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An improved resonant parametric perturbation for chaos control with applications to control of DC/DC converters*

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This paper presents an improved resonant parametric perturbation method based on the modulation of a nonlinear map for controlling chaos. The control target can be any periodic orbit, which is not necessarily what is embedded in the chaotic attractor. Application of the method is illustrated for a common current-programmed DC/DC converter which has been known to easily become chaotic for a wide parameter range. The control effects of chaos are demonstrated with computer simulations.

Keywords: chaos control, resonant parametric perturbation, DC/DC converter, current-programmed control

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1. Introduction

Chaos is known to exist in many physical and engineering systems, be it a beneficial or harmful phenomenon. When chaos is found undesirable for a particular system, as would be the case for most engineering applications, controlling it becomes necessary to avoid harmful consequences.[1,2]

Various methods for the control of chaos have been proposed. Their objectives fall into two general categories. In the first category, one of the infinitely many unstable periodic orbits within a chaotic attractor is first identified as the control target, and control action is directed to stabilize the system so that it settles down to the target periodic orbit. In the second category, a desired operating state is the control target, which is not necessarily one of those unstable orbits embedded in the chaotic attractor. Here, the control action is to achieve the desired operating state. The first type of control objective is usually achieved by feedback methods,[3−6] whereas the second type can be accomplished by non-feedback methods.[7−17] Examples of feedback methods include the Ott–Grebogi–Yorke (OGY) method,[3] occasional proportional feedback (OPF) method,[4] time-delayed feedback control method (TDFC),[5] differential feedback control,[6] etc. In these methods, system variables are measured, a control law is implemented and some control parameters varied to achieve the required control objective. On the other hand, for the non-feedback type of control, no system variables need to be measured and no specific periodic orbit has to be identified as the control target. Examples of non-feedback methods include adaptive control,[7] resonant parametric perturbation,[8−13] weak periodic perturbation,[14,15] entrainment and migration control,[16] periodic impulse control,[17] etc. Compared to feedback methods, non-feedback methods are simple and suitable for practical implementations.

Our attention in this paper is focused on the non-feedback type of control for controlling chaos. We consider the resonant parametric perturbation method and derive an improved strategy based on modulation of a nonlinear map. It is shown that this technique is highly suitable for controlling chaos in periodically driven systems. In this paper, we propose

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a common current-programmed DC/DC boost converter, and our objective is to stabilize it to any periodic state (period-1, period-2, period-3, etc). This improved resonant parametric perturbation method can be applied to other periodically driven systems such as pulse-width modulated power converters, Josephson junctions, and magnetoelastic beams.

2. Review of resonant parametric perturbation

Resonant parametric perturbation has been shown to suppress chaos.[8−13] In general, parametric perturbation can make a system chaotic, but applying it at appropriate frequencies can induce the system to stay in periodic regimes. Thus, the so-called resonant parametric perturbation is to perturb some parameters at appropriate frequencies, thereby converting a chaotic operation into a regular one.

The usual procedure is to choose a parameter that strongly affects the system and can be easily varied. Suppose this parameter is c. This parameter is then perturbed with the function $(1+\alpha\sin 2\pi ft)$ where $\alpha \ll 1$ and f is the perturbation frequency to be chosen. Effectively, we are replacing c by $c(1+\alpha\sin 2\pi ft)$ so that the largest Lyapunov exponent is reduced to below zero. This approach has been used by Lima and Pettini for stabilizing a chaotic Duffing–Holmes system.[8] In particular, it has been shown that when the perturbation frequency f resonates with the periodic driving frequency, say f_s, the largest Lyapunov exponent will approach zero from positive, and eventually chaos subsides and the periodic state emerges as the Lyapunov exponent falls further below 0. This phenomenon has been demonstrated analytically with Melnikov's method, and verified by simulations and experiments.[8]

Variations of the above procedure have been proposed. For instance, the weak periodic perturbation method[14,15] makes use of external periodic forcing to weaken chaos. When the external forcing frequency resonates with an unstable periodic orbit of the original system, the resonating unstable periodic orbit will be inspired while other unstable periodic orbits remain suppressed. Thus, the system settles down to the resonating, now stable, periodic orbit.

The resonant parametric perturbation method has been successfully applied to control chaos in a range of systems, and it has been demonstrated that resonant frequencies up to three times the driving frequency can be effectively applied to stabilize orbits of one period, one-half period and one-third period. In Section 3, we will apply the resonant parametric perturbation to control a common current-programmed DC/DC converter which has been known to exhibit chaos in a wide parameter range. The method is effective for stabilizing periodic orbits of period-1, period-2, period-4, but totally inadequate for periodic orbits of longer periods. In Section 4, we will propose and demonstrate an improved approach for stabilizing periodic orbits of any desired periods.

3. Application of resonant parametric perturbation to control of chaos in current-programmed DC/DC converters

3.1. Overview of circuit operation

The current-programmed boost converter is considered here.[18,19] It consists of an inductor, a switch, a diode, a capacitor and a resistor load, as shown in Fig.1(a). When the switch is turned on, the inductor current rises up linearly, and when the switch is turned off, the inductor current ramps down and discharges through the diode to the load. To determine the turn–off instant, the inductor current is compared with a reference current, $I_{\rm ref}$. When the inductor current reaches $I_{\rm ref}$, the switch is turned off. Moreover, turn-on is done periodically. Fig.1(b) shows some typical waveforms. The state equation can be written as

$$\dot{x} = \begin{cases} A_{\rm on}x + B_{\rm on}E, & \text{switch on}, \\ A_{\rm off}x + B_{\rm off}E, & \text{switch off}, \end{cases} \tag{1}$$

where x denotes the state variable, i.e. $x = [i_{\rm L}, v_{\rm o}]^{\rm T}$, the A's and B's are the system matrices given by

$$A_{\rm on} = \begin{bmatrix} 0 & 0 \\ 0 & -1/RC \end{bmatrix}, \quad B_{\rm on} = \begin{bmatrix} 1/L \\ 0 \end{bmatrix}, \quad A_{\rm off} = \begin{bmatrix} 0 & -1/L \\ 1/C & -1/RC \end{bmatrix}, \quad B_{\rm off} = \begin{bmatrix} 1/L \\ 0 \end{bmatrix}. \tag{2}$$

To complete the model, we need to include the control equation, which can be expressed as $i_{\rm L}(dT) - I_{\rm ref} = 0$, where d is the duty ratio defined as the fractional period in which the switch is turned on, and T is the switching period. "Exact" cycle-by-cycle simulation can thus be performed using the above equations. In this paper, we use SIMULINK to perform all simulations.

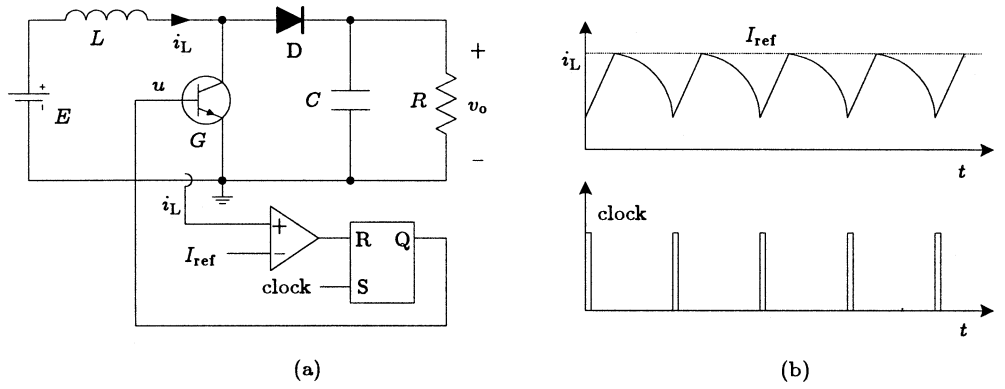


Fig.1. Current-programmed boost converter. (a) Schematic diagram, (b) inductor current waveform.

3.2. Chaotic behaviour

The afore-described boost converter has been shown previously to exhibit period-doubling bifurcation, border collision bifurcation and chaos.[18−20] A typical bifurcation diagram is shown in Fig.2(a), where I_{ref} is chosen as the bifurcation parameter, and the corresponding variation of the largest Lyapunov exponent is shown in Fig.2(b). For this particular choice of parameter values, regular periodic operation is maintained when I_{ref} is below about 1.7A. Beyond this value of I_{ref}, period-doubling and border collision occur. The circuit exhibits chaos when I_{ref} exceeds about 2.7A. Figure 3 shows the phase portrait, a Poincaré section and the corresponding power spectrum for the case where I_{ref}=4A, which corresponds to chaotic operation.

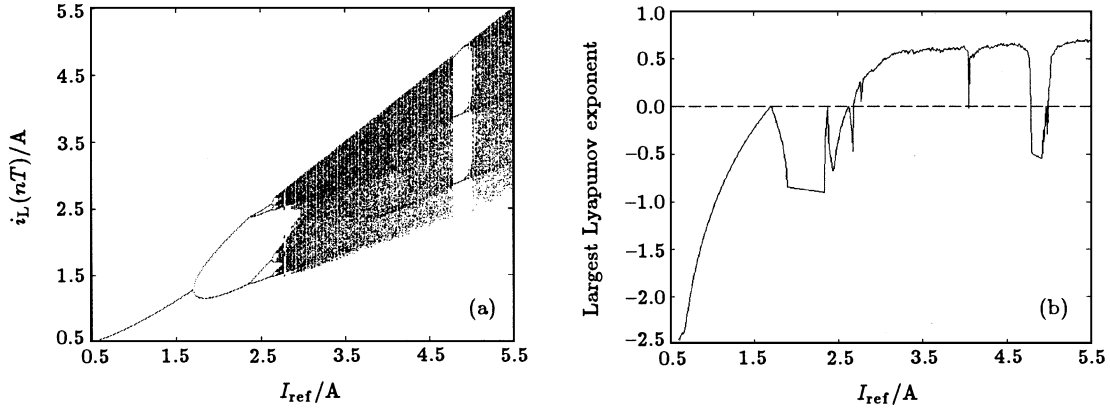


Fig.2. Bifurcation of current-programmed boost converter, with L=1mH, C=12μF, R=20Ω, T=1/10000s, and E=10V. (a) Bifurcation diagram with I_{ref} as the bifurcation parameter, (b) largest Lyapunov exponent.

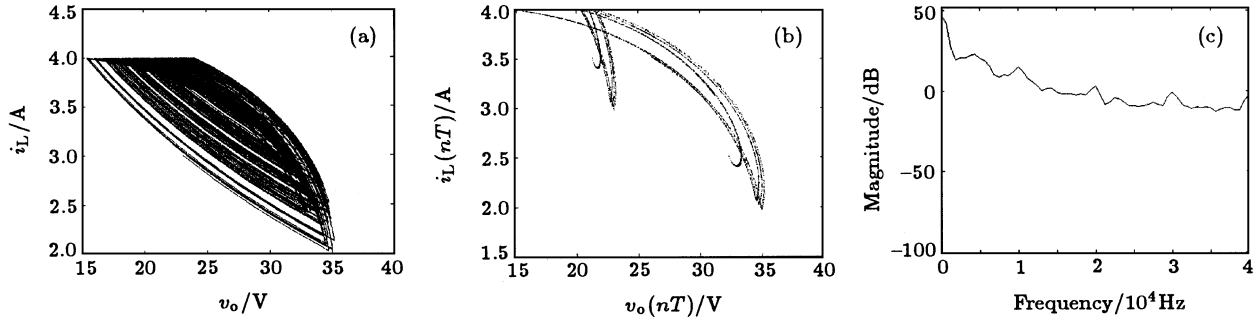


Fig.3. Chaotic operation of current-programmed boost converter, with L=1mH, C=12μF, R=20Ω, f_s=10kHz, E=10V and I_{ref}=4A. (a) Phase portrait, (b) Poincaré section, (c) power spectrum.

3.3. Control of chaos by resonant parametric perturbation

Consider the current-programmed DC/DC converter with L=1mH, C=12μF, R=20Ω, f_s=10kHz, E=10V and I_{ref}=4A. For this set of parameters, the circuit operates chaotically with a largest Lyapunov exponent of 0.6305. Our objective now is to stabilize this chaotic converter to some periodic orbit, e.g. period-1, period-2, etc. The application of the resonant parametric perturbation method involves, first of all, selecting an appropriate parameter to be perturbed. Here we choose the reference peak inductor current I_{ref} as the perturbing parameter. Essentially we replace I_{ref} by $I_{ref}(1+\alpha\sin 2\pi ft)$, where α is the perturbation amplitude, f is the perturbation frequency, and thus the term $(\alpha\sin 2\pi ft)$ is the resonant perturbation applied to I_{ref}.

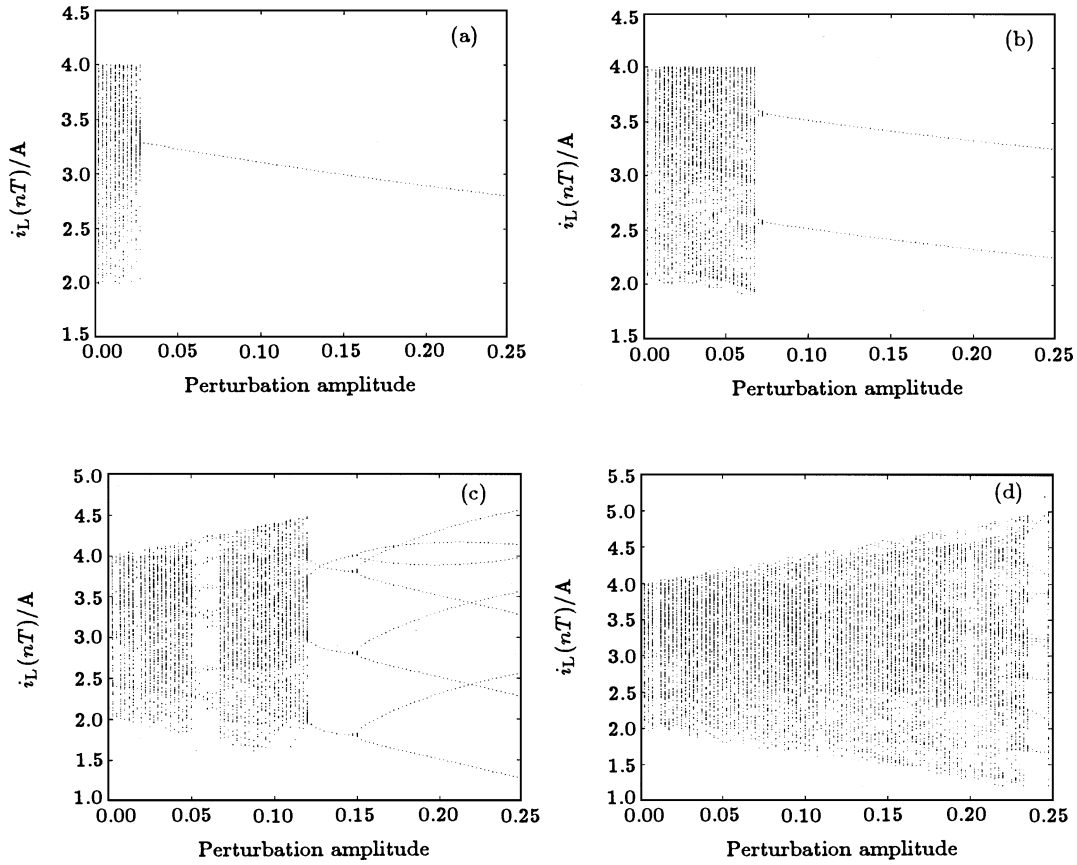


Fig.4. Application of resonant parametric perturbation to a chaotic current-programmed boost converter, with L=1mH, C=12μF, R=20Ω, T=1/10000s, E=10V, I_{ref}=4A, and perturbation frequency being (a) 10kHz, (b) 5kHz, (c) 2.5kHz and (d) 1.25kHz, respectively.

The perturbation frequency f is set to the driving frequency and its subharmonics, i.e. 10kHz, 5kHz, 2.5kHz, 1.25kHz, etc. The simulation results are shown in Fig.4, from which we clearly observe the following:

(1) The converter can be stabilized to period-1, period-2 and period-4 operations when the perturbation frequency f is set, respectively, at 10kHz, 5kHz and 2.5kHz. In these cases, the perturbation amplitude α has been varied in the range 0.0025 to 0.25. Figures 4(a) to 4(c) show the bifurcation diagrams for these three cases, all with the perturbation amplitude serving as the bifurcation parameter.

(2) The converter cannot be stabilized to a period-8 (1.25kHz) orbit when the perturbation frequency f is set at 1.25kHz. No effective perturbation amplitude can be found in this case. Figure 4(d) shows the bifurcation diagram with the perturbation amplitude serving as the bifurcation parameter.

Thus, we have demonstrated the control of chaos in this current-programmed boost converter using the resonant parametric perturbation method. However, the method fails to stabilize orbits of long periods. In the following we will propose an improved resonant

parametric perturbation method which can stabilize orbits of very long periods.

4. An improved resonant parametric perturbation based on modulation of nonlinear maps

Chaotic systems are sensitive to resonant perturbation of parameters, and are very much so for perturbations at the system's driving frequency. Thus, the resonant parametric perturbation technique, as demonstrated in the foregoing, is most effective for stabilizing the system at its driving frequency. However, the control effect weakens for orbits of long periods. In this section we modify the resonant perturbation method so that it strongly suppresses the chaotic operation and stabilizes the system to an orbit of any arbitrary period.

The basic idea of the proposed technique is to inject stronger periodicity to the parametric perturbation. That is to say, we can use specific kinds of perturbation patterns that contain strong periodicity. For example, perturbation patterns can be derived from a nonlinear map. Suppose the parametric perturbation is applied to c. Essentially the perturbed parameter, $\tilde{c}$, is given by

$$\tilde{c} = c\,(1 + \alpha \sin 2\pi f t + \beta L(t))\,, \qquad (3)$$

where f is set at the driving frequency of the converter, $L(t)$ is the output from a nonlinear iterative map, α and β are the perturbation amplitudes. A convenient choice for $L(t)$ is the logistic map[21] because it can generate sequences of any period. In this case we define $L(t)$ as

$$L(t) = x_n - \bar{x}, \quad \text{for} \quad \frac{n}{f} \le t < \frac{n+1}{f}, \qquad (4)$$

where x_n is generated by the recursive formula, i.e. logistic map

$$x_n = 1 - \mu x_{n-1}^2 \qquad (5)$$

for n=1, 2, 3,..., and $\bar{x}$ is the average value of the sequence $\{x_n\}$ in the steady state. Thus, $L(t)$ always has a zero average. Now, by choosing μ, we can inject the desired periodicity to the parametric perturbation. For example, μ=0.5 corresponds to period-1, μ=1 corresponds to period-2, μ=1.75 corresponds to period-3, μ=1.3 corresponds to period-4, etc. The bifurcation diagram and the corresponding variation of the Lyapunov exponent of the logistic map are show in Ref.[21].

By choosing α, β and μ, we expect to stabilize the system to an orbit whose period is determined by the chosen $L(t)$. In the next section we illustrate the method with the current-programmed boost converter.

5. Application of improved resonant parametric perturbation to control of chaos in current-programmed boost converters

We consider again the current-programmed boost converter which operates chaotically for some given ranges of parameters. Here we make an attempt to stabilize the system to a periodic orbit of any desired period using the improved resonant parametric perturbation method described earlier. The parameter to be perturbed is again $I_{\rm ref}$, and the perturbed parameter is as given in (3), i.e.

$$\tilde{I}_{\rm ref} = I_{\rm ref}\,(1 + \alpha \sin 2\pi f t + \beta L(t))\,. \qquad (6)$$

The choice of $L(t)$ is as given in Eqs.(4) and (5), i.e. the logistic map with zero mean. In the following we demonstrate the stabilization of periodic orbits by computer simulations.

Table 1. Choice of μ for stabilization of periodic orbits for α=0.1 and β=0.025 (from simulation).

Period	μ used	Measured Lyapunov exponent
1	0.50	−0.6238
2	1.00	−1.6319
3	1.75	−0.1633
4	1.30	−0.7799
8	1.37	−0.0281
16	1.395	−0.0716
32	1.4007	−0.0345

The system is set to operate in a chaotic regime with L=1mH, C=12μF, R=20Ω, T=1/10000s, E=10V and $I_{\rm ref}$=4A. We then introduce the logistic map modulation by assigning a non-zero value for β, say 0.025. The effect of this additional perturbation can be illustrated by plotting the bifurcation diagram and the corresponding largest Lyapunov exponent $\lambda_{\max}$, as shown in Fig.5 for the case where α=0.1 (the similar results for other cases, such as α=0.15 and 0.2, etc. are omitted for the sake of simplicity). Clearly, in all these cases, we can stabilize the system to a periodic orbit of any period by choosing an appropriate value for μ. For instance, choosing μ=1 should give a period-2 orbit, etc. Table 1 summarizes the values of μ used in each case and the measured largest Lyapunov exponents.

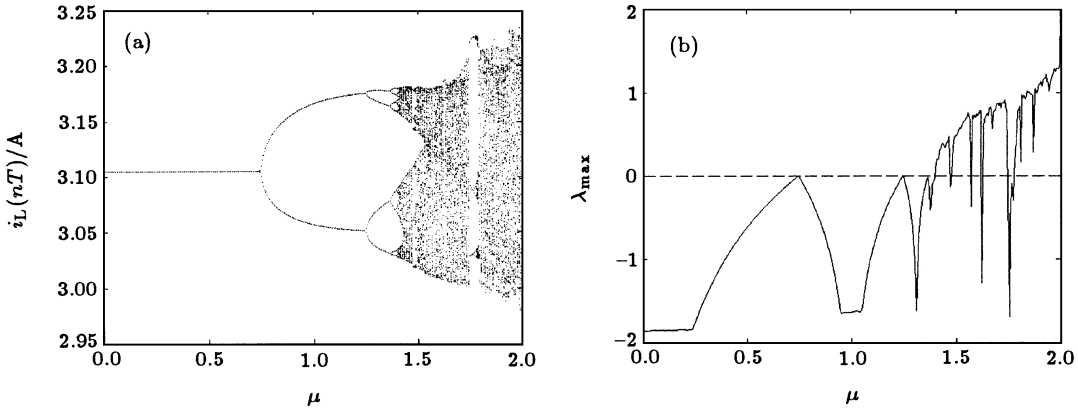


Fig.5. Bifurcation diagram (a) and the corresponding largest Lyapunov exponent (b) vs μ for α=0.1 and β=0.025.

6. Conclusion

Resonant parametric perturbation is an effective approach for controlling chaos. In this paper we apply this method to the current-programmed boost converter driven by a fixed frequency clock. Such kind of system has been found to behave chaotically for a wide range of circuit parameters. However, most applications demand a stable periodic operation. It is therefore important from the practical point of view that simple methods can be used to control chaos. In this paper an improved parametric perturbation based on modulation of a nonlinear map has been proposed for suppressing chaos and stabilizing the system to an orbit of any desired period. The method takes on a non-feedback configuration and hence is very easy to implement in practice.

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