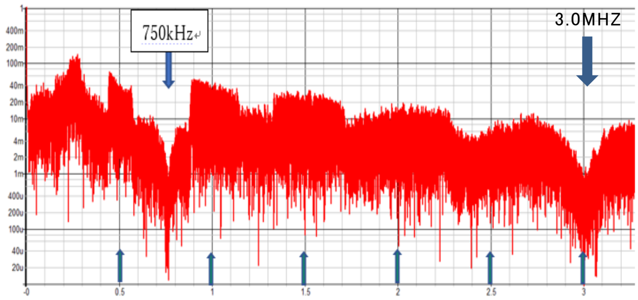


Fig. 12 Simulated spectrum with EMI reduction

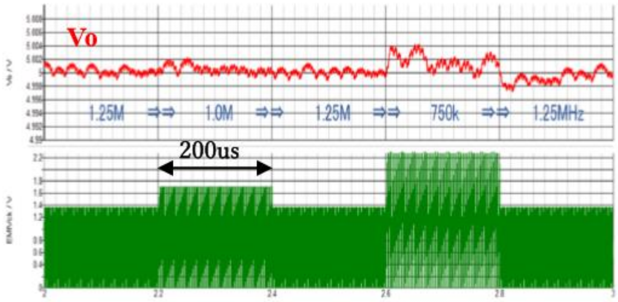


Fig. 13 Transient response for Fin change

3.4. Direct generating the clock pulse (N=2)

When N=2 and Fin=1.25MHz are set in Eq. (12), the clock frequency is automatically calculated as Fck=500kHz and the notch frequency appears at F=1.27MHz between the 2nd and the 3rd harmonics of the clock frequency shown in Fig. 14. The relationship between the period of the clock pulse and that of the input signal is as the next equation.

$$Tck = 2.5 \cdot Tin \qquad (8')$$

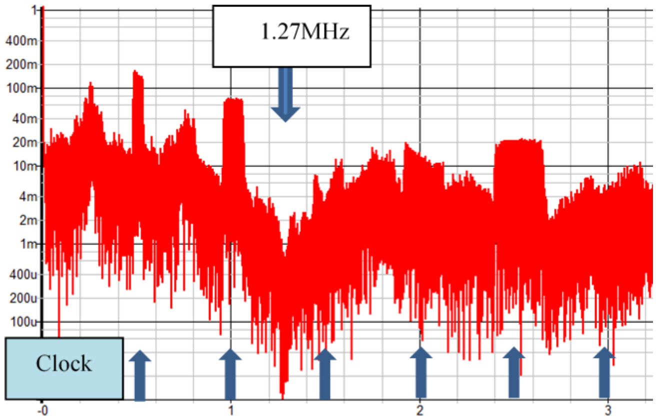


Fig. 14 Simulated spectrum with N=2

3.5 Simulation with the condition Do < 0.2

When the conditions Vin=5V, Vout=1.2V and the input frequency Fin=500kHz, the duty ratio is Do=Vout/Vin=0.24. According to Eq. (9) ~ (12), T_H and T_L are got as the next equations.

$$T_H = 0.24T_{ck} + 0.5T_n \qquad (13)$$

$$T_L = 0.24T_{ck} - 0.5T_n \qquad (14)$$

When N=1 in Eq. (6), T_L has to be set -0.185. This is no good because of a negative number.

It is important to investigate the relationship between the input frequency Fin and the static duty ratio Do. Do is limited by Fin and N. The limitation of Do is calculated as below. Usually, Vo is set less than half of Vin (Do < 0.5), then set T_L= 0 and T_H = 2·Tin.

$$Tck=(N+0.5) \cdot Tin$$

$$Tck > T = (N+0.5)Do \pm 0.5Tin > 0 \qquad (15)$$

$$\therefore \quad 2N \cdot Tin/(2N+1) > D_O > Tin/(2N+1) \qquad (16)$$

When N=1, $(1/3) < Do < (2/3)$ (17)

N=2, $(1/5) < Do < (4/5)$ (18)

4. Conclusion

This paper has proposed the new technique to generate the notch characteristics at the desired frequency in the noise spectrum of the switching converter. The clock pulse and the coding pulses are automatically generated and the notch characteristic automatically appears at the input frequency where the notch frequency Fn appears between the clock frequency Fck and its 2nd harmonic or the 2nd and the 3rd harmonics. In the direct generating method, the settling time of transient response for Fin change is only two clocks. We also discussed the range of Do and T_L.

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