Simulation on staggered parallel boost converter with double integral sliding mode control

Meng Zhang¹,²,³, Jing Chen²,¹, Xianbao Lan¹,² and Chun Xiao²,¹

¹ School of Automation, Wuhan University of Technology, Wuhan 430070, P.R. 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: zhangmeng1030@whut.edu.cn

Abstract. As a non-linear input power source, fuel cells have soft output characteristics, slow dynamic response, and short service life. In order to improve the service life of the fuel cell, this paper conducts a simulation study on an interleaved parallel boost circuit based on double integral sliding mode control. The interleaved parallel structure is used to reduce the input current ripple of the fuel cell, and the state space average equation is used for modeling. At the same time, the double integral sliding mode control can improve the dynamic performance of the Boost converter. A hysteresis control is added after the sliding mode control to weaken the chattering effect of the sliding mode control. Matlab simulations show that the interleaved parallel Boost circuit with double integral sliding mode control can control the output current ripple of the fuel cell within 1% and make the output voltage have good dynamic performance.

1. Introduction

New energy vehicles use fuel cells as their energy source. In order to match the output voltage required by the fuel cell and the load, the Boost converter has become an indispensable component of the fuel cell vehicle power system. The design of Boost converter should not only avoid shortening the life of fuel cell [1-2], but also ensure the reliable and stable operation of the system.

Traditional Boost converters are mostly controlled by PI controller. The PI control algorithm is simple and easy to implement, but it is not suitable for nonlinear systems. Boost converters for fuel cells have problems such as large overshoot and slow dynamic response according to traditional PI control.

The inductance current of the Boost converter with the interleaved parallel structure can realize automatic current sharing. At the same time, the output current ripple frequency is twice the switching frequency, and the ripple peak value is reduced. When the duty cycle is 0.5 in two phases, the relationship between the ratio r of the fuel cell output current ripple and the branch current ripple can theoretically be 0% [3], so it can effectively improve the service life of the fuel cell. At the same time, the voltage stress of the switch tube has been reduced, which simplifies the design of the radiator [4-7], so in this paper, the interleaved parallel topology is used as the research object.

Sliding mode control (SMC) is also called sliding mode variable structure control. The sliding mode is to move the controlled object's state trajectory to the switching surface of the state space set in advance, and is not affected by system parameters and load changes. This makes the accused object possess strong robustness [8]. Because Boost converter is a variable structure system, and sliding
mode control is suitable for variable structure system, it is widely used. Order reduction can be achieved due to sliding mode control. When a fixed frequency sliding mode controller is used, the robustness and adjustability of the converter system will deteriorate under the reduced-order sliding mode control. The introduction of additional integral control variables into the fixed frequency sliding mode controller can alleviate this phenomenon. The steady-state error increases as the switching frequency of the converter decreases, and the fixed frequency is easier to limit the occurrence of noise [9]. At the same time, according to the literature hysteresis control can effectively weaken the chattering effect of sliding mode control [10]. Mohammadali Ghafarian et al. proposed an adaptive fuzzy sliding mode control methodolog, which realized the high-precision positioning and tracking of the XYZ piezoelectric driven monolithic micro-nano manipulator [11] So sliding mode control can be proved to be very good for implementing nonlinear control.

Therefore, in this paper, a staggered parallel topology is used to improve the output current ripple of the fuel cell. Aiming at the non-linear characteristics of the fuel cell, combined with double integral sliding mode control, the Boost converter parameter calculation and control analysis are carried out, and the simulation research is carried out by Matlab.

2. Topological structure and parameter design

2.1. State space equation

The two-phase interleaved parallel Boost converter is simply the interleaved parallel connection of two classic single-phase Boost converters, as shown in Figure 1. \( L_1 \) and \( L_2 \) are inductors, \( S_1 \) and \( S_2 \) are switching devices, \( D_1 \) and \( D_2 \) are diodes, \( C \) is capacitance, \( R_0 \) is load, \( V_i \) is input voltage, \( V_o \) is output voltage. Since the two main power switches \( S1/S2 \) are switched on and off alternately, the duty ratios of the switches \( S1 \) and \( S2 \) are the same, and the phase difference of the driving signals is 180 degrees. The frequency of the input combined current is twice that of the single-phase Boost converter. Therefore, the two-phase interleaved parallel Boost converter is suitable for high frequency, high power and high current occasions [7].

\[
\begin{align*}
L_1 \frac{di_{L1}}{dt} &= V_i - (1-D)V_o \\
C \frac{dV_o}{dt} &= (1-D)i_{L1} - \frac{V_o}{R}
\end{align*}
\]

Figure 1. The structure of two interleaved Boost converters in parallel.

The state space averaging method needs to average the inductor current and capacitor voltage in a period, so it is not necessary to model according to the working state. Since the state equations of the two inductors are the same in one cycle, only the inductance equation of one phase is considered. According to Kirchhoff’s law of voltage and current, the state space average equation of the Boost converter in a complete cycle is obtained.

Therefore, in the entire cycle, \( D \) is the duty cycle of the switching device, and \( i_{L1} \) is the current of \( L1 \), the state equation of the single-phase interleaved parallel Boost circuit is:

\[
\begin{align*}
L_1 \frac{di_{L1}}{dt} &= V_i - (1-D)V_o \\
C \frac{dV_o}{dt} &= (1-D)i_{L1} - \frac{V_o}{R}
\end{align*}
\]
2.2. Parameter calculation
In the simulation, Matlab's own fuel cell stack is used as input power supply, and PEMFC-6kW-45V is selected, a non-linear power supply with an input voltage range of 37V-65V, rated output voltage is 90V, and a switching frequency is 50kHz.

The interleaved parallel symmetrical Boost converter has a suppressive effect on the current ripple due to its interleaved parallel structure. The inductance is calculated by setting the current ripple rate of the inductor L1 and L2 branch to 1%. The main function of the output capacitor is used to filter out high-frequency voltage ripple to keep the voltage smooth and to stabilize the DC bus voltage when the load changes suddenly. The larger the capacitance of the design capacitor, the better. However, the cost and dynamic response of the Boost converter cannot be designed to be large in the design. In practice, the main consideration is that the voltage ripple of the output voltage is less than 1%. Specific parameters are shown in Table 1.

| Table 1. Parameter setting. |
|-----------------------------|
| **Element** | **Parameter** |
| Fuel cell stack | PEMFC-6kW-45V |
| L1=L2 | 14.1mH |
| C | 14.4μF |
| Load resistance R0 | 1.35Ω |

3. Boost converter control strategy
Under ideal sliding motion, σ is a sliding surface composed of x₁, x₂, x₃, and x₄, and k₁, k₂, k₃, k₄ are their coefficients respectively the system trajectory always moves along σ = 0, so make ̇σ = 0, and get the equivalent control as:

\[
u_{eq} = 1 + \frac{V_i - k_1 \frac{V_o}{R} - k_2 x_1 - k_3 x_2 - k_4 x_4}{k_1 i_{t1} - V_o}
\]  

\[
\begin{align*}
di_{t1} &= \frac{1}{L} \frac{V_i - V_o}{L} - \frac{k_1 V_o}{R} k_1 i_{t1} - V_o \\
\frac{dV_o}{dt} &= \frac{k_1 V_o}{R} + k_2 x_1 + k_3 x_2 + k_4 x_4 - V_i i_{t1} - V_o
\end{align*}
\]

In order to ensure that the designed SMC has a sliding mode motion state, it needs to meet the reachability condition. According to the Lyapunov stability theorem: \(V = 0.5σ^2\), if the system is to be stable, it needs to meet \(̇V = σ̇σ < 0\).

When \(\frac{di_{t1}}{dt} = \frac{dV_o}{dt} = 0\), the steady-state equation can be obtained as shown:

\[i_{t1} = \frac{V_o^2}{V_o R}
\]

Linearize Equation (4) near the equilibrium point, the linear characteristic equation can be obtained as shown:

\[s^3 + (-a_{11} - a_{22}) s^2 + (a_{11} a_{22} - a_{12} a_{21} - a_3) s + (a_{11} a_{22} - a_{12} a_{21}) = 0
\]
Therefore, according to the Routh criterion, the following conditions must be met if the system needs to be stable:

\[
\begin{align*}
-a_{11} - a_{22} &> 0 \\
-a_{11}a_{22} - a_{12}a_{21} - a_j &> a_{11}a_{22} - a_{13}a_{23} \\
-a_{11}a_{22} - a_{12}a_{23} &> 0
\end{align*}
\] (6)

Therefore, combining the existence condition of the sliding mode surface and the system stability judgment condition, the controller coefficient can be set as \(k_1 = 0.49\), \(k_2 = 2.7\), \(k_3 = 3.4576\), \(k_4 = 32\), \(k_5 = 10\), \(k_6 = 3\).

Equation (2) is the expression of the control law \(u\) in an ideal state. However, this directly implemented control law will cause chattering effects, so hysteresis control is introduced to reduce the system switching frequency and switch this at a very high frequency phenomenon. This time Formula (2) is rewritten as follows:

\[
u = \begin{cases} 
0, & \sigma > d \\
1, & \sigma < -d \\
\text{Keep}, & -d < \sigma < d
\end{cases}
\] (7)

where, \(k\) represents the hysteresis width of the Boost converter. At the same time, according to the following formula, the hysteresis width \(k\) can be calculated as 1.5:

\[
d = \frac{V_i(V_i - V_o)}{2fLV_i}
\] (8)

4. Simulation model and result analysis

4.1. Simulation modeling

Figure 2 is a Boost converter simulation model chart based on the voltage outer loop current inner loop double closed loop PI control, its structure parameter is shown in Table 1. In order to verify the robustness of the control part, the experiment changed the load resistance from 1.35\(\Omega\) to 1.6\(\Omega\) at 0.25s.

![Simulation model of boost converter controlled by PI.](image)
Figure 3. Simulation model of Boost converter controlled by SMC.

Figure 3 is a simulation model diagram of Boost converter with hysteresis double integral SMC. Compared with Figure 2, only the control part is replaced with hysteresis double integral SMC.

4.2. Simulation results

Figure 4 shows the $V_O$ waveform of the Boost converter under PI control. It can be seen from the figure that when the load resistance is 1.35 $\Omega$, the overshoot of the $V_O$ is 0.025s and the response time is 0.025s, and after 0.25s load resistance jumps. The overshoot of the $V_O$, the output reaching steady state time is 0.27s, and the response time is 0.02s.

Figure 5 is the $V_O$ waveform diagram of the Boost converter under SMC. Compared with the $V_O$ under PI control, the output voltage of SMC has no overshoot, the response speed against interference is also improved, and the robustness has reached expectations aim.

Figure 6 shows the output current waveform of the Boost converter under PI control. The maximum steady-state input current $I_{max}$ is 133.6A, the minimum $I_{min}$ is 132.9A, and the ripple rate is less than 1%.

Figure 7 shows the output current waveform of the Boost converter under SMC. The maximum value of the input current $I_{max}$ is 132.5A, the minimum value $I_{min}$ is 132.9A, and the ripple rate is 0.45%.
Through comparison, it can be concluded that the system dynamic response of the Boost converter using the SMC is faster than that of the PI controller, and the overshoot is much smaller than the Boost converter under the PI controller. After interference, it has good robustness and can quickly reach the desired output voltage. Due to the use of the interleaved parallel topology, the ripple of the fuel cell output current is well suppressed, not exceeding 1%, reaching the expected effect has verified the feasibility of the scheme.

5. Conclusions
The main purpose of this paper is to analyze and calculate and simulate the topology and control strategy of Boost converters for fuel cells. The topology structure of staggered parallel connection is combined with a double integral SMC with hysteresis link instead of the original PI controller. The experimental results show that the scheme enables the system to have rapid response capability, greatly reduces the overshoot of the system, suppresses the output current ripple of the fuel cell, improves the service life of the fuel cell, and increases the robustness of the system.
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