Study on Chaos Control in PFC Boost Converter Based on the Delay Feedback Control

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Abstract: In Power-Factor-Correction (PFC) Boost Converter, due to the wide fluctuations of the voltage as the power frequency is 50 HZ, the fast-scale instability and chaotic phenomena are apt to appear in circuits. The method commonly used to weaken the unstable phenomena is to introduce the slope compensation. However, since the design of slope signals lacks of theoretical basis, the overcompensation surfaces from time to time, which leads to the substantial drop of input power factors. According to this situation, we introduce the delay feeback control to stabilize the unstable periodic tracks of chaotic attractors. Researches demonstrate that the design of the delay feedback compensation rage is determined by the four main circuit parameters (the switching cycle, input voltage, output voltage, and inductor) of the converter. Abundant conclusions of simulation experiments testify that the proper delay feedback compensation range not only controls the fast-scale bifurcation and chaotic phenomena, but also maintains the higher input power factor.

Keywords: PFC Boost Converters; Peak Current Mode Control; Fast-Scale Instability; Chaos; Delayed Feedback Control.

1. Introduction

Since the 1990s, many experts and scholars have made in-depth researches of varied bifurcation and chaotic phenomena. They have discovered numbers of bifurcation and chaotic phenomena and established some fairly mature research methods, such as the numerical iterative method used to create the discrete model of low-dimensional DC-DC converter[1-3], and the Jacobian matrix used to judge the stability[4,5]. However, the nonlinear phenomena of AC-DC converter circuit are seldom involved in these researches, and the studies on the control of that are fewer. In the switching power supply, due to common use of the rectifying and filter circuit, bifurcation and chaotic phenomena exert more serious pollution to harmonic currents of the power grid. To reduce the damage caused by harmonic current pollution, people have intensively applied Power Factor Correction (PFC for short) in power electronic circuits as effective methods to suppress this pollution. By adopting PFC , the currents on the side of power grid have no harmonic wave, and the most ideal situation is that the input current of the power is also in the form of sine wave, as well as consistent with the phase of alternating voltage. At this moment, for the alternating power system, the power supply is equivalent to a pure resistance, and the current absorbed form the power grid is merely active current. Consequently, the loss and cost drop to a minimum, and the interruption to other devices becomes less[6].

In the application of the converter with original power factor correction, Boost converter is a sort of topological structure most commonly used[7-9]. To get input nearly unit power factors and the output voltage, the input current plastic technology with multiplying unit as its core can be employed, including peak current mode control, average current mode control, etc. But attributed to the wide fluctuation of the sine input voltage, the converter is apt to produce time-domain fast-scale instability and chaotic phenomena when using these control methods [10-18]. A common solution is to add slope compensation so as to narrow the range of the unstable phenomena [7-9]. But the slope compensation has no certain design criteria, so the design experience plays a dominant role, overcompensation occurs frequently, which causes the rise of the total harmonic distortion (THD) of the input current and leads negative influences to the power factor.

In 1992, the famous scholar Pyragas proposed the Time-Delayed Feedback Control (TDFC), which was later improved and developed by him and other scholars. This approach is simple and effective for keeping Unstable Periodic Orbits (UPO) in chaotic attractors steady[19]. It turns out that it is also applies to the chaos control of PFC Boost converter.

2. Basic Principle

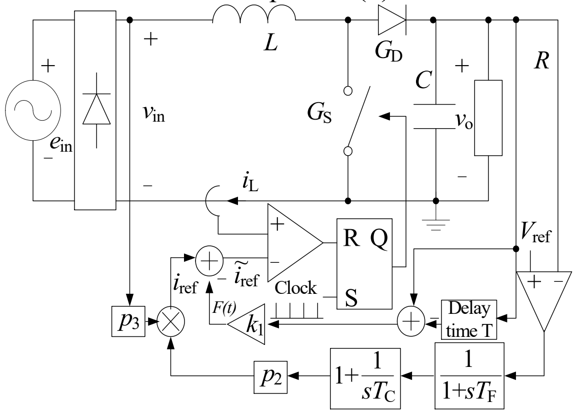
The basic circuit topology of PFC Boost converter of the peak current mode is shown in Figure 1(a). The main circuit of Boost converter is a second-order circuit, including the inductor L, the switching G_S, the diode G_D, the input capacitor C and the load R. Because the circuit works in the Discontinuous Conduction Mode (DCM) when applied in PFC, there are three switching states in a switching cycle: (1) the switching G_S is on, the diode G_D is off; (2) the switching G_S is off, the diode G_D is on; (3) the switching G_S is off, the diode G_D is off. The correspondent state equation describing system operation is as follows [20]

$$\begin{cases} \dot{x} = A_1 x + B_1 E & G_S \text{ on}, \; G_D \text{ off} \\ \dot{x} = A_2 x + B_2 E & G_S \text{ off}, \; G_D \text{ on} \\ \dot{x} = A_3 x + B_3 E & G_S \text{ off}, \; G_D \text{ off} \end{cases} \tag{1}$$

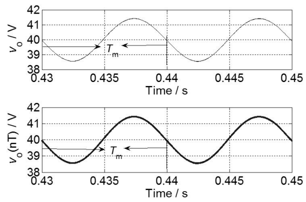
Among them, x is the state vector, i.e. x=[i_L, v_o]^T, the coefficient matrixes are:

$$A_1 = A_3 = \begin{bmatrix} 0 & 0 \\ 0 & -1/RC \end{bmatrix}, A_2 = \begin{bmatrix} 0 & -1/L \\ 1/C & -1/RC \end{bmatrix}, B_1 = B_2 = \begin{bmatrix} 1/L \\ 0 \end{bmatrix}, B_3 = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{2}$$

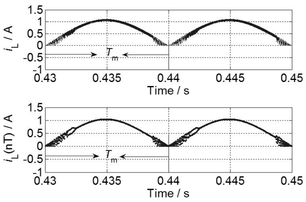
Based on the equations (1) and (2), we can set up the accurate Simulink simulation model of the system by combining the voltage and the current dual loop control showed in Figure 1(a). However, within a power frequency, the converter works in DCM only when the inductor current nearby zero-crossing, and a major part work in the Continuous Conduction Mode (CCM). Therefore, in the following part of theoretical analysis, we can only take its two working states in consideration, i.e. the former two situations in the equation (1).



(a)The basic circuit diagram



(b) The time domain waveform of the out-put voltage (up)



(c) The time domain waveform of the inductor current

The stroboscopic sampling waveform of the output (up); The stroboscopic sampling waveform of the voltage (down); inductor current (down)

Figure1. The parallel PFC Converter under the Current Mode Control

To eliminate the fast-scale instability and the chaotic phenomena, we introduce the delay feedback control into the circuit. The approach of the delay feedback control refers to make the input signal or output signal of the chaotic system appear a signal difference after a certain time delay, and add this signal difference to some variable or parameter of this chaotic system through the amplification after a feedback gain, in order to change the operating state of the system and achieve the transformation from the chaotic to the stable single cycle. In the equation

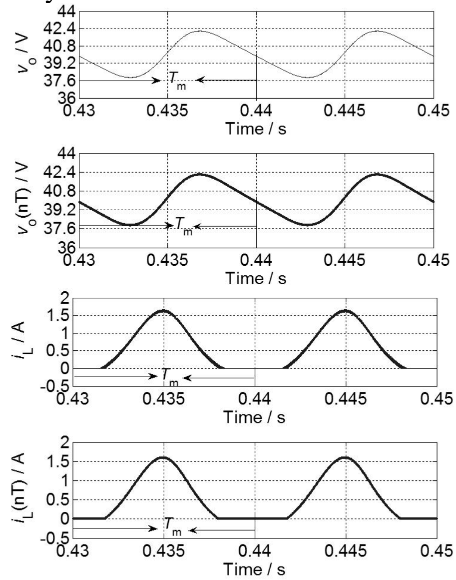
$$F(t) = k_1[v_0(t-\tau) - v_0(t)] \tag{3}$$

in Figure 1, $v_0(t)$ is the output variable of the capacitor voltage, τ is the delay time of the system, $v_0(t-\tau)$ is the output variable of the capacitor voltage after the delay time τ, k_1 is feedback control gain. When the system is not controlled, $F(t)=0$, it means no feedback control, i.e. $\tilde{i}_{ref} = i_{ref}$, because of the wide fluctuation range of the alternating reference voltage v_{ref},the PFC Boost converter controlled by the peak current mode will confront the situation that the duty cycle is quite large within half a power frequency cycle, which lead to the fast-scale instability and chaotic phenomena, in this case the system is chaotic; when the system is controlled, the signal of the delay feedback control $F(t) = k_1[v_0(t-\tau) - v_0(t)]$, i.e. the reference current i_{ref} minus $F(t)=k_1[v_0(t-\tau)-v_0(t)]$ gets the reference current $\tilde{i}_{ref}$, then comes to $\tilde{i}_{ref}=i_{ref}-k_1[v_0(t-\tau)-v_0(t)]$. When the clock pulse signal comes, the switching G_S is on, and the inductor current rises; when the inductor current reaches $\tilde{i}_{ref}$, G_S is off, the inductor current drops until the next clock pulse comes. The reference current i_{ref} is usually the sine modulation of the output voltage with amplified error, (i.e. to multiply the input voltage v_{in} after rectifying), then the peak value of the inductor current can follow the waveform of sine input voltage, and the circuit can get near unity power factor.

Based on the equations (1) and (2) and the circuit in Figure 1(a), the circuit parameters are: the peak value of the input voltage $e_{in}=22\text{V}$, the inductor L=2mH, the capacitor $C=470\mu\text{F}$, the load R=100Ω, the switching cycle $T_s=20\mu S$, the working frequency f_m=50HZ, the reference voltage $V_{ref}=40V$, the feedback gain $p_2=1/60$, the gain $p_3=0.08$, the time constant of the low pass filter $T_F=4ms$, and the time constant of the converter $T_C=20ms$. Through the accurate Simulink model simulation of the system, we can get the time domain waveform of the inductor current as Figure 1(b) shows and the stroboscopic sampling waveform of the inductor current as Figure 1(c) shows. From the figures, we can see that the upper parts on the left and right branches appear fast-scale bifurcation within a working cycle of PFC Boost converter. As we know, the reference current is time-varying, so these two branches of fast-scale bifurcation are in asymmetry. To control the unstable phenomena, we adopt the approach of delay feedback control in circuit design (the compensation signal in Figure 1(a) $F(t)=k_1[v_0(t-\tau)-v_0(t)]$, and the compensation reference current is $\tilde{i}_{ref}=i_{ref}-k_1[v_0(t-\tau)-v_0(t)]$.

3. The Numerical Simulation Results of the Delay Feedback Control to Chaos

By controlling the chaotic phenomena shown in Figure 1, we can get the control results as shown in Figure 2 through Matlab numerical simulation, with the simulation optimal compensation range k_1 as 22. In Figure 2, there are the time-domain and stroboscopic-sampling numerical simulation waveforms of the output voltage and inductor current, from which we can not see the fast-scale bifurcation and the chaotic phenomena; thereby we think that the circuit operates in a regular state of overall stability.



(a) The time domain waveform of the out-put voltage (up); (b) The time domain waveform of the inductor current

The stroboscopic sampling waveform of the output (up); The stroboscopic sampling waveform of the

voltage (down); inductor current (down)

Figure2 The Working Waveform under the Proper k_1

4. The Choice of the Feedback Gain and Delay Time in the Delay Feedback Approach

(1) The delay time $\tau=T=20\mu s$

When set up $k_1=19-24$ after a number of simulations, the chaotic system can be controlled at the stable cycle 1 state.

Table 1. The Comparison of the Circuit Performance Between before and after the Chaos Control

Feedback gain k_1 /the power factor before and after the chaos control, the total harmonic distortion of the output capacitor voltage(THD)	PF before and after the chaos control	THD before and after the chaos control
$k_1=19$	0.9963/0.9257	0.0867/0.4077
$k_1=20$	0.9963/0.9156	0.0867/0.4382
$k_1=21$	0.9963/0.9042	0.0867/0.4714
$k_1=22$	0.9963/0.8913	0.0867/0.5078

$k_1 = 23$	0.9963/0.8765	0.0867/0.5482
$k_1 = 24$	0.9963/0.8598	0.0867/0.5931

Due to the addition of the feedback gain k_1 , the peak value of inductor current drifts away from the sine reference current i_{ref} , THD of the average inductor current is a little bigger compared with that without the addition of the feedback gain k_1 , and the power factor drops. Compared Table 1, we can conclude that the controlled system has good stability and dynamic response as $k_1 = 22$.

(2) The delay time $\tau = 2T = 40\mu s$

When set up $k_1 = 10.5 - 12$ after a number of simulations, the chaotic system can be controlled at the stable cycle 2 state.

Table 2. The Comparison of the Circuit Performance Between before and after the Chaos Control

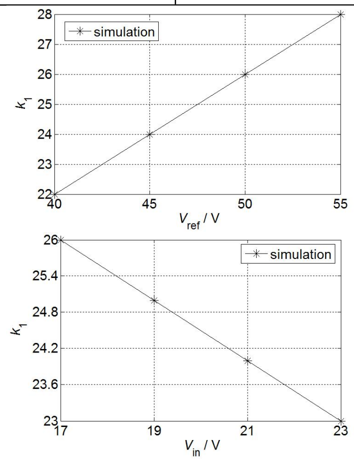
Feedback gain k_1 / the total harmonic distortion of the output capacitor voltage before and after the chaos control(THD)	PF before and after the chaos control	THD before and after the chaos control
$k_1 = 10.5$	0.9963/0.8974	0.0867/0.4909
$k_1 = 10.8$	0.9963/0.8890	0.0867/0.5143
$k_1 = 11.1$	0.9963/0.8799	0.0867/0.5393
$k_1 = 11.4$	0.9963/0.8696	0.0867/0.5670
$k_1 = 11.7$	0.9963/0.8580	0.0867/0.5979
$k_1 = 12$	0.9963/0.8453	0.0867/0.6315

Due to the addition of the feedback gain k_1 , the peak value of inductor current drifts away from the sine reference current i_{ref} , THD of the average inductor current is a little bigger compared with that without the addition of the feedback gain k_1 , and the power factor drops. Compared Table 2, we can conclude that the controlled system has good stability and dynamic response as $k_1 = 11.7$.

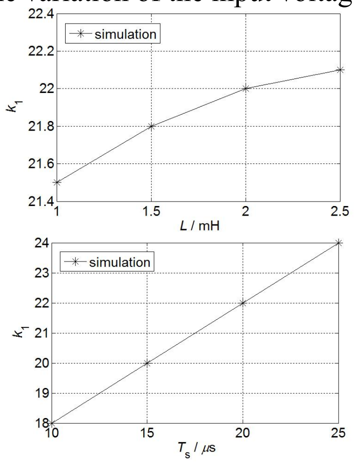
As the above figures and tables show, the time delay feedback approach can effectively control the chaotic phenomena in circuits, if the delay time is set as $\tau = nT$, the converter can be controlled at the cycle n state.

5. The Influence Factors of the Delay Feedback Compensation Range

The delay feedback compensation range is to some extent influenced by the reference voltage V_{ref}, the input voltage V_{in}, the switching cycle T_s, and the variation of the inductor L. Through many accurate simulations of circuits, the paper presents the influences of the variation of these parameters to the delay feedback compensation range, see Figure 3. Based on analysis and observation, we find that the needed feedback gain k_1 rises with the increase of the reference voltage V_{ref}, the inductor L and the switching cycle T_s, and while the input voltage V_{in} increases, the needed feedback gain k_1 decreases. Therefore, the analysis results supply a good guidance to the design and control of the stable circuits.



(a) The variation of the reference voltage V_{ref} (b) The variation of the input voltage V_{in}

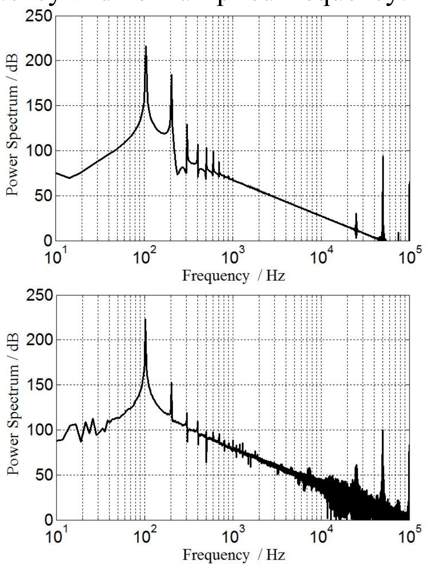


(c) The variation of the inductor L (d) The variation of the switching cycle T_s

Figure 3. The Accurate Simulation of the Design of the Delay Feedback Compensation Range

6. The Influence of the Delay Feedback Control to System Performance

After comparing before and after the chaos control (Figure 1 and 2), the circuit performance has a considerable improvement. Figure 4 is the power spectrum analysis of the input capacitor voltage. Without control, the chaotic phenomena appear in some time sections within a power frequency cycle (see Figure 1(c)). Therefore, in the correspondent power spectrum Figure 4(a), there are some spread spectrum behaviors near 50kHZ switching frequency. Correspondently, the chaotic phenomena get suppressed when the circuit applies the delay feedback control approach. In Figure 4(b), the spectrum reflects the working frequency of 50HZ, the switching frequency and its multiplied frequency.



(a) Before the chaos control (correspondent to Figure 1) (b) After the chaos control (correspondent to Figure 2)

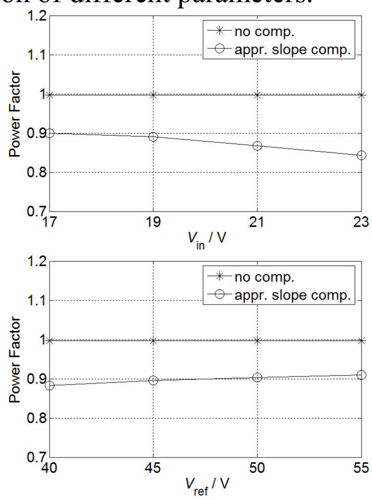
Figure 4. The Power Spectrum of the Output Capacitor Voltage before and after the Chaos Control

We select a waveform of a working frequency, and get the average inductor current ripple, the maximum inductor current ripple and the minimum inductor current after calculation. In Table 3, we can see the considerable promotion of all indicators after the application of the chaos control. That's because the appearance of bifurcation and chaos phenomena aggravate the irregularity of the switch shift, which leads to the increase of circuit ripples and current stress in the switch devices. If the electric motor carries loads, its acoustic noise and mechanical vibration will increase, which is harmful to the system operation. After the chaos control, the system works steadily at the switching frequency, the time domain waveform presents the smooth half sine wave, thereby any bifurcation and chaotic phenomena will not occur, and the system operates steadily and reliably.

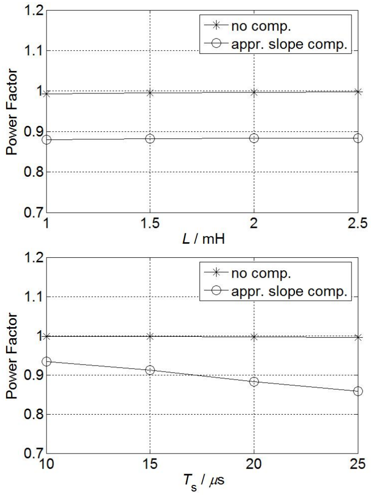
Table 3. The Comparison of the Circuit Performance Between before and after the Bifurcation Control

	Before the bifurcation control (figure 1)	After the bifurcation control (figure 2)
Average inductor current ripple(A)	0.1845	0.1283
Maximum inductor Current ripple(A)	0.4823	0.2135
Minimum inductor current ripple(A)	0.0018	0

When some parameters in the circuits change, the PFC Boost converter of the peak current mode appears the fast-scale bifurcation and chaotic behaviors, which can be controlled by introducing the proper delay feedback can control at this time. The introduction of the proper delay feedback makes the average vale of the inductor current further deviate from the standard sine wave, and consequently, the input power factor will fall to some extent. But the proper delay feedback compensation range can not only control the fast-scale bifurcation and chaotic phenomenon, but also can reduce the power factor to the minimum. Figure 5 reflects the variation of the power factor on the condition of different parameters.



(a) The variation of the input voltage V_{in}
(b) The variation of the reference voltage V_{ref}



(c)The variation of the inductor L

(d) The variation of the switching cycle T_s

Figure 5. The Influence of the Proper Delay Feedback to the Power Factor

When there is no compensation, although the fast-scale bifurcation and chaotic phenomena exist in the circuit, the power factor can still keep at a high level. With the increase of the voltage input V_{in} or the switching cycle T_s and the reduction of the reference voltage V_{ref} or the inductor L, the power factor will descend.

7. Conclusions

The delayed feedback approach is adopted to deal with the chaotic phenomena occurring in the more complex circuits in power electronic circuits, like PFC Boost Converter. The chaotic phenomena get effective control and achieves the transformation of the periodic state from the chaotic state to the steady state. The results of the control make the system back to the unstable periodic orbits (UPO) in the chaos of the original system. Through a large number of simulations, we summarize how the different feedback gain k_1 and different delay time τ influence the system performance and how the circuit parameters affect the feedback gain k_1, so as to provide a reliable theoretical guidance for the design of the circuit stability.

Acknowledgments

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