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Study of Bifurcation and Chaos in the Current-Mode Controlled Buck-Boost DC-DC Converter (Ⅱ)*

——Numerical Analysis and Experiment

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Abstract: The first flip bifurcation point of Buck-Boost converter has been studied in detail by using fixed point and stability theory. 3-D parameter space of stable region is given. Furthermore, the hardware of 20kHz current-mode controlled Buck-Boost converter has been built and the experiment results verify the theoretical analysis which has been presented in our other papers.

Key words: power electronics; bifurcation; chaos; model
Document code: A

Buck-Boost DC-DC 变换器中分叉与混沌问题的研究(Ⅱ)

——数值分析与实验

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摘要: 研究了电流控制型 Buck-Boost 变换器中的分叉与混沌问题. 在连续模式下的 Buck-Boost 变换器的离散数学模型基础上,从不动点及稳定性理论的角度对 Buck-Boost 变换器的第一分叉点进行了严格的数值分析,得到了三维参数空间曲面图. 此外,建立了实验硬件电路,实验结果验证了理论分析.

关键词: 电力电子; 分叉; 混沌; 建模

1 Introduction

The switched-mode DC-DC converters that have been widely used in many industrial products may be thought of as nonlinear and time-varying systems. Hence, DC-DC converters exhibit a wide range of bifurcation and chaos behavior under some conditions. In the first part of the paper, i.e. modeling and simulation, we have derived an iterative map for the Buck-Boost converter under current-mode control. The bifurcation and chaos phenomena have been deeply studied under variation of a range of circuit parameters, such as input voltage, reference current, load resistance, inductor and capacitor. And, the simulation results including the strange attractors, bifurcation diagrams and waveforms have been presented in detail. In this paper, the experimental evidence is provided to verify the predicted phenomena. At the same time, the onset of the first flip bifurcation point can be exactly located by using fixed point and stability theory, and 3-D parameter space of stable region is also presented.

This paper is organized as follows. In Section 2, the fundamental theories about fixed point and stability theory are presented. In Section 3, with the help of fixed point and stability theories, the onset of the first period-doubling bifurcation point is rigorously located. In Section 4, the boundary equations and 3-D parameter space are discussed. In Section 5, we present the experimental system of the 20kHz current-mode controlled Buck-Boost converter. The experimental results are shown in detail. A conclusion is given in Section 6.

2 Fundamental theories

In this section, we present the fundamental theories of

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fixed point and stability theory.

Definition 2.1 For one-dimensional mapping G: $\mathbb{R}^n \to \mathbb{R}^n$; $x \to G(x)$, there may be some special points x_e that satisfy the equation $x_e = G(x_e)$. Such a point is called a fixed point of the mapping.

Definition 2.2 Similarly, for n-dimensional mapping G, there may be a special vector x_e that satisfies the equation $x_e = G(x_e)$. Such a vector is called a fixed point of the n-dimensional mapping.

The fixed points have a very great influence on the behavior of the system. In particular, stable behavior is connected with an attracting fixed point, which by association is called a stable fixed point. This is a member of the class of attractors, which also includes limit cycles and the strange attractors of chaos. The stability of the fixed points of the mapping determines the local stability of the continuous-time system. An attracting fixed point of the mapping corresponds to a stable periodic steady state of the continuous-time system.

Definition 2.3 A flip (or period-doubling) bifurcation occurs when one of the eigenvalues of the Jacobian matrix of the mapping at the fixed point equals to -1.

Stability Theory[1] A fixed point of a one-dimensional mapping is stable if and only if the gradient of the mapping at the fixed point lies between -1 and 1, i.e. if

$$\left|\left(\frac{\mathrm{d}G}{\mathrm{d}x}\right)_{x=x_e}\right| < 1$$

Similarly, a fixed point of an n-dimensional mapping is stable if and only if its characteristic multipliers all lie within the unit circle in the complex plane.

3 Numerical analysis of the first flip bifurcation point

From the simulation results, we know that when the bifurcation parameter is varied, Buck-Boost converter bifurcates to period-2 from period-1, bifurcates to period-4 from period-2, and then goes to chaos via period-doubling route. Therefore, the analysis of first flip bifurcation point is particularly important. In this section, the onset of the first period-doubling bifurcation point is rigorously located. The boundary equations and 3-D parameter in Buck-Boost converter space are discussed with the help of the numerical analysis.

3.1 The discrete model of Buck-Boost converter

The discrete model has been derived in the first part of the paper. In our simulation study, the parameters of the Buck-Boost converter satisfy the following relationship because of the condition of practical circuit for maintaining continuous inductor conduction mode and low output ripple.

$$1 - \frac{4R^2C}{L} < 0, \text{ that is: } R > \frac{1}{2}\sqrt{\frac{L}{C}}. \quad (1)$$

Therefore the iterative mapping can be written as follows

$$\begin{cases} i_{n+1} = e^{\alpha t_n'}[c_1\cos(\beta t_n') + c_2\sin(\beta t_n')], \\ v_{n+1} = -Le^{\alpha t_n'}[(c_1\alpha + c_2\beta)\cos(\beta t_n') + \\ \qquad (c_2\alpha + c_1\beta)\sin(\beta t_n')], \end{cases} \quad (2)$$

where

$$\alpha = -\frac{1}{2RC},\ \beta = \frac{1}{2RC}\sqrt{\frac{4R^2C}{L} - 1},\ t_n = \frac{L}{E}(I_{\text{ref}} - i_n),$$

$$t_n' = T - t_n = T - \frac{L}{E}(I_{\text{ref}} - i_n) = T - \frac{L\cdot I_{\text{ref}}}{E} + \frac{L}{E}\cdot i_n,$$

$$c_1 = I_{\text{ref}},$$

$$c_2 = -\frac{1}{\beta}\left(\frac{1}{L}\cdot v_n\cdot e^{-\frac{t_n}{RC}} + I_{\text{ref}}\cdot\alpha\right) =$$

$$-\frac{1}{\beta}\left(\frac{1}{L}\cdot v_n\cdot e^{-\frac{1}{RC}\cdot\frac{L}{E}(I_{\text{ref}} - i_n)} + I_{\text{ref}}\cdot\alpha\right).$$

In order to simplify the calculation, a substitution of $k_1 = \frac{1}{RC}\cdot\frac{L}{E}$, $k_2 = \frac{L}{E}$, $k_3 = T - \frac{L\cdot I_{\text{ref}}}{E}$ is made. Hence t_n, t_n', c_2 can be rewritten as:

$$t_n = k_2(I_{\text{ref}} - i_n),\ t_n' = k_3 + k_2\cdot i_n,$$

$$c_2 = -\frac{1}{\beta}\left(\frac{1}{L}\cdot v_n\cdot e^{-k_1\cdot(I_{\text{ref}} - i_n)} + I_{\text{ref}}\cdot\alpha\right).$$

The iterative mapping of the Buck-Boost converter can be rewritten as follows.

$$\begin{cases} i_{n+1} = \\ e^{\alpha(k_3 + k_2\cdot i_n)}[I_{\text{ref}}\cos(\beta(k_3 + k_2\cdot i_n)) + \\ -\frac{1}{\beta}(\frac{1}{L}\cdot v_n\cdot e^{-k_1(I_{\text{ref}} - i_n)} + I_{\text{ref}}\cdot\alpha)\sin(\beta(k_3 + k_2\cdot i_n))], \\ v_{n+1} = \\ Le^{\alpha(k_3 + k_2\cdot i_n)}[\frac{1}{L}\cdot v_n\cdot e^{-k_1\cdot(I_{\text{ref}} - i_n)}\cos(\beta(k_3 + k_2\cdot i_n)) + \\ (\frac{\alpha}{\beta}\cdot\frac{1}{L}\cdot v_n\cdot e^{-k_1\cdot(I_{\text{ref}} - i_n)} + \frac{\alpha^2 + \beta^2}{\beta}\cdot I_{\text{ref}})\sin(\beta(k_3 + k_2\cdot i_n))]. \end{cases} \quad (3)$$

A matrix is usually used to represent the mapping:

$$\begin{bmatrix} i_{n+1} \\ v_{n+1} \end{bmatrix} = \begin{bmatrix} f_1(i_n, v_n, \varphi) \\ f_2(i_n, v_n, \varphi) \end{bmatrix}, \quad (4)$$

where φ is the bifurcation parameter. It can be the input voltage E, reference current I_{ref}, resistor R, capacitor C

and inductor L.

3.2 Calculation of the fixed point

For an n-dimensional system, a fixed point is a vector x^* that satisfies the equation $x^* = F(x^*)$. Therefore, for a discrete model, a fixed point is the solution that satisfies the equation $x_{n+1} = x_n$ when the steady state is reached. For the Buck-Boost converter, the fixed point x_e is the solution of the following difference equations:

$$\begin{cases} e^{\alpha(k_3+k_2\cdot i_n)}[\, I_{ref}\cos(\beta(k_3 + k_2 \cdot i_n)) + \\ -\dfrac{1}{\beta}(\dfrac{1}{L}\cdot v_n\cdot e^{-k_1(I_{ref}-i_n)}] + \\ I_{ref}\cdot \alpha)\sin(\beta(k_3+k_2\cdot i_n))] - i_n = 0, \\ Le^{\alpha(k_3+k_2\cdot i_n)}[\dfrac{1}{L}\cdot v_n \cdot e^{-k_1\cdot(I_{ref}-i_n)}\cos(\beta(k_3+k_2 \cdot i_n)) + \\ (\dfrac{\alpha}{\beta}\cdot\dfrac{1}{L}\cdot v_n\cdot e^{-k_1\cdot(I_{ref}-i_n)} + \\ \dfrac{\alpha^2+\beta^2}{\beta}\cdot I_{ref})\sin(\beta(k_3+k_2\cdot i_n))] - v_n = 0. \end{cases} \tag{5}$$

Obviously, equations in (5) are transcendental ones and the analytical solution cannot be obtained, so they can only be solved by numerical method, such as Newton-Raphson method. Here, the 'fsolve' in MATLAB is used to solve the transcendental equations.

3.3 Derivation of Jacobian Matrix

If the mapping of the Buck-Boost converter is written as (4), the Jacobian Matrix of the mapping at the fixed point x_e is expressed in the following.

$$J(x_e) = \begin{bmatrix} \dfrac{\partial f_1}{\partial i_n} & \dfrac{\partial f_1}{\partial v_n} \\ \dfrac{\partial f_2}{\partial i_n} & \dfrac{\partial f_2}{\partial v_n} \end{bmatrix}_{x=x_e}, \tag{6}$$

where, each item in the matrix, i.e. $\dfrac{\partial f_1}{\partial i_n}$, $\dfrac{\partial f_1}{\partial v_n}$, $\dfrac{\partial f_2}{\partial i_n}$, $\dfrac{\partial f_2}{\partial v_n}$, can be derived by (3) and (4).

$$\frac{\partial f_1}{\partial i_n} = -e^{\alpha(k_3+k_2\cdot i_n)}\{\frac{k_2}{L}\cdot v_n\cdot e^{-k_1\cdot(I_{ref}-i_n)}\cos(\beta(k_3+k_2\cdot i_n)) + [\frac{\alpha\cdot k_2 + k_1}{BL}\cdot v_n \cdot e^{-k_1\cdot(I_{ref}-i_n)} + \frac{\alpha^2+\beta^2}{\beta}\cdot k_2\cdot I_{ref}]\sin(\beta(k_3 + k_2\cdot i_n))\}, \tag{7}$$

$$\frac{\partial f_1}{\partial v_n} = -\frac{1}{\beta L}\cdot e^{\alpha(k_3+k_2\cdot i_n)}\cdot e^{-k_1\cdot(I_{ref}-i_n)}\sin(\beta(k_3+k_2\cdot i_n)), \tag{8}$$

$$\frac{\partial f_2}{\partial i_n} = L\cdot e^{\alpha(k_3+k_2\cdot i_n)}\{[\frac{2k_2\alpha + k_1}{L}\cdot v_n\cdot e^{-k_1\cdot(I_{ref}-i_n)} + k_2\cdot(\alpha^2+\beta^2)\cdot I_{ref}]\cos(\beta(k_3+k_2\cdot i_n)) + [\frac{k_2\cdot(\alpha^2-\beta^2)+k_1\alpha}{\beta L}\cdot v_n\cdot e^{-k_1\cdot(I_{ref}-i_n)} + \frac{k_2\cdot\alpha(\alpha^2+\beta^2)}{\beta}\cdot I_{ref}]\sin(\beta(k_3+k_2\cdot i_n))\}, \tag{9}$$

$$\frac{\partial f_2}{\partial v_n} = Le^{\alpha(k_3+k_2\cdot i_n)}[\frac{1}{L}\cdot e^{-k_1\cdot(I_{ref}-i_n)}\cdot\cos(\beta(k_3+k_2\cdot i_n)) + \frac{\alpha}{\beta L}\cdot e^{-k_1\cdot(I_{ref}-i_n)}\cdot\sin(\beta(k_3+k_2\cdot i_n))]. \tag{10}$$

3.4 Eigenvalues of Jacobian Matrix

It is well known that the eigenvalues of Jacabian Matrix provides a useful method to evaluate the dynamics of the systems. The eigenvalues can be obtained by solving the following polynomial equations.

$$\det[\lambda I - J(x_e)] = 0, \tag{11}$$

where $J(x_e)$ is the Jacobian Matrix which was found previously. Here, we will mainly study the variation of the eigenvalues as input voltage E and reference current I_{ref} are varied. If one of the eigenvalues equals to -1, the corresponding bifurcation value is the first period-doubling bifurcation point when the bifurcation parameter is changed.

Firstly, the loci of the eigenvalues are examined as the input voltage E is changed. The set of circuit parameters used is the same as in the simulation, i.e. I_{ref} = 4A, $R = 20\Omega$, $L = 0.5$mH, $C = 4\mu$F, $T = 50\mu$s (f = 20kHz). The calculation result is listed in Table 1 and the loci of characteristic multipliers are illustrated in Fig. 1

Table 1 The characteristic multipliers with E as a bifurcation parameter (P1 refers to period-one)

E/V	Fixed point: i_L/A v_c/V	Eigenvalues: λ_1, λ_2	Remarks
45	2.0288, 38.2242	−0.9663, 0.3579	Stable P1
44.5	2.0407, 38.1792	−0.9748, 0.3578	Stable P1
44	2.0527, 38.1330	−0.9835, 0.3577	Stable P1
43.9	2.0552, 38,1236	−0.9835, 0.3577	Stable P1
43.8	2.0576, 38.1141	−0.9870, 0.3577	Stable P1
43.7	2.0600, 38.1046	−0.9888, 0.3576	Stable P1
43.6	2.0625, 38.0950	−0.9906, 0.3576	Stable P1
43.5	2.0649, 38.0854	−0.9924, 0.3576	Stable P1
43.4	2.0673, 38.0757	−0.9942, 0.3576	Stable P1
43.3	2.0698, 38.0660	−0.9960, 0.3576	Stable P1
43.2	2.0722, 38.0562	−0.9978, 0.3575	Stable P1
43.1	2.0747, 38.0464	−0.9996, 0.3575	Stable P1
43.09	2.0750, 38.0454	−0.9998, 0.3575	Stable P1
43.08	2.0752, 38.0444	−1.0000, 0.3575	Period-doubling

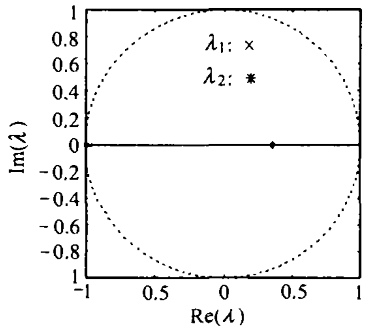


Fig. 1 Loci of eigenvalues with E as the bifurcation parameter

For large input voltage E (greater than 43.08V), both of the eigenvalues are located within unit circle in the complex plane. As E decreases, one of the eigenvalues goes toward -1. When $E = 43.08$V, one of the eigenvalues equals to -1, which implies the occurrence of period-doubling bifurcation. It agrees with the simulation result in the first part of the paper.

Secondly, the eigenvalues are used to predict the onset of flip bifurcation if reference current I_{ref} is changed. Here the set of circuit parameters is also the same as in the simulation, i.e. $E = 12$V, $R = 20\Omega$, $L = 0.5$mH, $C = 4\mu$F, $T = 50\mu$s ($f = 20$kHz). Here, the detailed calculation result and the loci of characteristic multipliers are omitted.

It is found that at $I_{ref} = 1.1142$A, one of the eigenvalues is equal to -1, which implies the occurrence of period-doubling bifurcation. It agrees with the simulation result as shown in the first part of the paper.

4 Boundary equations and 3-D parameter space

In a power converter, the most probably variable parameters are input voltage E, reference current and load resistor R. The other parameters, such as inductor L, capacitor C and switching frequency f, are generally fixed at the designed state. Because some parameters are fixed while the others are changeable, the different combinations of circuit values lead to bifurcation and chaos. Therefore, it is particular important to study when the first period-doubling bifurcation occurs under E, I_{ref} and R parameter space.

Based on the previous analysis, it is clear that the solution of the fixed point cannot be expressed as an analytical form since the fixed point of the Buck-Boost converter is a set of transcendental equations. Therefore the eigenvalues of Jacobian Matrix of the mapping at the fixed point cannot be expressed as a formula, either. The only way to study the first period-doubling bifurcation is the numerical method.

The following study about the parameter space is about the input voltage E as the bifurcation parameter. Other fixed circuit parameters are listed as follows. $L = 0.5$mH, $C = 4\mu$F, $f = 20$kHz.

4.1 Boundary equations at different loads

When $R = 20\Omega, 30\Omega, 40\Omega$ and the reference current is varied in step. The first period-doubling bifurcation point can be calculated via the method stated in Section 3. Hence a series of first flip bifurcation points can be obtained under different reference currents I_{ref}. The calculation result is listed in Table 2.

Table 2 The first flip bifurcation point with various loads R

Reference current I_{ref}/A	E/V for first bifurcation point $R = 20\ \Omega$	$R = 30\ \Omega$	$R = 40\ \Omega$
1	10.77	13.513	15.822
2	21.54	27.024	31.644
3	32.31	40.539	47.466
4	43.08	54.05	63.289
5	53.85	67.56	79.11
6	64.62	81.07	94.93
Boundary condition for stable	$E > 10.77I_{ref}$	$E > 13.5115I_{ref}$	$E > 15.8217I_{ref}$

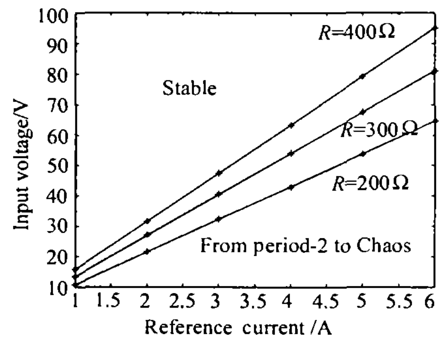


Fig. 2 The parameter space with various loads

Based on the calculation results in Table 2, the boundary conditions can be obtained through least square method (LMS) as shown in Fig. 2. The Buck-Boost converter works in the stable region if input voltage E and reference current I_{ref} satisfy the following boundary equation (12) when $R = 20\Omega$.

$$E > 10.77I_{ref} \tag{12}$$

Contrarily, the Buck-Boost converter will go to chaos via period-doubling route if input voltage E and reference current I_{ref} satisfy the following equation (13).

$$E \leqslant 10.77 I_{ref} \qquad (13)$$

Similarly, other boundary equations under different loads can be obtained. Here, we do not repeat the specific procedure.

4.2 3-D Parameter space

Plotting the first flip bifurcation points into a 3-dimensional space, a 3-D parameter space can be obtained in Fig.3.

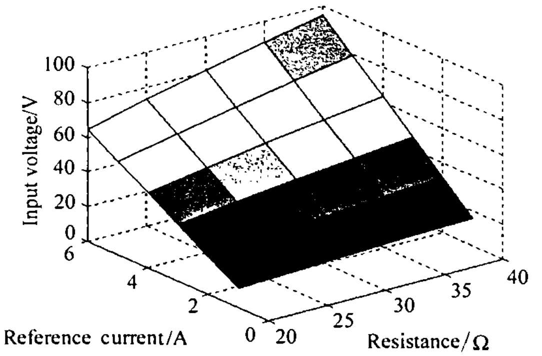


Fig. 3 3-D parameter space of Buck-Boost converter

The surface means the boundary condition. It consists of the first flip bifurcation points under different parameters. Above the surface, the converter is in stable state. Under the surface, the system will go to period-2, period-4, etc, then enter chaos via period-doubling route.

Therefore if enough boundary equations are obtained in advance, with the help of the parameter space the power electronics engineers can place the normal operating point far away from the boundary region to maintain a desirable behavior. It is particularly meaningful to power supply design.

5 Experimental system and experimental results

5.1 Experimental system of the 20kHz Buck-Boost converter

In order to verify the theoretical and simulation results in the first part of the paper, the experimental circuit of 20kHz current-mode controlled Buck-Boost converter is built and shown in Fig.4. In order to make the circuit close to ideal state, we choose a tantalum type capacitor C which is with low equivalent series resistance. To avoid high frequency effect, the switching frequency is chosen at 20kHz, which is the lowest frequency in practical power converter, though stated as the highest one in several papers[1~8]. Here, a power MOSFET and a fast recovery diode are used. The winding resistance of inductor L is about 0.5Ω, which is the greatest deviation from the theoretical model because this value is assumed to be zero in our theoretical analysis. The small resistor that is connected to the positive port of LM339 works as a current sensor of inductor L. It is used to detect the peak current of L, so we can keep it in this position.

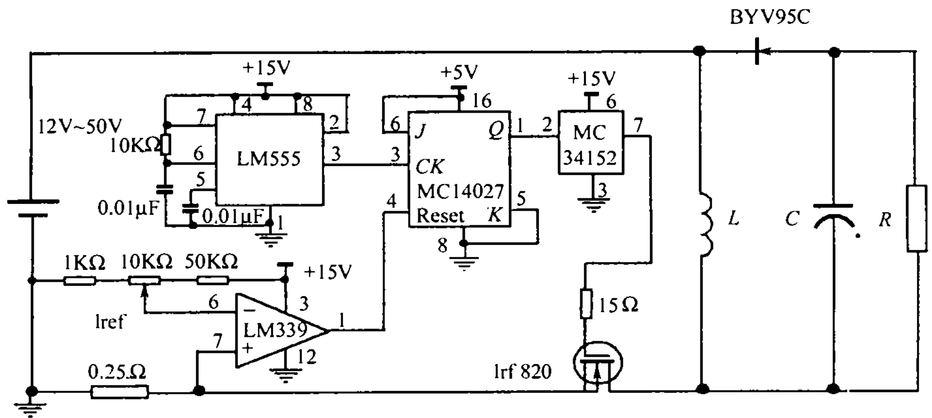
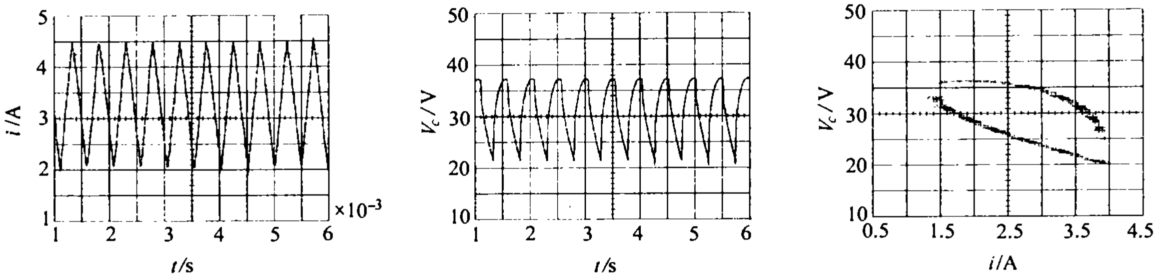


Fig. 4 The experimental circuit of the 20kHz Buck-Boost converter

5.2 Experiment results

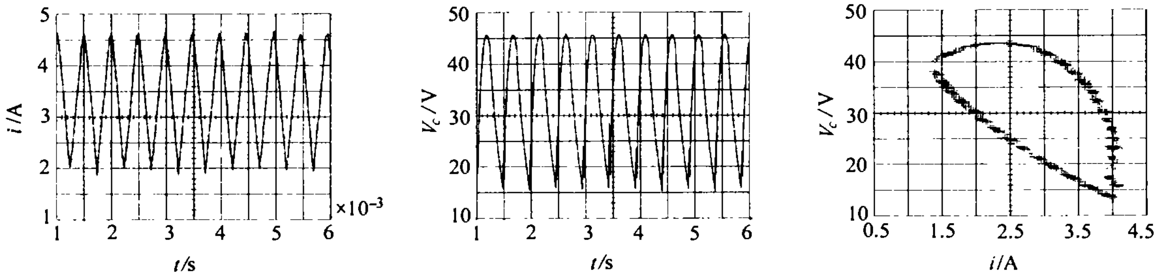
Our experiment is divided into three parts. They are about I_{ref}, E, and R as bifurcation parameters respectively. The following are the experimental results.

It can be seen that the experimental results have firmly verified the theoretical analysis and simulation results in the first part of the paper. Consequently, the model developed in the former paper is correct.



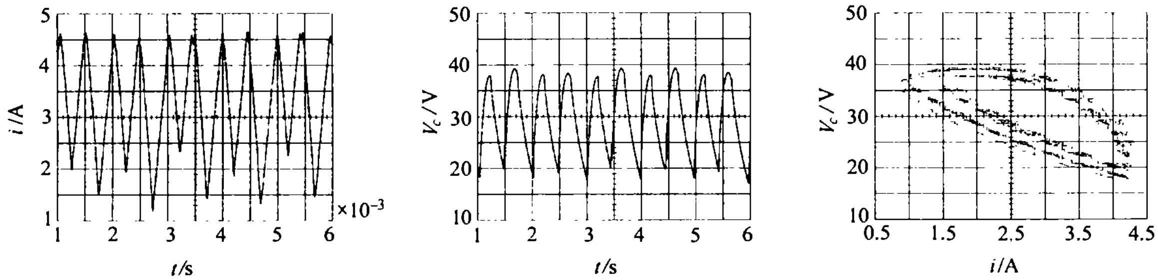
(a) Experimental waveform for i (b) Experimental waveform for V_c (c) Period-1 experimental phase portrait

Fig. 5 Period-1 waveforms and phase trajectory of Buck-Boost converter with I_{ref} =1A



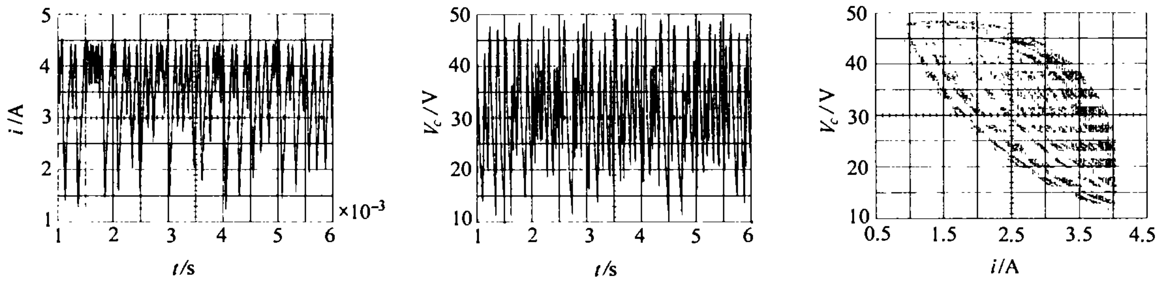
(a) Experimental waveform for i (b) Experimental waveform for V_c (c) Period-2 experimental phase portrait

Fig. 6 Period-2 waveforms and phase trajectory of Buck-Boost converter with I_{ref} = 1.5A



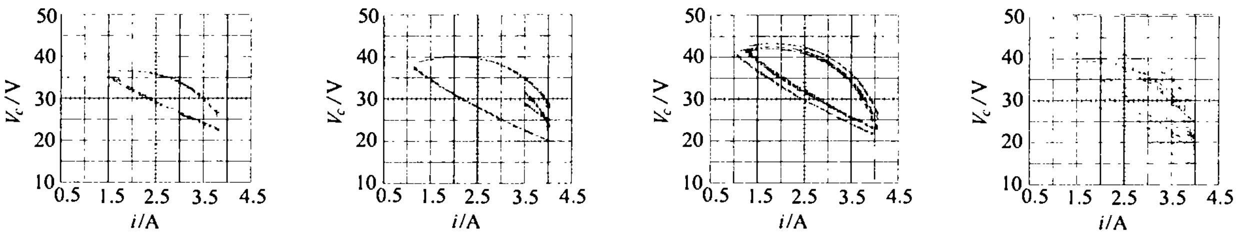
(a) Experimental waveform for i (b) Experimental waveform for V_c (c) Period-4 experimental phase portrait

Fig. 7 Period-4 waveforms and phase trajectory of Buck-Boost converter with I_{ref} = 1.8A



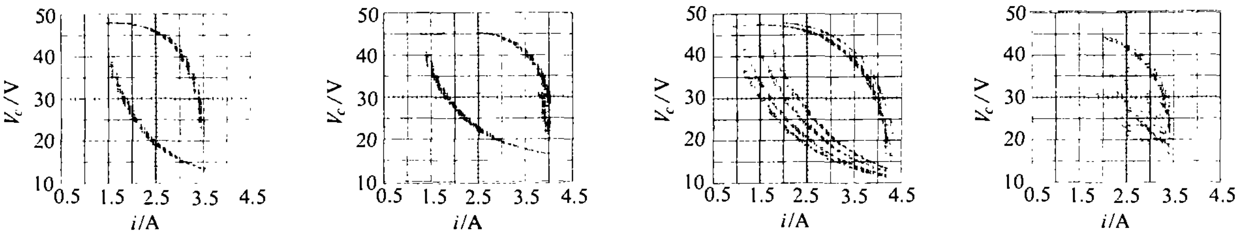
(a) Experimental waveform for i (b) Experimental waveform for V_c (c) Experimental phase portrait

Fig. 8 Chaotic waveforms and phase trajectory of Buck-Boost converter with I_{ref} = 4.5A



(a) E=50V, period-1 (b) E=35, period-2 (c) E=25V, period-4 (d) E=20V, chaos

Fig. 9 Phase trajectory of Buck-Boost converter with E as bifurcation parameter



(a) R=2 Ω, period-1 (b) R=3.8 Ω, period-2 (c) R=6 Ω, period-4 (d) R=12 Ω, chaos

Fig. 10 Phase trajectory of Buck-Boost converter with R as bifurcation parameter

6 Conclusion

It is well known that the topologies of DC-DC converters are changed due to the switching operation. This results in a nonlinear time-varying system. Hence, DC-DC converters exhibit a wide range of bifurcation and chaos behavior under some conditions. In this paper, the experimental evidence is provided to verify the predicted phenomena. At the same time, the onset of the first flip bifurcation point can be exactly located by using fixed point and stability theories. 3-D parameter space of stable region is also presented.

Based on the iterative map of Buck-Boost converter, the fixed point and Jacobian Matrix $J(x_e)$ of the mapping at the fixed point is obtained. With the help of the loci of eigenvalues of Jacobian Matrix, the first bifurcation point of Buck-Boost converter is investigated in detail. The theoretical analysis agrees with the numerical simulation.

The research about the domains of bifurcation and chaos in the parameter space is particularly important because the power electronics engineers must choose the parameter values in order to obtain the desired behavior. Moreover, the engineers will consciously avoid the bifurcation and chaos domains if they thoroughly understand when the nonlinear phenomena occur. In this paper, based on the numerical analysis, the parameter space and boundary condition of stable region in Buck-Boost converter are obtained.

Moreover, the hardware of the 20kHz current-mode controlled Buck-Boost converter has been built. The experimental results have been presented to verify bifurcation and chaos phenomena, which have been analyzed and studied in detail in the first part of the paper. It is stated that there is a great agreement between the theoretical study and experimental results.

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