Control mode and topology of hydrogen fuel cell DC/DC converter

Zhihua Li1,2,3, Jing Chen2,1, Chun Xiao2,1 and Zhenglong Chen1,2

1 School of Automation, Wuhan University of Technology, Wuhan 430070, China
2 Foshan Xianhu Laboratory of the Advanced Energy Science and Technology Guangdong Laboratory, Xianhu hydrogen Valley, Foshan 528200, P.R. China
3 E-mail: lizihua_luoyue@foxmail.com

Abstract. The decrease in hydrogen fuel cell durability is due to the excessive input current ripple of the DC/DC converter. An improved DC/DC converter is used to reduce the input current ripple in order to solve this problem. This DC/DC converter is modified on the basis of a staggered BOOST DC/DC converter, the input current ripple of the DC/DC converter is effectively reduced. In this paper, the principle of current ripple generation is analyzed, the operation mechanism of the DC/DC converter is analyzed, the corresponding control mode is selected. The DC/DC converter designed is simulated. The result is shown as below: the input current ripple coefficient of DC/DC Converter is controlled to less than 1%, the smoothness of the output current of hydrogen fuel combustion battery is guaranteed.

1. Introduction

Hydrogen fuel cell vehicles have entered a stage of rapid development, the development of hydrogen fuel cell vehicles is still limited by the service life of hydrogen fuel cell, with the rapid development of hydrogen fuel cell technology [1]. DC/DC Converter is an essential part of a hydrogen fuel cell vehicle powertrain in order to match the voltage between the hydrogen fuel cell and the auxiliary power supply. The topology of the DC/DC converter is divided into two categories, non-isolated and isolated [2]. In non-isolated topology, BUCK, BOOST and BUCK-BOOST are widely used. Algorithms and theoretical studies of such topology have been thoroughly studied. This type of topology is characterized by simple structure, low number of switching devices and simple design of inductive capacitors, but the design of inductive capacitor is difficult [3]. In some cases where isolation is required, an isolation topology is used. In the isolated DC/DC converter, the transformer is added to the input and output stages, and the switching frequency of the switching device in the converter is generally in the tens of thousands of Hz. Isolated DC/DC converter topology is widely used including phase shift ingress, half-bridge LLC, full bridge LLC, full bridge CLLC, push-pull and backfiring, but the control of the converter is more difficult. In this paper, the principle of current ripple generation is analyzed, the input filter inductor is referenced in the interlaced BOOST DC/DC converter, and the current ripple is reduced due to the corresponding control mode being selected. Simulation experiments were carried out, and the ability of the topology and control mode to suppress the input current ripple was verified.
2. DC/DC converter topology
The DC voltage fluctuations in the output of the DC/DC converter are caused by the converter's high-speed turn-on and off, which is the voltage ripple. In order to suppress current ripple, a suitable DC/DC converter topology needs to be selected.

2.1. Mechanism of current ripple generation
BUCK topology is used to explain the mechanism of current ripple. The simplest BUCK topology is shown in Figure 1.

![Simplest BUCK topology](image)

With the continuous switching ingenuity, the current in inductive L fluctuates up and down around the effective value of the output current, capacitor C is constantly charged and discharged, and the ripple voltage consistent with the switching frequency is also generated at the output. Under ideal conditions, the output voltage ripple is consistent with the voltage pulsation value of capacitor C, and the capacitive voltage peak is calculated as:

\[ \Delta U_c = \frac{\Delta I}{8 \times fC} \]

In equation, \( \Delta I \) is the AC component of the current in inductor, \( f \) is the switching frequency, and the \( C \) is the output capacitor value.

The output current ripple is mainly caused by the high frequency ripple with the consistent switching frequency, the resonant noise in the power switch process and the common mode noise ripple caused by the parasitic parameters. Different measures are required to suppress current ripples for different components of current ripples, the following are two common methods used to suppress current ripple.

Methods of increasing operating frequency, increasing output filter inductor and selecting large-capacity output capacitors are used, for high-frequency ripple. It is important that the ripple generated by capacitor charge and discharge is much smaller than the ripple produced by ESR, so the ESR resistance value of the capacitor should be concerned rather than the capacity of the capacitor, and the ESR capacitor should be chosen for small capacitor. In addition, secondary voltage regulation can be performed using multi-stage filtering and linear power supplies.

Power diodes with small junction capacitors and short recovery time, increasing suitable absorption circuits and reducing wiring length are used, for switching noise. Increasing common mode filtering to filter out and reducing switching burr stoking is used to reduce common mode noise in output ripple. On this basis, a filter inductor is added to the BOOST DC/DC converter to reduce the input current ripple.
2.2. Topology analysis
This is not enough for hydrogen fuel cells, although the input current ripple can be reduced by the existing multiphase BOOST topology. In order to improve the working environment of hydrogen fuel cells further, the unique filter inductor is introduced on the input side of the non-isolated staggered BOOST topology, and the input current ripple is significantly reduced due to the addition of inductors. The topology of the DC/DC is shown in Figure 2.

![Figure 2 Topology of the DC/DC](image)

In the figure, L1, L2, and L3 are the boost inductance of each phase circuit, V1, V2, and V3 are diodes, S1, S2, and S3 are three-phase IGBT switches, C1 and C2 are output capacitance and input capacitance, Z is the load resistance, L4 is the unique filter inductance on the input side and the I in is the input current. The designed DC/DC topology is suitable for high power or medium power requirements. Hydrogen fuel cell voltage and current ripple are effectively reduced, voltage current stress on power devices is reduced and output power levels are increased because multiphase interlaced topology is used.

3. DC/DC converter control mod
This paper is based on the output characteristics of hydrogen fuel cells. The control mode is divided into continuous control mode and discontinuous control mode for basic BOOST converter.

(1) Continuous control mode (CCM)

\[ U_{in}D_T S = (U_c - U_{in})(1-D)T_S \]  

(2)

(2) Discontinuous control mode (DCM)

\[ U_{in}D_T S < (U_c - U_{in})(1-D)T_S \]  

(3)

In equation(2) and equation(3), D is the duty cycle, \( T_S \) is the switching period, \( U_{in} \) and \( U_c \) are the input voltage and output voltage of the converter, respectively. The transfer function of the designed DC/DC converter into the output can be derived in CCM mode, using the open-loop input impedance of the BOOST circuit.

\[ G_c(S) = \frac{D'}{a_2s^3 + a_3s^2 + a_4s + a_0} \]  

(4)

While, \( a_0 = D'^2 \), \( a_1 = \frac{L + L_1}{R} \), \( a_2 = L_1C + L_2C \), \( a_3 = \frac{LL_1C}{R} \), \( a_4 = LCL_1C \).
The transfer function of the output to the input of the BOOST circuit in inductive current discontinuous mode (DCM):

\[ G_p(s) = \frac{D}{a_3s^3 + a_2s^2 + a_1s + a_0} \]  

(5)

While, \( a_0 = 1, a_1 = \frac{L_1D^2}{R} + RC \frac{M - 1}{2M - 1}, a_2 = L_1C_1 + L_1CD^2 \frac{M}{2M - 1}, a_3 = L_1C_1C \frac{M - 1}{2M - 1} \).

The CCM mode and the DCM mode are different in that the converter has three operating states during the switching cycle, so the average variable of the switching assembly must be considered in conjunction with the three states of the variable. When DC/DC works in CCM mode, the system is a fourth-order system, and the characteristic equation of its transfer function has a conjugate compound root with a negative real part, that is, the system has attenuation oscillation, which can be seen by the transfer function in the two control modes of the DC/DC converter obtained above. The system is a third-order system, the root of the characteristic equation is negative and the system is stable when the system is operating in DCM mode. As can be seen above, DC/DC operates very stable and non-oscillating in DCM mode. In order to ensure the stability of the DC/DC converter, the control mode of the DC/DC converter is selected as DCM mode.

4. Simulation analysis

Under the SIMULINK environment of MATLAB, the simulation model of DC/DC converter is constructed to compare the input current ripple under the same power level with or without input filter inductor. The DC/DC converter input voltage is 140V, and the corresponding input current simulation result is shown in Figure 3 when the output voltage is 520V.
The input current curve at the steady state without filter inductor on the input side is shown in Figure 3(a). It can be seen from the figure that the input current ripple without filter inductor is about 20A; The steady-state input current with a 120µH filter inductor added to the input is shown in Figure 3(a), and the current ripple is reduced to 0.09A. It can be seen that the addition of the filter inductor on the input side effectively reduces the DC/DC input current ripple and extends the service life of the fuel cell stack.

5. Conclusion
In this paper, the mechanism of current ripple generation is studied, and a new DC/DC topology with input filter inductor is used to reduce current ripple, which seriously affects the fuel cell life due to the hydrogen fuel cell output current ripple assembly. The transfer function of the system is studied in depth, and the appropriate control mode is selected to ensure the stability of the system. The ripples of the topological structure with input filter inductor and no input filter inductor are compared by using MATLAB software simulation. The results were shown from the experiment: the DC/DC converter is designed to not only have the function of raising voltage, but also effectively reduce slower fuel cell current ripple. Ripple coefficient is controlled within one percent, hydrogen fuel cell working environment is improved. It is of great significance to extend the service life of hydrogen fuel cell.

Acknowledgments
This work was financially supported by the natural science foundation of Zhejiang Province (Granted No: LY14E070003). This work was supported by Major Open Fund Projects from Foshan Xianhu Laboratory of the Advanced Energy Science and Technology Guangdong Laboratory (XHD2020-003).

References
[1] Yang Zibin. Development status and industrialization of hydrogen fuel cell vehicles in China [J]. Automotive Practical Technology, 2019 (16): 31-33.
[2] Yuan Qingping, Wang Huaqiang. A dual inductive isolated BOOST converter with output resonance voltage doubler [J]. Journal of Yunnan University (Natural Science Edition), 2015, 37 (3): 373-379.
[3] Chen Zhangyong, Xu Jianping, Wu Jianxue, et al. Coupled inductor zero input ripple high gain non-isolated DC-DC converter [J]. Proceedings of the CSEE, 2014, 34 (33): 5836-5845.
[4] He Jintao, Zheng Chuanbi. Analysis of the development trend of hydrogen fuel cell vehicles [J]. Heavy Vehicles, 2019 (4): 24-26.
[5] Yang Jian. Technical characteristics and application of hydrogen fuel cells [J]. Communication Power Technology, 2016, 33 (3): 83-85.
[6] Cao Xiaojuan, Tuo Chaoyong, Song Xiaolin. A high boost ratio DC/DC converter suitable for fuel cell vehicles [J]. Power Electronics Technology, 2014, 48 (5): 62-64.
[7] Bai Wei, Qi Bojin, Wang Dianlong. Research on DC/DC converters for fuel cell buses based on DSP control [J]. Power Technology Application, 2007 (3): 10-13.
[8] N. Videau, G. Fontes, D. Flumian. High Ratio Non-Isolated DC–DC Converter for Hydrogen Battery Using a 50 kW PEM Fuel Cell [J]. Fuel Cells, 2017, 17(2).
[9] Damien Guilbert, Arnaud Gaillard, Ali Mohammad. Investigation of the interactions between proton exchange membrane fuel cell and interleaved DC/DC BOOST converter in case of power switch faults[J]. International Journal of Hydrogen Energy, 2015, 40(1):519-537.
[10] Sang C. Lee, Woo Young Jung. Graphical Analysis of a DC-DC Converter Effect on a Fuel Cell: D-transformation[J]. Energy Procedia, 2016, 88:647-651.