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Filter based non-invasive control of chaos in Buck converter

Wei-Guo Lu *, Luo-Wei Zhou, Quan-Ming Luo, Xiao-Feng Zhang

State Key Laboratory of Power Transmission Equipment & System Security and New Technology (Chongqing University), Chongqing 400044, China

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Abstract

A non-invasive method for controlling chaos in the voltage-mode Buck converter is proposed by using a hybrid active filter based feedback controller in this Letter. The harmonic balance method is applied to obtaining the bifurcation-point equations of the controlled system. Hence, a stability-boundary diagram is constructed, through which the control parameters are chosen correctly. The results of simulation and experiment are given after all.

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Keywords: Control of chaos; Non-invasive control; Buck converter; Hybrid active filter

1. Introduction

Bifurcations and chaos are known to exist in the feedback controlled DC–DC converters [1–3]. Such nonlinear phenomena would deteriorate the performance of power converters. Furthermore, there are few effective approaches for precisely forecasting and controlling the state variables and output in chaos. Therefore, an effective way for suppressing the chaotic behavior in the DC–DC converters is of great significance in engineering. The voltage-mode Buck converter and the current-mode Boost converter are two earliest kinds of power converters for investigation of nonlinear behavior. The output voltage enters into chaos and behaves in pseudo-random state with the variation of its system parameters, which deteriorates the system working performance. Some methods including the Ott–Grebogi–Yorke (OGY) method [4,5], dynamic feedback method [6], washout filter based method [7] and time-delayed feedback method (TDFC) [8], etc., have been developed for the control of chaos in the DC–DC converters in last two decades. With respect to control effect, above chaos-control methods are classified into two kinds: invasive and non-invasive chaos control. By applying the invasive control method, the chaotic system would be stabilized in a new period-1 mode, which is not an expectant way for the DC–DC converters because the expectant performances of converters are determined. However, the non-invasive control [9–11] whose output vanishes at the target state has the advantages of less energy cost and minimal intervention to the controlled system, which are vital to power converters. By using the non-invasive chaos control, the controlled DC–DC converter can be stabilized in the unstable period-1 orbit within the chaotic attracter of the controlled system. Among the aforementioned methods, the OGY method and the TDFC method are featured with non-invasive effect, but the target orbit need be first identified for the OGY method. In Ref. [8], the TDFC method has been applied to the control of chaos in a voltage-mode Buck converter and its control parameters were ascertained analytically by using Flouquet theory. However, the realization of proposed control in engineering is not involved in it. In addition, because its feedback signals are introduced into the power-stage circuits, the controller realization in engineering would be difficult.

Based upon the above analysis, here an alternative non-invasive control algorithm for the control of chaos in a voltage-

* Corresponding author at: College of Electrical Engineering, Chongqing University, Chongqing 400044, China. Tel.: +86 023 65103558.

E-mail addresses: reedlu1013@gmail.com (W.-G. Lu), zluowei@cqu.edu.cn (L.-W. Zhou).

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mode Buck converter is proposed. In this method, a hybrid active filter (HAF) is employed instead of a delay line used in the TDFC method and it is realized in engineering easily. The stability boundary of the controlled system is determined by applying the harmonic balance method, through which the control parameters are ascertained for the following simulation and experiment work.

The rest of this Letter is organized as follows. In Section 2, the schematic diagram and dynamic model of Buck converter with HAF based feedback control are given and the bifurcation-point equations are derived. Sections 3 and 4 are devoted to the simulation results and the experiment results, respectively. This Letter ends with conclusions in Section 5.

2. Buck converter with HAF based feedback control

2.1. Derivation of the dynamic model for the controlled Buck converter

In this section, a dynamic model of the voltage-mode Buck converter with HAF based controller is presented. The transfer function of the HAF based controller is defined as $G_f(s)$. The input of the proposed controller should be chosen from the state variable or the output for detecting the nonlinear behaviors of the controlled system. Furthermore, we can found that the non-invasive effect of the proposed controller can be realized when the following frequency-domain conditions are guaranteed: $G_f(j0)=0$, $G_f(j2\pi/T)=0$, where T is the switching period of the controlled Buck converter, i.e. the control target orbit. Therefore, we can define $G_f(s)$ as the forms of

$$G_f(s)=k_2\frac{s(s^2+\omega_s^2)}{M(s)}, \tag{1}$$

where ω_s is equal to $2\pi/T$, k_2 is the gain of the proposed controller, and $M(s)$ is a third-order polynomial.

From Eq. (1), we know that while the controlled system is stabilized in the target period-1 mode the controller output vanishes, while in other situations the output has a non-zero value. Therefore, the HAF based controller is featured with a self-stable control effect. In addition, $G_f(s)$ can be separated into two parts: a first-order high-pass filter and a second-order notch filter. Hence, we have

$$G_f(s)=G_{f1}(s)G_{f2}(s), \tag{2}$$

where,

$$G_{f1}(s)=p_1\frac{s}{s+a},\quad a>0, \tag{3}$$

$$G_{f2}(s)=p_2\frac{s^2+\omega_s^2}{s^2+bs+\omega_s^2},\quad b>0, \tag{4}$$

where, p_1 and p_2 are the gains of $G_{f1}(s)$ and $G_{f2}(s)$, respectively, and $k_2=p_1p_2$.

We apply HAF based feedback control to a voltage-mode Buck converter. The corresponding schematic diagram is shown in Fig. 1, where, Δv_{con} is the output voltage of HAF based controller, V_{in} is the input voltage which is assumed constant, v_o is the output voltage, V_{ref} is the reference voltage, $v_{ramp}=V_l+(V_h-V_l)\,\mathrm{mod}(t/T,1)$ is the saw-tooth voltage, v_d is the diode voltage, v_{con} is the original feedback control voltage, v'_{con} is the new feedback control voltage, k_1 is the feedback gain for the original control.

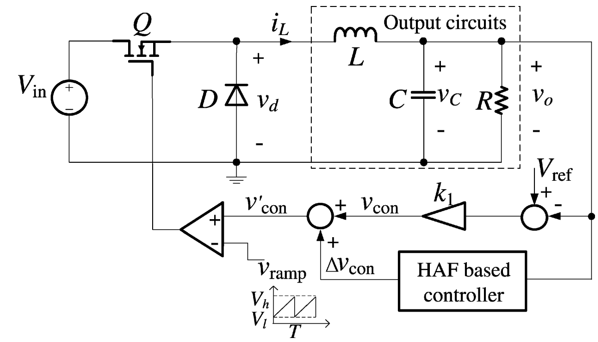

Fig. 1. The schematic diagram of the voltage-mode Buck converter with HAF based controller.

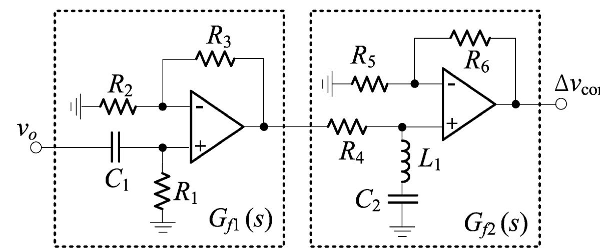

Fig. 2. The circuits for the hybrid active filter (HAF) based controller.

While Δv_{con} is equal to zero, the system is the conventional voltage-mode Buck converter. The principle of the voltage-mode Buck converter is given as follows. While the control voltage v'_{con} is smaller than the ramp v_{ramp}, the comparator output a high level to drive the switch Q open, v_d is equal to V_{in} and v_o and v'_{con} increase. While v'_{con} intersects the ramp and keeps larger than v_{ramp}, the switch keeps the closed state until v'_{con} decreases lower than v_{ramp}, at this moment v_d is equal to zero. While in steady state all above situations are repeated in every switch period.

From Fig. 1, we have

$$v_{con}=k_1(V_{ref}-v_o), \tag{5}$$

$$v'_{con}=v_{con}+\Delta v_{con}. \tag{6}$$

According to the transfer function $G_f(s)$ (seen in Eq. (2)) the corresponding circuits for HAF based controller are constructed as shown in Fig. 2, where two active filter based circuits are realized for $G_{f1}(s)$ and $G_{f2}(s)$, the output voltage v_o is chosen as the input of the HAF based controller (seen in Fig. 1).

Note that while choosing the input voltage as the bifurcation parameter period-doubling bifurcation is the route to chaos for the voltage-mode Buck converter [3]. Therefore, we can control chaos indirectly by enlarging the bifurcation point of the Buck converter. In the following work, we will present a dynamic model of Buck converter and use the harmonic balance method for determining the bifurcation point as reported in Ref. [12].

Fig. 3 shows the dynamic model of Buck converter, where $V_o(s)$ and $V_d(s)$ are the Laplace transforms of $v_o(t)$ and $v_d(t)$. $G_1(s)$ is the dynamical model of the output circuits in Buck