Study on Entropy Characteristics of Buck-Boost Converter with Switched Capacitor Network

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***Abstract*—Switched capacitor network has been widely used in power electronic circuits. buck-boost converter with switched capacitor network can achieve better voltage-drop effect under the same input voltage and switch duty cycle. Based on discrete iterative mapping model of peak current controlled buck-boost converter with switched capacitor network, this paper studies the entropy characteristics to analyze the nonlinear dynamic behavior of the converter. First, two-dimensional entropy of the converter is obtained, which reflects the overall statistical characteristics. Then, the numerical sequence distributions of buck-boost converter with switching capacitor network are also analyzed under different load resistors. Finally, the nonlinear dynamical analysis for the converter is verified by experimental results.**

Keywords—Buck-boost converter, switched capacitor network, nonlinear dynamic, Entropy

I. INTRODUCTION

DC-DC converter is a nonlinear variable structure system working in the switching mode, so it will produce a lot of nonlinear phenomena, such as period-doubling bifurcation, Hopf bifurcation, Flip bifurcation, boundary collision bifurcation and so on [1-4]. Since all actual circuit systems have nonlinear characteristics, the nonlinear circuit analysis method is adopted to analyze DC-DC converter [5-8]. Extensive application of nonlinear dynamics in DC-DC converter has greatly promoted the development of nonlinear circuit theory.

Switched capacitor network was first proposed in the 1970s, and has been more and more widely used [9-11]. The research on chaotic phenomena in buck-boost converter with switched capacitor network has been analyzed in detail [12], where the accurate discrete-time model of the converter is established. Based on the discrete-time model, the bifurcation diagram and its corresponding Lyapunov exponents are obtained by numerical simulation. The nonlinear characteristics of first-order DC-DC converter, using one-dimensional entropy, are investigated in [13]. For the traditional buck-boost converter, the nonlinear dynamics of the system and its generation mechanism are analyzed in detail in [14].

In this paper, the nonlinear characteristics of the high-order system are analyzed by applying the two-dimensional entropy. Because the statistical characteristics of sequence entropy can reflect the overall characteristics, a new way is used to study the effects of the load resistor of the converter on nonlinear behavior of the system. Then, the correctness of the theoretical analysis of the nonlinear behavior of buck-boost converter with switched capacitor network is verified through the circuit experiment. The experimental results indicate that entropy can accurately distinguish the period doubling bifurcation and chaotic behavior of the converter in the nonlinear dynamical evolution process.

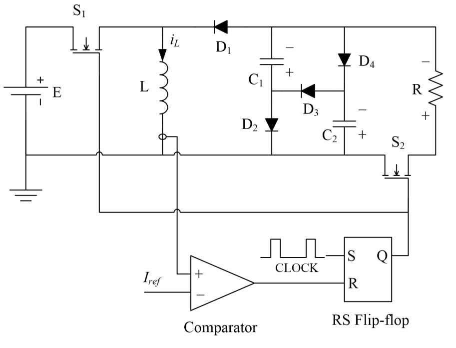


Fig. 1. Buck - boost converter with switched capacitor network.

II. MODEL OF BUCK-BOOST CONVERTER WITH SWITCHED CAPACITOR NETWORK

The circuit diagram of buck-boost converter with switched capacitor network is shown in Fig. 1. According to [9], the discrete-time iterative map model of the converter can be given as

$$x_{n+1} = \begin{cases} f_1(x_n), & i_n \le I_1 \\ f_2(x_n), & I_1 \le i_n \le I_2 \\ f_3(x_n), & i_n \ge I_2 \end{cases} \tag{1}$$

When $i_n \leqslant I_1$, the discrete-time iterative map is given as

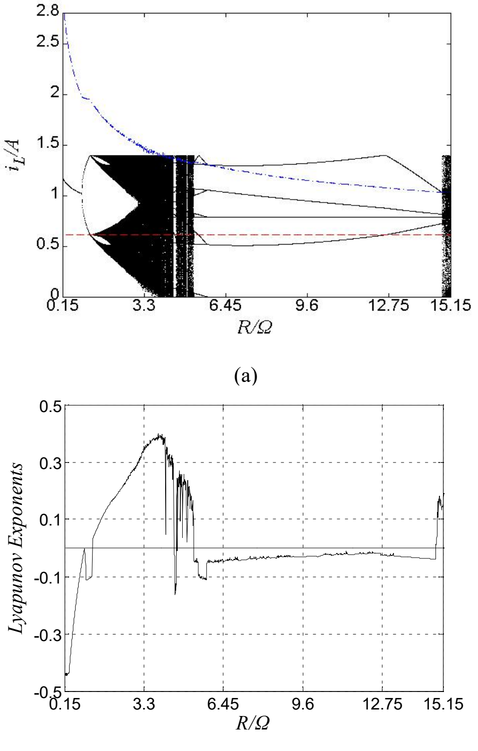
$$x_{n+1} = \begin{bmatrix} i_{n+1} \\ v_{n+1} \end{bmatrix} = f_1(x_n) = \begin{cases} i_n + \frac{ET}{L} \\ v_n e^{\frac{-T}{2RC}} \end{cases} \tag{2}$$

When $I_1 \leqslant i_n \leqslant I_2$, the discrete-time iterative map is given as

$$x_{n+1} = \begin{bmatrix} i_{n+1} \\ v_{n+1} \end{bmatrix} = f_2(x_n) = \\ \begin{cases} I_{ref} \cos\left(\mathrm{w}(T-\tau_1)\right) + K_1 sin(w(T-\tau_1)) \\ v(\tau_1)\cos\left(w(T-\tau_1)\right) + K_2 \sin\left(w(T-\tau_1)\right) \end{cases} \tag{3}$$

When $i_n \geqslant I_2$, the discrete-time iterative map is given as

$$x_{n+1} = \begin{bmatrix} i_{n+1} \\ v_{n+1} \end{bmatrix} = f_3(x_n) = \begin{cases} 0 \\ v(\tau_2) \end{cases} \tag{4}$$



(a)

(b)

Fig. 2. (a) Bifurcation diagram with the load resistor R as the bifurcation parameter. (b) The corresponding Lyapunov exponent diagram [9].

In the dynamic study of buck-boost converter with switched capacitor network, the dynamical evolution process of the system is firstly analyzed by bifurcation diagram and the corresponding Lyapunov exponent [9], based on the discrete-time iterative map (1). The circuit parameters of the converter are selected as follows: the switching period T=100 us, the input voltage E = 5 V, the inductor L = 634 uH, the capacitor C = 220 uF and the reference current I_{ref} = 1.4 A. Bifurcation diagram and Lyapunov exponents of the inductor current, with the load resistor R as bifurcation parameter, can be obtained, as shown in Fig. 2. Then the nonlinear characteristics of the converter are analyzed, according to the statistical characteristics of numerical sequence and the entropy characteristics of the system.

III. ENTROPY CHARACTERISTICS OF THE CONVERTER

Many scholars try to use different methods to reveal the chaotic mechanism in DC-DC converter, and entropy theory is a very unique research method. The entropy distribution and numerical sequence distribution of the first-order DC-DC converter have been studied in [10]. This paper attempts to study the two-dimensional entropy and entropy sequence distribution of buck-boost converter with a synchronous switched capacitor network. The nonlinear dynamic evolution process of buck-boost converter with switched capacitor network is verified from the view of entropy.

Entropy is defined as the expected value of discrete random variables, and it is a scale representing the total amount of information from the mean meaning. The one-dimensional entropy is expressed as:

$$H = -\sum_{i=1}^{N} p(x_i) log_2 p(x_i) \tag{5}$$

where, N is the number of characters and $p(x_i)$ is the probability distribution of the i th character. When $p(x_i)$=0, then $0 * log_2 0 = 0$. Thus, the definition of two-dimensional entropy is

$$H = -\sum_{i=1}^{N} \sum_{j}^{M} p(x_i y_j) log_2 p(x_i y_j) \tag{6}$$

where N and M are the number of characters of x and y respectively, and $p(x_i\, y_j)$ are the probability distribution of two-dimensional joint variables. When $p(x_i\, y_j)$ =0, then $0 * log_2 0 = 0$.

In order to further verify the correctness of the dynamic model of the converter and understand the dynamic evolution process of buck-boost converter with switched capacitor network, the entropy characteristics of the circuit system are described using MATLAB software. The initial parameter values of the circuit described in [9] are still used in the model. Entropy mean value diagram and numerical sequence distribution diagram are used to illustrate the correctness of the previous theoretical analysis.

Fig. 3 shows the entropy distribution of the converter with the load resistor R as the parameter. Fig. 4 shows the numerical sequence distribution of inductive current i_L in buck-boost converter with switched capacitor network at the load resistors of 0.5 Ω, 1 Ω, 3 Ω, 4 Ω, 10 Ω, 15 Ω, respectively.

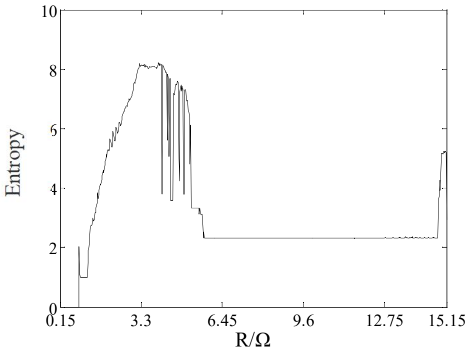


Fig. 3. Average entropy diagram of the converter with different values of the load resistor R.

When R=0.5Ω, it can be seen from Fig. 4 that the system works in a stable state, and the entropy value can be solved by (6) as zero. When R=1Ω, it can be found that entropy is one. When the system is in the chaotic state, it can be seen from (6) that the entropy value increases with the increase of R, which reflects that the value of i_L appears in a larger range and the randomness is higher. The entropy value decreases around R=4.45 Ω and R=5.2 Ω, which indicates that the system has a tangent bifurcation around R=4.45 Ω and R=5.2 Ω, and the system changes from chaotic state to periodic state. Therefore, all the data are concentrated in a few statistical intervals, which leads to a decrease in entropy value. It is interesting to note that entropy can accurately reflect the complex nonlinear dynamics of the converter, which is related to the Lyapunov exponent corresponding to bifurcation diagram. On the other hand, the numerical sequence distribution under the different conditions, as shown in Fig. 4, are also applied to investigated the complex nonlinear dynamics of buck-boost converter with switched capacitor network.

As can be seen from Fig. 4, the numerical sequence distributions of the converter corresponding to different load resistors R are obviously different. When R=0.5Ω, Fig. 4 (a) corresponds to the state of period 1. The sequence of the system is distributed at a point, and the probability is about 1. When R=1Ω, Fig.4 (b) corresponds to the state of period 2. The sequence of the system is evenly distributed at two points, and the probability of each point is 0.5. As the load resistor R increases, the system enters into the CCM chaotic state. When R=3 Ω, Fig. 4 (c) shows the sequence distribution corresponding to the CCM chaotic state. The sequence distribution of the system is in two regions, and the distribution probability of each point in the two regions is different, indicating that the system works in the DCM chaotic state. When R=4 Ω, Fig. 4 (d) corresponds to the DCM chaos state. When R=10 Ω, Fig. 4 (e) corresponds to periodic 5 states. The sequence of the system is distributed at 5 points, and the distribution probability of each point is approximately equal, indicating that the system enters a multi-periodic state. When R=15 Ω, Fig. 4 (f) corresponds again to the chaotic state of DCM, indicating that there is an intermittency chaotic state in the system, but the sequence distribution at this time is significantly different from that in Fig. 4 (d).

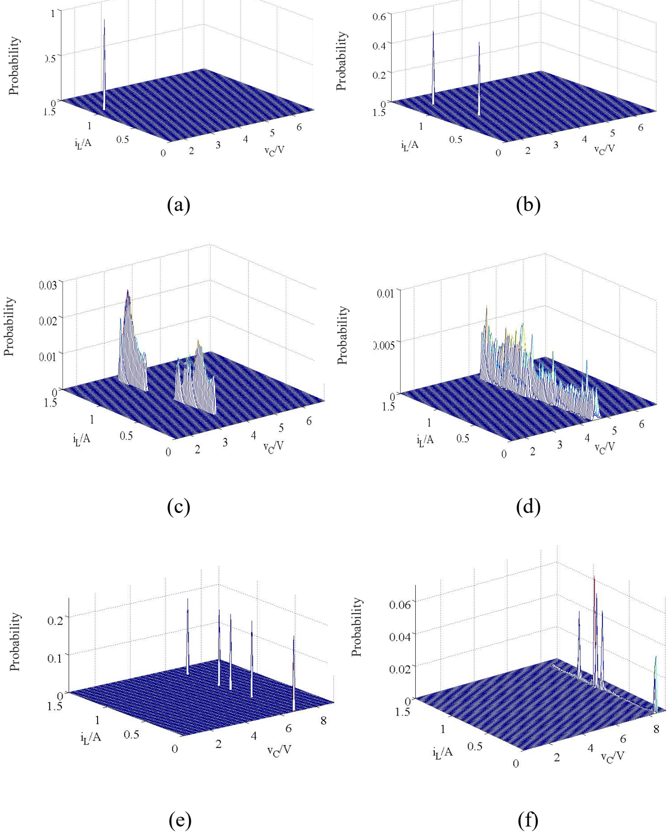


Fig. 4. The numerical sequence distribution of the converter as the load resistor R changes. (a) R=0.5Ω (period-1 state), (b) R=1Ω (period-2 state), (c) R=3Ω (CCM chaos state), (d) R=4Ω (DCM chaos state), (e) R=10Ω (multi-period state), (f) R=15Ω (DCM chaos state).

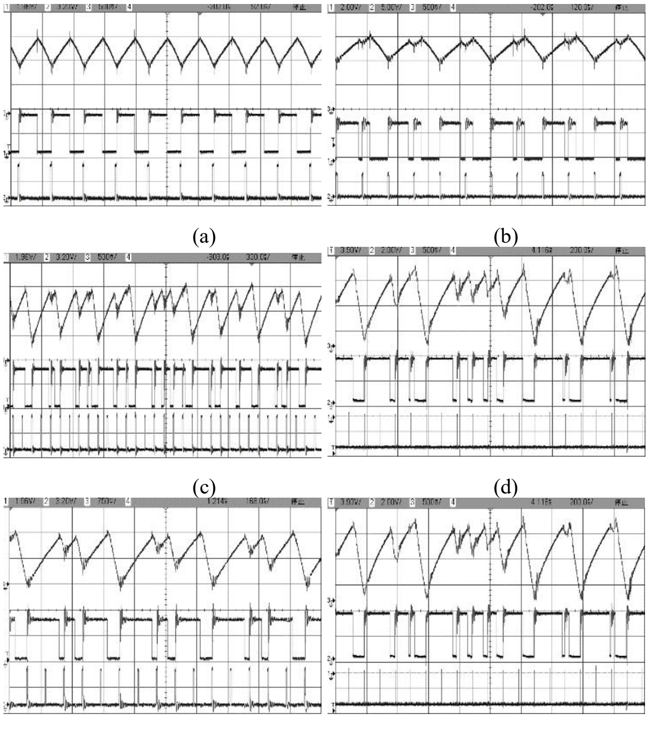
IV. EXPERIMENTATION

In order to verify the correctness of the above theoretical analysis, a prototype based on buck-boost converter with switched capacitor network is made, and the relevant circuit experiments are carried out.

The switch in the converter adopts IRF3205, and the driving circuit is based on the driving chip A3180. The circuit parameters are consistent with the circuit parameters in [9]. The experimental waveforms of the inductance current i_L, the driving signal d_n and the clock signal of the converter are obtained when the load resistor R changes.

Fig. 5 shows the experimental waveforms of buck-boost converter with switched capacitor network, with load resistors R of 0.5 Ω, 1 Ω, 3 Ω, 4 Ω, 10 Ω, and 15 Ω, respectively. From top to bottom, the experimental waveforms are the inductance current i_L, the drive signal d_n of the switch IRF3205 and the clock signal of the converter. According to Fig. 5 (a)-(b), when the load resistance R is 0.5Ω, and 1 Ω, the converter works in period-1 state and period-2 state respectively. When R= 3 Ω, the system enters the CCM chaotic state, as shown in Fig. 5 (c). Fig. 5 (d) is the waveform of the system operating in DCM chaotic state when R= 4 Ω. When R= 10 Ω, as shown in Fig. 5 (e), the system enters a multiperiodic state again. When R=15 Ω, the system enters the DCM chaotic state again, as shown in Fig. 5 (f).

The experimental results show that bifurcation and chaos exist in buck-boost converter with switched capacitor network, under the peak current control. With the increase of the load resistor R, the system experiences period-1 state, period-2 state, CCM chaotic state, DCM chaotic state, multi-periodic state, and DCM chaotic state again. This is consistent with the conclusion obtained from the bifurcation diagram, the Lyapunov exponent diagram. In this paper, the entropy and the numerical sequence distribution of the converter are also obtained, according to (6), which verifies the correctness of the nonlinear dynamical analysis of buck-boost converter with switched capacitor network.


(a) (b)

(c) (d)

(e) (f)

Fig. 5. Experimental waveforms of the inductor current i_L (top), the driving signal d (middle), and the clock signal (bottom) with the load resistor R variation [9]. (a) R=0.5Ω (period-1 state), (b) R=1Ω (period-2 state), (c) R=3Ω (CCM chaos state), (d) R=4Ω (DCM chaos state), (e) R=10Ω (multi-period state), (f) R=15Ω (DCM chaos state).

V.   CONCLUSIONS

In this paper, the evolution process of nonlinear dynamics of buck-boost converter with switched capacitor network is studied in a new way from the view of entropy characteristics and numerical sequence distribution. Entropy can accurately distinguish the period doubling bifurcation and chaotic behavior of the converter in the process of nonlinear evolution. With the change of load resistance, the converter transits from the stable state to periodic-two state, and then enters into CCM chaotic state. With the further increase of load resistance, the converter finally enters into DCM chaotic state, due to the boundary collision. It is interesting to note that entropy diagram can accurately reflect the complex nonlinear dynamics of the converter, which can also be proved by Lyapunov exponents corresponding to the bifurcation diagram. Finally, the correctness of the above theoretical analysis is further verified by the experimental time domain waveforms.

ACKNOWLEDGMENT

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