Application of chaotic pulse width modulation control for suppressing electromagnetic interference in a half-bridge converter

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Abstract: It was proposed in the former research that chaos control can be used to suppress electromagnetic interference (EMI) in DC–DC converters. Analysis on a half-bridge converter is detailed in this study. Here, the practical example of the power supply of personal computers is given to show that, with an external chaotic signal to a pulse width modulation control circuit, the proposed approach can reduce EMI by reducing the amplitudes of power signals such as transformer current and output inductor currents at multiples of fundamental frequency.

1 Introduction

Chaos theory was considered one of three monumental discoveries of the twentieth century, together with the theory of relativity and quantum mechanics. As a very special non-linear dynamical phenomenon, chaos has reached its current outstanding status from being merely a scientific curiosity in the mid-1960s to an applicable technology in the late 1990s [1, 2].

Chaos system appears randomly because of becoming sensitive to its initial conditions and status. However, chaos refers to deterministic behaviour which complies with physical or mathematical principles [3, 4]. Chaos theory has been widely applied in social science, economics, political science, biology, philosophy, physics and, of course, engineering applications, such as cryptography, chemical mixing and electromagnetic compatibility (EMC) [2]. Since Deane and Hamill delivered the paper in 1996 [5], chaos has shown its potential value for engineering application in power electronics.

As switch-mode power supplies have lower power consumption compared to linear ones, switch-mode power supplies have been increasingly widely applied in various electrical and electronic devices. Especially, DC–DC converters have electronic switches running at high frequency and produce jumping and leaping signals such as the currents through the inductors and the voltages across the capacitors, which lead to electromagnetic interference (EMI), including conducted and radiated ones, and impair other devices' performance and harm human being's health.

The differences between periodic and chaotic signals are shown in Fig. 1. Each power spectrum density (PSD) is demonstrated in the right column, from which EMI can be estimated and observed normally according to the power distribution with frequency. Fast Fourier transform (FFT) wave of signals can also be used to investigate EMI, because FFT shows the amplitude of every frequency component.

The upper waves refer to the chaotic signal and the lower to the periodic one. It is seen from the lower right sub-figure in Fig. 1 that the large peaks are located at the multiples of the fundamental frequency. Nevertheless, this is inherent in periodic systems which imply EMI. It is supposed that if the systems operate in chaotic modes, the peaks can be spread over the entire frequency band, thus, the peaks are suppressed, implying the reduction of EMI, as shown in the upper right sub-figure of Fig. 1, which is called chaos modulation [6]. Chaos modulation can be used to suppress EMI due to the pseudo-randomness and continuous spectrum features of chaos.

The application of chaos control to reducing EMI in DC–DC converters has been well investigated, including the system design, dynamics analysis, simulations and hardware implementations of chaotic pulse width modulation (PWM) in DC–DC converters [6–10]. In our former research work [6–8, 11], a systematic method has been proposed, including chaos-based analogue/digital, hard/soft switching PWM, for DC–DC converters. It can replace traditional filters and shielding to some extent, which imply high cost, large volume and weight and low efficiency. Thus, it provides a potential solution for EMI problems. However, the models studied in [6–8], such as boost converters, are too ideal and they lack practical applications. Therefore, in this research, a practical example, an ATX2.0 half-bridge converter, is adopted, into which a chaotic PWM is to be embedded for suppressing EMI. It is expected that once it is made available as a marketable hardware design, its commercial future is tremendous.

The rest of this paper is organised as follows: in Section 2 we simplify symmetrical half-bridge topology to be equivalent to one buck converter. This section takes the voltage-controlled PWM as an example, applying the external disturbing signal to realise chaotic PWM control in suppressing EMI. A system description of ATX2.0 power supply with chaos-based PWM design is given in section 3. In Section 4, simulation is given to verify the proposed method by comparing the FFT spectra of transformer current and output inductor currents of the chaos-based PWM with that of the

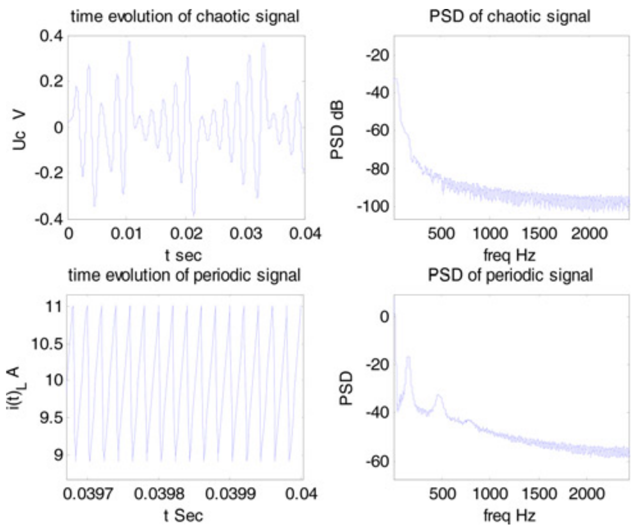


Fig. 1 *Time evolution and spectra of periodic and chaotic signals*

conventional PWM. Meanwhile, experimental tests are provided in the same section. Finally, a conclusion is given in Section 5.

2 Half-bridge converter with PWM control

2.1 Equivalent model of half-bridge topology

Half-bridge converter equips two main power switches and one multiple-output transformer, which operate at high frequency (HF). Complicated structure brings more considerations on analysis and design than buck or boost converters. Fig. 2 shows a typical half-bridge topology. The circuit model is derived under the following assumptions [12, 13]:

(1) Switching transistors ($S1$, $S2$) are identical.
(2) Diodes ($D1$, $D2$) are identical.
(3) Transistor output capacitances and diode capacitances are neglected which implies that switching losses are assumed to be zero.
(4) The output impedance of the input voltage source is zero.
(5) Two secondary windings of the transformer are identical.
(6) PWM module realises the symmetric control scheme. PWM1 has the same duty as PWM2.

Two PWM pulses control two switches being ON or OFF in turn. It is necessary to set up the dead- time during that period both of the two switches are prohibited conducting to avoid short circuit. Two PWM pulses have the same duty named by D and the same cycle denoted by T. In a complete cycle, the current of the output inductor is

$$i_{\mathrm{L}}(t) = \begin{cases} f_1(i_{S1}), & 0 \le t < 0.5T \\ f_2(i_{S2}), & 0.5T \le t < T \end{cases} \tag{1}$$

where i_{S1} and i_{S2} are currents through two transistors. One can deduce another equation

$$i_{\mathrm{L}}(t) = f_1(i_{S1}) + f_2(i_{S2}) \tag{2}$$

On the basis of the previous assumptions, each of two-output windings of transformer exerts the same impact on the inductor L, so that the whole cycle can be divided into two half-cycles. The following are obtained

$$\begin{aligned} &f_1(i_{S1}) = f_2(i_{S2}) = f(i_S), \quad T_0 = 0.5T, \\ &D_0 = \frac{t_{\mathrm{on}}}{0.5T} = 2 \times \frac{t_{\mathrm{on}}}{T} = 2D, \quad f_0 = 2f \end{aligned} \tag{3}$$

Hence, in the cycle of T_0 the current through the inductor L is

$$i_{\mathrm{L}}(t) = f(i_S) \tag{4}$$

To sum up, a symmetrical half-bridge topology can be equivalent to a model with one switch from the point of view of the output circuit.

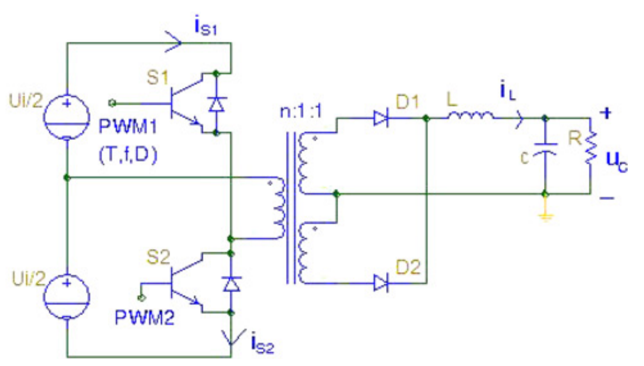


Fig. 2 *Half-bridge converter topology*

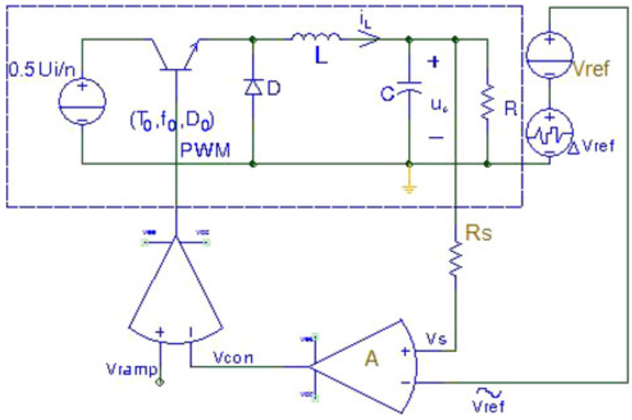


Fig. 3 *Equivalent buck topology and PWM control module*

The low-output-voltage half-bridge topology equates to one buck converter by adjusting some parameters. The input voltage source decreases to $0.5U_i/n$, the switching frequency doubles or the cycle halves, and the duty doubles. The equivalent circuit of Fig. 2 is shown in the dashed rectangle in Fig. 3.

2.2 Chaotic PWM control-based external disturbance

Here, analysis proceeds on the equivalent circuit. Assuming that the system functions in continuous current mode with the cycle T_0, each cycle consists of two periods denoted by T1 and T2. The switch turns ON and the diode turns OFF in T1, and the switch is OFF and the diode is ON in T2. This process becomes true depending on PWM control module, for which a scheme of voltage-feedback-controlled PWM is considered as shown in Fig. 3.

The sampling signal v_s of output voltage is compared with the reference voltage $\tilde{V}_{\mathrm{ref}}$ and the error between them is amplified to produce a controlling signal V_{con}. Normally, the reference voltage keeps constant. If an external tiny disturbance named ΔV_{ref} is exerted on it, there exists the equation

$$\tilde{V}_{\mathrm{ref}} = V_{\mathrm{ref}} + \Delta V_{\mathrm{ref}} \tag{5}$$

The controlling signal V_{con} is indicated

$$V_{\mathrm{con}} = A(v_S - \tilde{V}_{\mathrm{ref}}) \tag{6}$$

where A denotes the gain of the amplifier. Define the ramp waveform

$$V_{\mathrm{ramp}} = v_{\mathrm{L}} + (v_u - v_{\mathrm{L}})\left(\frac{t}{T_0} \bmod 1\right) \tag{7}$$

V_{con} and V_{ramp} are two input terminals of the comparator shown in Fig. 3. The output is high level when V_{ramp} is greater than V_{con} and the switch turns ON. Contrarily, the output is low level when V_{con} is greater than V_{ramp} and the switch turns OFF.

Some methods of chaotic PWM have been reported including adjusting circuit parameter [6, 7]. Changing reference voltage is classified into this kind. An external chaotic signal ΔV_{ref} is added to the constant reference voltage V_{ref} to make the synthetic signal $\tilde{V}_{\mathrm{ref}}$ chaotic. Naturally PWM changes in chaos.

How to produce chaotic signal? In recent decades, chaotic oscillators have been extensively investigated [6, 14–16]. Chaotic oscillators have been used in the PWM control of DC–DC converters to reduce EMI [5, 6, 17]. External chaotic signal is easy to implement and to control by analogue or digital circuit. Among the existing chaotic oscillators, Chua, Lorenz and Chen oscillators are well known. However, the digital signal finally escapes from chaos because of the limited precision of floating point arithmetic in a

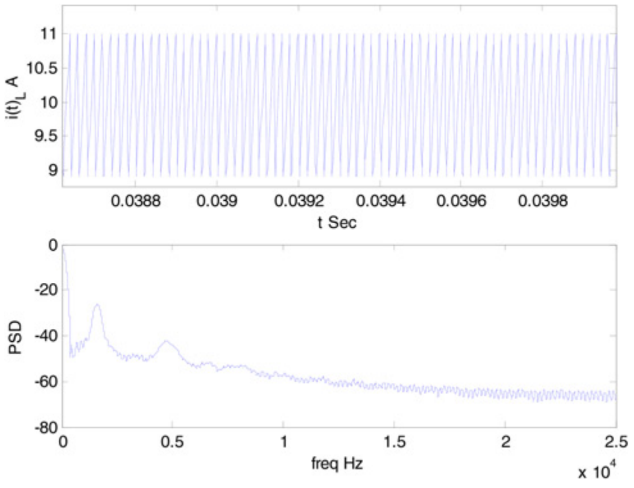


Fig. 4 *Current through inductor L and its PSD with conventional PWM control*

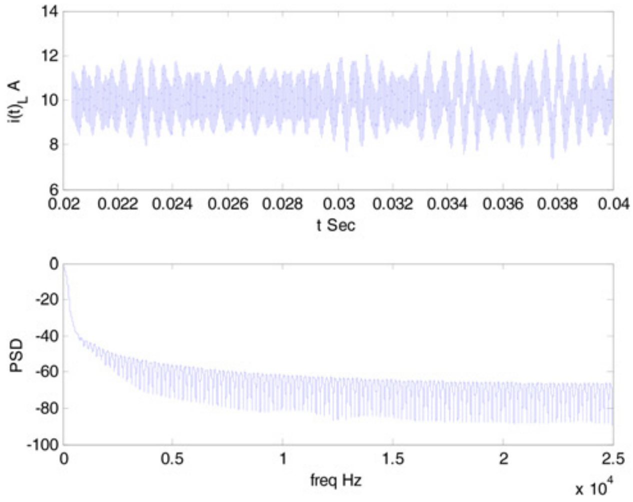


Fig. 5 *Current through inductor L and its PSD with chaotic PWM control*

micro-controller or micro-processor. The analogue signal is normally considered because of low cost and maturity. Analogue chaotic signal can be got from the famous Chua's oscillator, which can be described by the differential equations shown in the following equation

$$\begin{cases} \dfrac{\mathrm{d}u_1}{\mathrm{d}t} = \dfrac{1}{C_{11}}[(u_2 - u_1)G - f(u_1)] \\ \dfrac{\mathrm{d}u_2}{\mathrm{d}t} = \dfrac{1}{C_{22}}[(u_1 - u_2)G + i_1] \\ \dfrac{\mathrm{d}i_1}{\mathrm{d}t} = -\dfrac{1}{L_1}(u_2 + r_0 i_1) \end{cases} \tag{8}$$

Chua's oscillator operates in chaos when a set of appropriate parameters is selected [15]. Extract the proportion of u_2 as the value of ΔV_{ref}, that is

$$\begin{cases} \Delta V_{\text{ref}} = k u_2 \\ \tilde{V}_{\text{ref}} = V_{\text{ref}} + \Delta V_{\text{ref}} \end{cases} \tag{9}$$

Take equations from (5) to (8) into consideration and applying software MATLAB7.0 to simulating the current through the inductor and its PSD. Relative parameters are listed as follows

$$\begin{gathered} L = 20\ \mu\text{H},\ \ C = 1\ \text{mF},\ \ R = 1.2\ \Omega,\ \ k = 0.05 \\ f_0 = 2.5\ \text{kHz},\ \ 0.5U_i/n = 14.8\ \text{V},\ \ v_S = 0.25 v_O \\ V_{\text{ref}} = 2.70\ \text{V},\ \ A = 2,\ \ V_{\text{L}} = 0\ \text{V},\ \ V_U = 3.5\ \text{V} \end{gathered} \tag{10}$$

The results are shown in Figs. 4 and 5. It was observed that the amplitude peaks of PSD were flattened under chaotic PWM control, especially the peak at the fundamental frequency. On the other side, chaotic PWM control possibly leads to the increment of the output ripples, which can be controlled in an acceptable range by designing output filters or adjusting some parameters. Compared with conventional PWM control, EMI is suppressed and reduced. A power supply example is demonstrated to verify the practical effect in the next section.

3 Design of the chaos-based PWM in ATX power supplies

3.1 System design

Power supply ATX2.0 is a typical accessory of personal computers (PCs), which comprises of many modules. Among them, the PWM control circuit is to be driven by a chaotic signal, generated by Chua's circuit. The whole diagram of power supply ATX2.0 with chaos control is depicted in Fig. 6.

The main circuit consists of a half-bridge reverting module and a HF isolating transformer, which can generate multiple DC voltages such as ±5, ±12 V etc. Some other peripheral components are the auxiliary power, the signal detection and protection components. The main circuit is shown in the dash-dotted rectangle in Fig. 6.

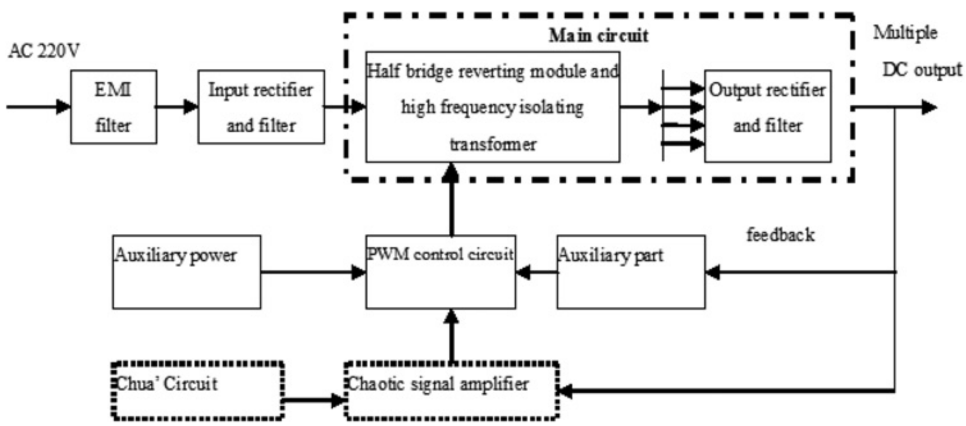


Fig. 6 *Schematic diagram of the computer power supply with chaotic control*

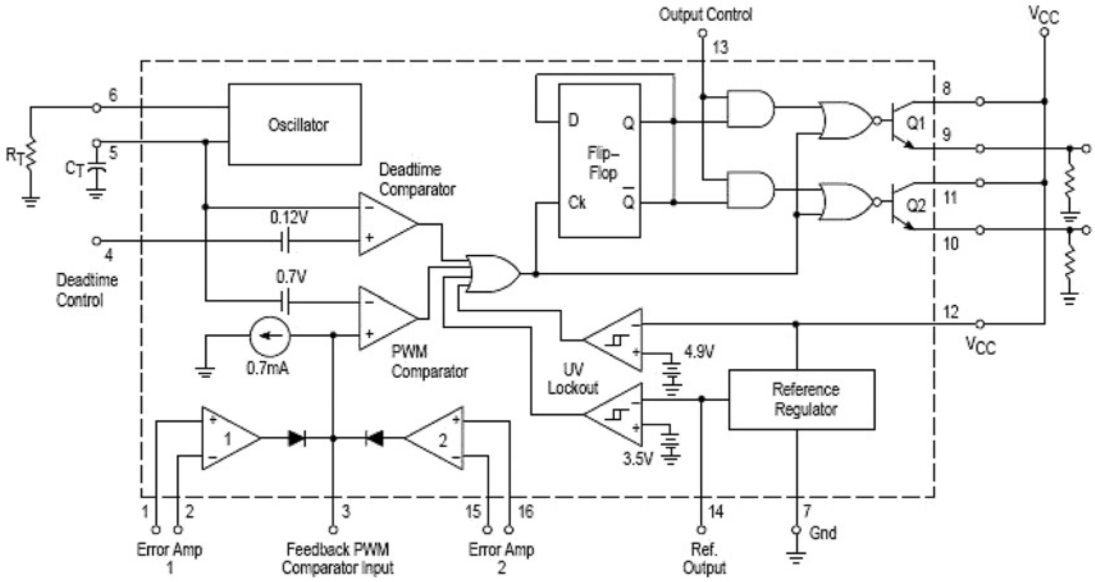


Fig. 7 *TL494 block diagram*

A special integrated circuit (IC) TL494 is used as the PWM control module [18]. The TL494 is a frequency-fixed PWM control circuit, incorporating the primary building blocks required for the control of a switching power supply, as shown in Fig. 7. Two error amplifiers process the errors. Two comparators control the dead-time and process the output feedback. NOR gates, enabled only if the flip-flop clock pulse changes to logic 0, are used to drive output transistors $Q1$ and $Q2$. An internal amplitude-fixed linear saw-tooth oscillator is frequency-–programmable because of two external components, R_T and C_T. The oscillator frequency is determined by

$$f_o = \frac{1.1}{R_T C_T} \tag{11}$$

Denote the signal at Pin 5 by u_{ct}, the input of the dead-time control comparator by u_{dead}, and the feedback signal at Pin 3 by u_{fdb}. By means of Pin 3 of TL494, impose a chaotic signal named u_{chao} to TL494. There exists [19]

$$u_{fdb} = u_{chao} \tag{12}$$

When $u_{ct} > u_{dead}$ and $u_{ct} > u_{chao}$–0.7, one has

$$\text{CK} = 0, \quad Q1_b = \bar{Q}n, \text{ and } Q2_b = Qn \tag{13}$$

otherwise

$$\text{CK} = 1, \quad Q1_b = 0, \quad Q2_b = 0 \tag{14}$$

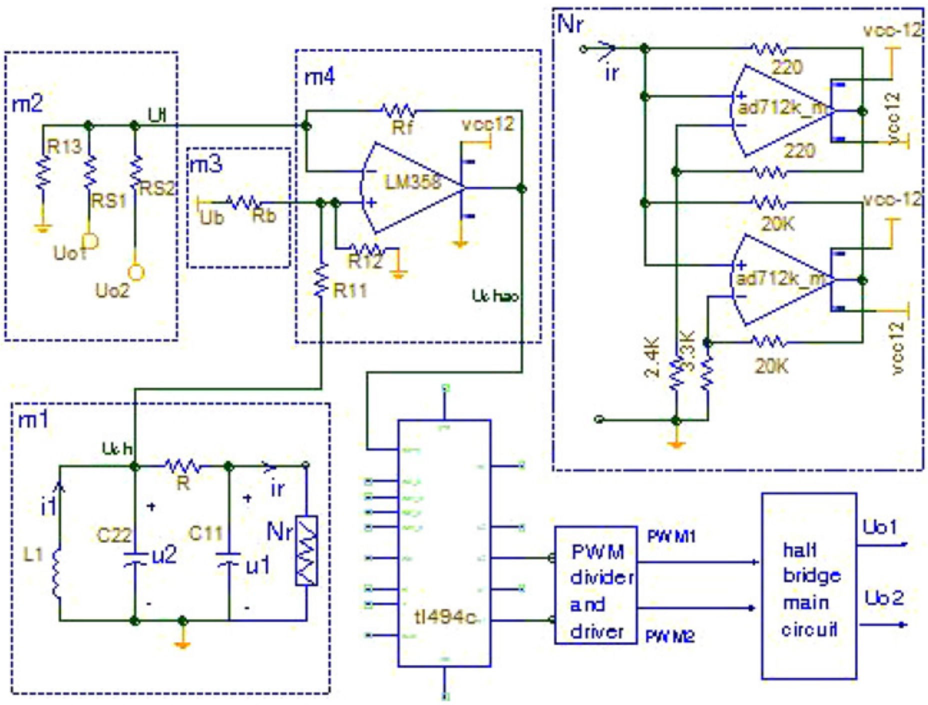
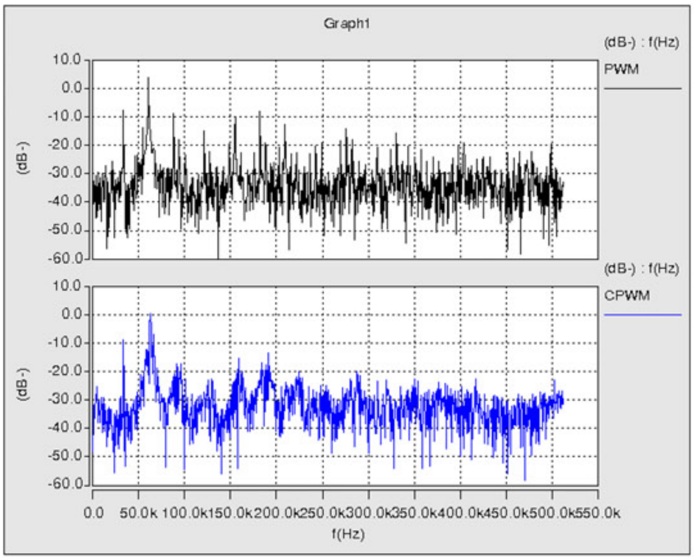
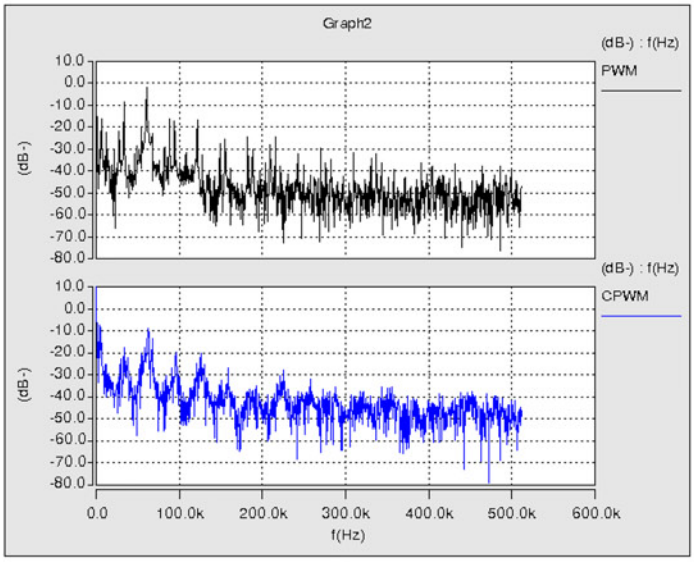


Fig. 8 *Chaotic PWM module*



a



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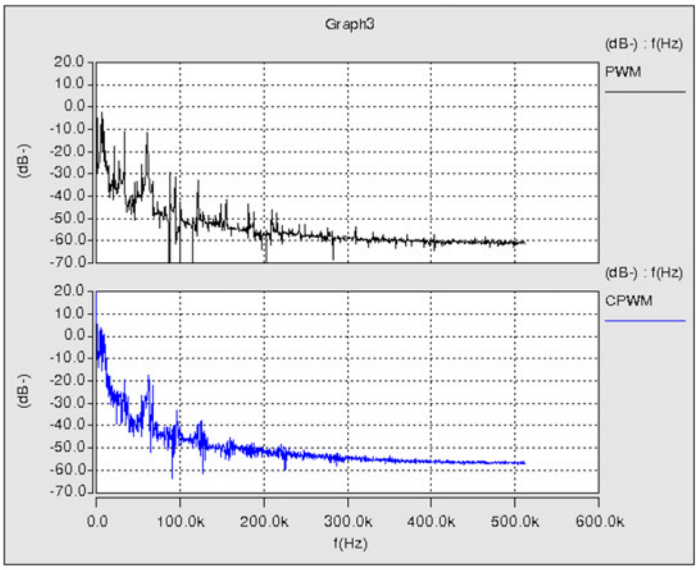

c

Fig. 9 *FFT spectra (upper waveform in each sub-figure corresponds to the conventional PWM, whereas the lower to the chaotic PWM)*
a Primary winding current i_P
b Inductor current i_{L+12}
c Inductor current i_{L+5}

Table 1 Amplitudes at the multiples of fundamental frequency

	Multiples	1	2	3	4	5	6	7	8
i_P, dB	PWM	−8	4	−9	−15	−10	−9	−12	−20
	CPWM	−9	0	−19	−22	−18	−14	−25	−25
	decrement	1	4	10	7	8	5	13	5
i_{L+12}, dB	PWM	−9	−2	−18	−18	−28	−27	−27	−32
	CPWM	−19	−10	−20	−20	−29	−38	−29	−32
	decrement	10	8	2	2	1	11	2	0
i_{L+5}, dB	PWM	−10	−11	−30	−32	−41	−43	−47	−52
	CPWM	−20	−18	−34	−39	−48	−50	−50	−53
	decrement	10	7	4	7	7	7	3	1

where Qn and $\bar{Q}n$ stand for the outputs of the flip-flop, and have opposite states. If Qn is at logic 1, then $\bar{Q}n$ is at logic 0. Any change in chaotic signal amplitude causes a corresponding change of the output pulse width, so the pulse width of the PWM varies chaotically.

3.2 Design of external chaos circuit

It is critical to design an external chaos module to connect Pin 3 of TL494 for chaotic PWM. Fig. 8 displays the detailed design. Module $m1$ is in charge of generating chaotic signal, $m2$ performs two-output-feedback sampling, $m3$ establishes the reference voltage and $m4$ fulfils amplifying.

In this paper, Chua's oscillator is adopted because of its simplicity and maturity. The diagram of which, labelled by $m1$, is shown in Fig. 8, where N_r is Chua's diode implemented by an active circuit, shown by the dot-dashed line rectangle [7]. Chua's oscillator can be described by the differential equations shown before in (8), where $f(.)$ stands for the reciprocal of Ohm to Chua's diode N_r and it is a three-segment piecewise-linear function [14]. G and r_0 stand for the reciprocal of the resistor R and the resistance of the inductor L_1, respectively.

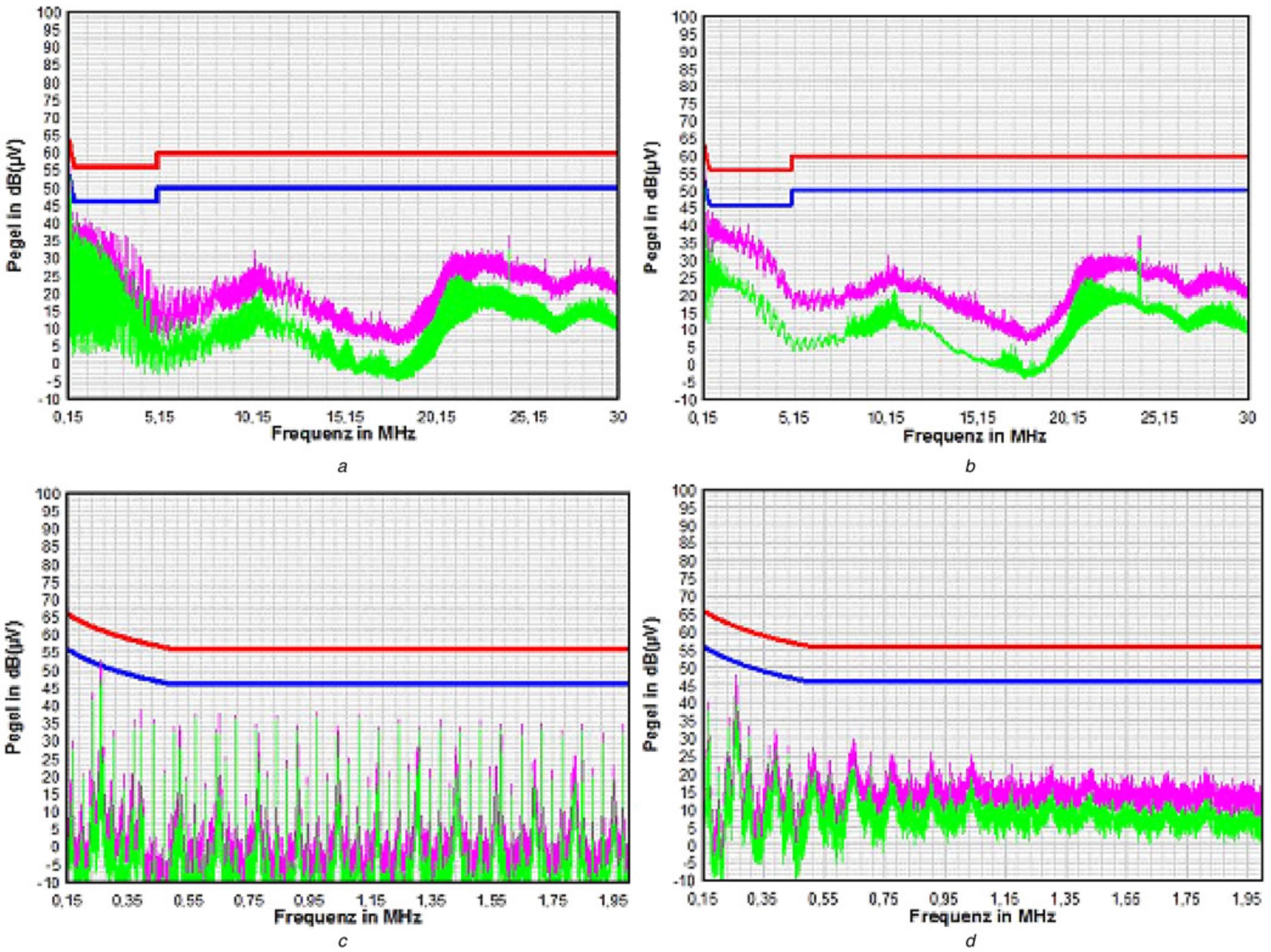

Fig. 10 *EMI test (upper SPAN:0.15–30 MHz, BW9 kHz, STEP:5 kHz; lower SPAN:0.15–2 MHz, BW200 Hz, STEP:100 Hz)*
a EMI for normal ATX2.0
b EMI for chaotic PWM
c EMI for normal ATX2.0
d EMI for chaotic PWM

The voltage at the feedback pin 3 of TL494 is required to vary between 0.5 and 3.5 V according to the specification of Pin 3 [18]. Thus, the amplifier is designed to scale the signal $u_{ch} = u_2$ into [0.5, 3.5].

4 Simulation and experimental tests

4.1 Simulation

Let $R_T = 12$ KΩ and $C_T = 1.5$ nF, and the parameters of other components are taken from a real ATX2.0 power supply. Therefore $f_0 = 50$ kHz and switching frequency f_s is one half of f_0.

The parameters of the Chua's oscillator are $L1 = 2.2$ mH, $C22 = 4.7$ nF, $C11 = 500$ pF and $R = 1.75$ kΩ. The parameters of the amplifying module are $R11 = R12 = R13 = 10$ kΩ, $Rs1 = 36$ kΩ, $Rs2 = 90$ kΩ and $Rf = 7$ kΩ.

The simulation is executed with Software Saber (Version 2008), and shows the results for ATX2.0 operating both in conventional PWM and chaos-based PWM (CPWM) using an external chaos generator. EMI reduction is measured by using FFT of the critical component signals such as the current through the HF transformer and the inductor currents of +12 and +5 V outputs, denoted by i_P, i_{L+12} and i_{L+5}. The results are given in Fig. 9. Table 1 shows the amplitudes at the multiples of fundamental frequency in PWM control and CPWM control.

Fig. 9 and Table 1 indicate that the amplitudes of the multiples of the baseband under the chaos-based PWM are greatly reduced, implying the reduction of EMI, compared with those under the conventional PWM.

4.2 Electromagnetic interference (EMI) tests

Experiment and hardware design also have been conducted to further verify the effectiveness of the chaotic PWM. The EMI tests are executed under the EMC standard EN55022 Class B conducted QP and EN55022 Class B conducted AV with the device ROHDE&SCHWARZ ESIB26 20 HZ–26.5 GHZ. The results of the EMI of the power supplier ATX2.0 applying the conventional PWM and the chaos-based PWM are given in Fig. 10, showing the effectiveness of using the chaos-based PWM in suppressing EMI.

5 Conclusion

The effectiveness of chaos control in suppressing EMI in DC converters gets verified on the half-bridge converter topology, which appears largely in engineering applications. A power supply ATX2.0 for PCs is used as a test bed which distinguishes it from the simple converter. In this paper, a chaos circuit is designed to generate chaotic signals and to integrate into the main board of the commercial power supply. Simulation and experimental results have shown that the chaos-based PWM method provides a potential solution to EMI problems in a complicated DC converter such as reducing the requirement of EMI filters, which is of some social and economic significance.

6 Acknowledgment

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