Chaos control of bi-directional DC-DC converter by resonant parametric perturbation method in a DC microgrid

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Abstract. Nonlinear phenomena and the control method of the bi-directional DC-DC converter in different operating modes are studied to solve the problem of unstable operation of the bi-directional DC-DC converter in a DC microgrid. The piecewise switch model is built by analyzing the topology and the working process of the bi-directional DC-DC converter as well as employing Matlab/Simulink software. The evolution of the bi-directional DC-DC converter from steady to bifurcation and chaos is got by simulating the piecewise switch model with reference current and output voltage as bifurcation parameters. Finally, the resonant parametric perturbation is applied to control the chaos in bi-directional DC-DC converter, and thereby the stability of the bi-directional DC-DC converter in a DC microgrid has been improved.

1. Introduction

With the development of distributed DC power supply and electrical energy storage equipment in the microgrid, DC microgrids have been highly concerned. As an important component of DC microgrid, bi-directional DC-DC converter also has developed and been widely used[1]. Bi-directional DC-DC converter, which is a strong nonlinear system, may appear irregular behaviors such as bifurcation and chaos when the circuit parameters are varied[2]. Therefore, knowing when and why bifurcation or chaos occurs in a bi-directional DC-DC converter and giving effective control in time will certainly help to improvement design and enhancement performance[3].

At present, most studies about bi-directional DC-DC converter had mainly focused on circuit topology and control strategy[4], but the study on chaotic characteristic is relatively few[5]. This paper, which takes bi-directional buck-boost converter as an object, focuses on nonlinear phenomena by using bifurcation diagrams[6], time-domain waveforms, phase portraits, resonant parametric perturbation method. Bi-directional DC-DC converter is developed on the basis of unidirectional DC-DC converter, and therefore there is a strong connection between the two kinds of converters on chaos analysis and control. But unlike unidirectional DC-DC converter, the inductance value of the circuit is unique because the bi-directional DC-DC converter belongs to common circuit. Therefore, engineers need to adjust the parameters reasonably in the analysis and design process to get the ideal effect.

2. Control strategies and modeling strategies

The main circuit topology of bi-directional DC-DC converter is shown in Figure 1.
Bi-directional DC-DC converter has three operation modes [7]: Buck mode, Boost mode and alternate mode. The alternate mode is equivalent to the alternation between Buck mode and Boost mode in a short time, and therefore this paper concentrates on the first two operation modes. Besides, Q₁ and Q₂ work in a complementary PWM manner. The inductor current \( i_L \) is therefore a triangle wave and the discontinuous inductor current, which occur in unidirectional DC-DC converter, will not occur over a period of time.

The converter mainly adopts voltage feedback control in Buck mode, whereas it adopts current feedback control in Boost mode, as shown in Figure 2. A judgment circuit is added to the circuit. If \( i_L > 0 \), the bi-directional DC-DC converter is in Buck mode. If \( i_L < 0 \), the bi-directional DC-DC converter is in Boost mode.

Similarly, the state equations in Boost mode can be described by:
\[
\begin{align*}
    i_L &= \frac{V_2 - V_o}{sL} \\
    V_o &= \frac{-V_o R_1 + i_L}{sC_1} 
\end{align*}
\] (4)

where \( V_0 = V_1 \).

The piecewise switch model is built based on (3) and (4) by employing Matlab/Simulink software[8]. The structure of the Simulink model is given in Figure 3.

Assuming that the circuit components are ideal devices, the bi-directional DC-DC converter is analyzed based on the parameters of Table 1 and Table 2.

**Table 1. Circuit parameters in Buck mode**

| Circuit components and parameters | Values |
|----------------------------------|--------|
| Inductance \( L \)               | 20mH   |
| Load resistance \( R_2 \)        | 8\( \Omega \) |
| Capacitance \( C_2 \)            | 22\( \mu \)F |
| Magnification times              | 8.4    |
| Input voltage \( V_1 \)          | 10V    |
| Reference voltage \( V_{ref} \)  | 11.3V  |
| Lower threshold of the ramp signal | 3V    |
| Upper threshold of the ramp signal | 8V    |
| Switching period \( T \)         | 400us  |

**Table 2 Circuit parameters in Boost mode**

| Circuit components and parameters | Values |
|----------------------------------|--------|
| Load resistance \( R_1 \)        | 20\( \Omega \) |
| Capacitance \( C_1 \)            | 30\( \mu \)F |
| Input voltage \( V_2 \)          | 5V     |
| Reference current \( i_{ref} \)  | 0.2A-2.5A |

Figure 3. Piecewise switch model of bi-directional DC-DC converter
3. Nonlinear analysis

3.1 Theoretical analyses on nonlinear behaviors

The nonlinear behavior of bidirectional DC-DC is strongly affected by input voltage $V_1$ or reference current $i_{ref}$, according to the Buck or Boost mode of the converter, respectively [9]. Therefore, the bifurcation diagrams of inductor current $i_L$ in Buck mode and Boost mode are got with $V_1$ and $i_{ref}$ as bifurcation parameters, respectively. The bifurcation diagrams are shown in Figure 4.

![Bifurcation diagram in Buck mode](image)

**Figure 4. Bifurcation diagram of bi-directional DC-DC converter**

With the change of $V_1$, the inductor current $i_L$ presents different performance in Buck mode as shown in Figure 4(a). The first bifurcation occurs at $V_1 = 26V$ and the converter enters into period-2 operation. As $V_1$ is continuously increased to 31V, the converter bifurcates to period 4. When the value of $V_1$ is further increased, the converter enters into chaotic regime.

With the change of $i_{ref}$, the inductor current $i_L$ presents different performance in Boost mode as shown in Figure 4(b). The first bifurcation occurs at $i_{ref} = 0.7A$ and the converter enters into period-2 operation. As $i_{ref}$ is continuously increased to 1.3A, the converter enters into chaotic regime and there is no apparent period-4 operation.

3.2 Simulation results on nonlinear behaviors

It is assumed that the value of $V_1$ or $i_{ref}$ is varied while other parameters are fixed. The piecewise switch model is then simulated and its inductor current $i_L$ and output voltage $V_o$ are sampled. Simulation results in Buck mode are shown in Figures 5, 6, 7 and 8.

![Inductor current waveform](image)
Figure 5. Diagram of period-1 operation with $V_1 = 18V$

Figure 6. Diagram of period-2 operation with $V_1 = 25V$
In Figure 5, it can be observed that when $V_1 = 18V$, the inductor current $i_L$ waveform is a periodic steady zigzag wave and the output voltage $V_o$ is a periodic steady sine wave. The corresponding phase portrait exhibits only one loop. Thus it can be seen that, the converter is in period-1 orbit.

In Figure 6, it can be observed that when $V_1 = 25V$, the inductor current $i_L$ and the output voltage $V_o$ waveforms present bifurcation but they are still periodic. The corresponding phase portrait also presents bifurcation. Thus it can be seen that, the converter is in period-2 orbit.

In Figure 7, it can be observed that when $V_1 = 31V$, four peaks appear in both the inductor current $i_L$ waveform and the output voltage $V_o$ waveform. The corresponding phase portrait exhibits two limit cycles. Thus it can be seen that, the converter is in period-4 orbit.

In Figure 8, it can be observed that when $V_1 = 50V$, the inductor current $i_L$ and the output voltage $V_o$ waveforms behave randomly. The corresponding phase portrait is distributed in a certain range randomly. Thus it can be seen that, the converter is working in the chaotic state.

The simulation results in Boost mode are shown in Figures 9, 10 and 11.
Figure 9. Diagram of period-1 operation with $i_{ref} = 0.4A$

Figure 10. Diagram of period-2 operation with $i_{ref} = 0.78A$
In Figure 9, it can be observed that when $i_{ref} = 0.4A$, the inductor current $i_L$ and the output voltage $V_o$ waveforms are periodic with their periods equal to the switching period. The corresponding phase portrait is a finite closed curve with only one loop. Thus it can be seen that, the converter is in period-1 orbit.

In Figure 10, it can be observed that when $i_{ref} = 0.78A$, the inductor current $i_L$ and the output voltage $V_o$ waveforms present bifurcation but they are still periodic with their periods equal to 2 times the switching period. The corresponding phase portrait also presents bifurcation. Thus it can be seen that, the converter is in period-2 orbit.

In Figure 11, it can be observed that when $i_{ref} = 1.3A$, the inductor current $i_L$ and the output voltage $V_o$ waveforms behave randomly. The corresponding phase portrait is distributed in a certain range randomly. Thus it can be seen that, the converter is working in the chaotic state.

4. Control of chaos
Resonant parametric perturbation can suppress chaos by giving perturbations to a parameter at appropriate frequencies. The principle of parameter selection is that the parameter can strongly affect the system and can be easily varied.

4.1 Simulation of chaos control in Buck mode
In Buck mode, the reference voltage $V_{ref}$ is chosen as the perturbation parameter to achieve the chaos control. Essentially we replace $V_{ref}$ by the perturbed reference voltage $V_{ref}'$, i.e.,

$$V_{ref}' = V_{ref} + A\sin(2\pi f + \phi) \quad (5)$$

The converter is in a chaotic state when $V_1 = 50V$ and chaos control is therefore carried out at this time. The harmonic signal superimposed in (5) should be set to the same frequency and phase as the periodic ramp signal $V_r(t)$. The parameters of the effective perturbation required can be obtained according to the stability criteria of Buck converter[10]. When the perturbation amplitude $A$ is about 20A and the optimal phase $\phi$ is about 0, the chaotic converter can be controlled to work on the period-1 orbit. The Simulink model with chaos control is shown in Figure 12. The simulated inductor current $i_L$ time-domain waveform after chaos control is shown in Figure 13.
From Figure 13, inductor current waveform becomes single periodic state after chaos control, which indicates that the system operates in period-1 steady state after adding chaos control.

4.2 Simulation of chaos control in Boost mode

In Boost mode, $i_{ref}$ is chosen as the perturbation parameter to achieve the chaos control. Essentially we replace $i_{ref}$ by the perturbed reference current $i_{ref}'$, i.e.,

$$i_{ref}' = i_{ref} + A \sin(2\pi f + \phi)$$  \hfill (6)

The converter is in a chaotic state when $i_{ref} = 1.3A$ and chaos control is therefore carried out at this time. The parameters of the effective perturbation required can be obtained according to the stability criteria of Boost converter[10]. When the perturbation amplitude $A$ is about 0.15A and the optimal phase $\phi$ is about 6, the chaotic converter can be controlled to work on the period-1 orbit. The Simulink model with chaos control is shown in Figure 14. The simulated inductor current $i_L$ time-domain waveform after chaos control is shown in Figure 15.
Figure 15. Inductor current waveform after chaos control

From Figure 15, inductor current waveform becomes single periodic state after chaos control, which indicates that the system operates in period-1 steady state after adding chaos control.

5. Conclusions

Nonlinear phenomena and the control method of bi-directional DC-DC converters are studied in this paper. Several conclusions can be drawn as follows,

1) In Buck mode, the system changes with the change of input voltage $V_1$. The first bifurcation occurs at $V_1 = 26V$ and the converter enters into period-2 operation. As $V_1$ is continuously increased to 31V, the converter bifurcates to period-4. When the value of $V_1$ is further increased, the converter enters into a chaotic regime.

2) In Boost mode, the system changes with the change of reference current $i_{ref}$. The first bifurcation occurs at $i_{ref} = 0.7A$ and the converter enters into period-2 operation. As $i_{ref}$ is continuously increased to 1.3A, the converter enters into the chaotic regime and there is no apparent period-4 operation.

3) The stability of the bi-directional DC-DC converter has been improved through using resonant parametric perturbation method. In Buck mode, when the perturbation amplitude $A$ is about 20A and the optimal phase $\phi$ is about 0, the chaotic converter can be controlled to work on the period-1 orbit. In Boost mode, when the perturbation amplitude $A$ is about 0.15A and the optimal phase $\phi$ is about 6, the chaotic converter can be controlled to work on the period-1 orbit.

Acknowledgment

This Project (ZR2018MF005) was supported by the Natural Science Foundation Shandong Province, China.

References

[1] Y.G.Yan. Bi-directional DC-DC Converters[M]. Phoenix Science Press, 3-9, (2004).
[2] E.Lenz, D.J.Pagano. Nonlinear Control for Bidirectional Power Converter in a dc Microgrid [J]. Ifac Proceedings Volumes, 46, 359-364, (2013).
[3] C.K.Tse, M.D.Bernardo. Complex Behavior in Switching Power Converters [J]. P IEEE, 90, 768-781, (2002).
[4] X.H.Xu, C.B.Zheng, C.G.Hu, et al. Design of Bi-directional DC-DC Converter[C]. C IND ELECT APPL, 2283-2287, (2016).
[5] Y.Mei, X.Q.Li. A New Control Method of Balancing Inductor Current for Interleaved Parallel Bi-directional DC-DC Converter[C]. IPEMC, 2988-2992, (2016).
[6] X.R.Li, Y.L.Zhu, R.Shen. Control of chaos of the linear-mode switched-capacitor converter[J]. Journal of Xidian University, 42, 110-114, (2015).
[7] K.Suresh, R.Arulmozhiyal. Design and Implementation of Bi-directional DC-DC Converter for Wind Energy System[J]. CS, 07, 3705-3722, (2016).
[8] Z.H.Li, G.H.Zhou, X.T.Liu, et al.Dynamical modeling and analysis of buck converter operating in pseudo-continuous conduction mode[J]. ACTA PHYS SIN-CH ED, 64, 209-218, (2015).
[9] A.M.Harb, S.M.Harb, I.E.Batarseh. Chaos and Bifurcation of Voltage-Mode-Controlled Buck Dc-Dc Converter with Multi Control Parameters[J]. INT J SIMUL MODEL, 30, 472-478, (2010).
[10] L.H.Wang. Study on Chaos Theory Applied in Photovoltaic DC Microgrid System[D]. Beijing Jiaotong University, 69-84, (2017).