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Published in:
Intelligent Systems and Applications

DOI (link to publication from Publisher):
10.1007/978-3-030-29516-5_72

Publication date:
2019

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Hajizadeh, A. (2019). Fuzzy Sliding Mode Control of Onboard Power Electronics for Fuel Cell Electric Vehicles. In Y. Bi, R. Bhatia, & S. Kapoor (Eds.), *Intelligent Systems and Applications: Proceedings of the 2019 Intelligent Systems Conference (IntelliSys) Volume 1* (Vol. 1, pp. 956-965). Springer. Advances in Intelligent Systems and Computing https://doi.org/10.1007/978-3-030-29516-5_72

Fuzzy Sliding Mode Control of Onboard Power Electronics for Fuel Cell Electric Vehicles

Amin Hajizadeh(✉)

Department of Energy Technology, Aalborg University, Esbjerg, Denmark
aha@et.aau.dk

Abstract. In this study, the designing of an intelligent robust control system for onboard power electronic converter, which is utilized in fuel cell electric vehicle, is concerned. It employs sliding-mode control that integrates a fuzzy tuning approach. The DC-DC converters which are employed for the integration of fuel cell power source can regulate the input voltage and provide the output power with high efficiency. Among them, the buck-boost converters with non-inverting property are offered to gain buck and boost features. The proposed control strategy consists of fuzzy logic and sliding mode control methods to synthesize the gains of both controllers. To achieve this goal, a nonlinear average model of the converter is extracted. Then a fuzzy sliding mode controller is planned to adjust the output voltage of the converter. Furthermore, robustness and stability of the controller are proved by Lyapunov theory and they are fulfilled completely. The obtained computer results demonstrate the ability of the control policy throughout diverse situations.

Keywords: Fuzzy sliding mode control · Onboard power electronic · Fuel cell electric vehicle

1 Introduction

Integration of onboard power electronic converters to electric propulsion system is a very stimulating research topic. The fuel cell is one of the future-looking power sources which is used in an electric vehicle. But the high variation of its output voltage makes that to employ buck-boost converter to get the benefits during operating low-power and high-power situations. These two cases are essential for fuel cell electric vehicle during charging and discharging the battery [1, 2]. As fuel cells function in a large variety of power, it is vital that the DC-DC converters provide high efficiency at the entire power range [3, 4]. In addition, the DC-DC converter should provide the buck and boost conditions for the fuel cell voltage [5]. By reason of its straightforwardness, less electrical stress on components, and high efficiency, the non-inverting buck-boost converter is employed for this application [6]. Lately, in past studies, some research works have been established for controlling this sort of DC-DC converter [4, 7]. They are including the classic and state feedback control approaches. The main drawback of these methods is that they are designed based on the constant operational point and in they cannot handle properly variations of the load voltage and current. Another technical challenge is the existence of zeros in the transfer function of the DC-DC converter

Y. Bi et al. (Eds.): IntelliSys 2019, AISC 1037, pp. 956–965, 2020.
https://doi.org/10.1007/978-3-030-29516-5_72

in the right half plane (RHP) which limit the response of the controller. The right half plane zero adds negative phase to the system and it makes the phase of system increases from 0 to −90°. This causes a delay in the system response which can lead to instability [6].

Consequently, a proper control strategy should be developed to overcome these restrictions. Several control approaches have been addressed for the power flow control of fuel cell electric vehicle. The power flow regulation between the fuel cell and the supplementary energy storages is the main objective. In [8] and [9], intelligent control methods based on artificial intelligence are applied in a hybrid power train of fuel cell electric vehicle. In [10], a control algorithm based on cascade architecture is implemented for a hybrid power train including fuel cell, battery and supercapacitor to sustain the DC-bus voltage and state of charge (SOC) of battery bank within acceptable boundaries concurrently. In [11], to regulate the fuel cell output power, which is influenced by the variation of battery's SOC, a combination of cascade control and lookup tables-based approach is proposed. Most of the research studies on power management of fuel cell electric vehicle rely on the experimental rules, as presented in [12]. Generally, these rules are achieved using the examination of powertrain characteristics and employing human knowledge. In [13], model predictive control (MPC) is offered for distribution of power between fuel cell and battery. However, the MPC needs high computational complication which makes the real-time control of electric power train is challenging. Therefore, it is essential to introduce a control strategy for electric power train which has adaptive characteristic and it should be robust under parameters uncertainties and load power variation.

For this purpose, in this paper fuzzy sliding mode control is developed for the power electronic converter of fuel cell electric vehicle. This controller method is more robust and fast compared to conventional controllers. This paper is prearranged in the subsequent sections. Section 2 describes the model of the power train system on power electronic converter. In Sect. 3, the fuzzy sliding mode control is established in detail, including the stability and adaptivity analyses. Simulations are provided and debated to confirm the proposed control approach in Sect. 4. Finally, a conclusion is offered in Sect. 5.

2 Onboard Power Electronic for Electric Power Train

The modeling of the electric power train is presented in this section. It is an important matter that should be carefully investigated. Figure 1 demonstrates the block diagram of electric vehicle including fuel cell stack and battery bank. The main electric components of the electric vehicle are included a battery bank, power electronic converter, whereas the electrochemical elements are fuel cell stack and battery bank.

The precise models relating the dynamic performance of each of these components are specified in [10]. In this paper, the focus is on the power of electronic converter modeling. Therefore, the non-inverting buck-boost is considered, and the electrical circuit representation of the DC-DC converter is revealed in Fig. 2. The converter contains buck and boost operational functions which it operates in three different modes in a cascade form. It can regulate the output voltage of the converter based on the input voltage variations [3].

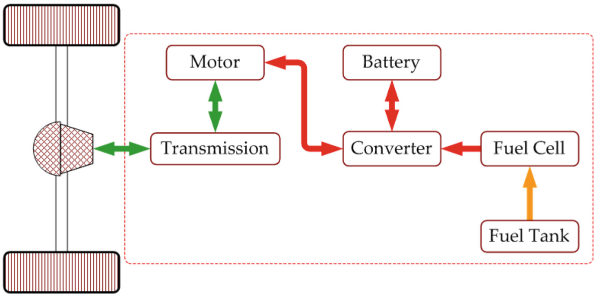

Fig. 1. A block plan of fuel cell power train

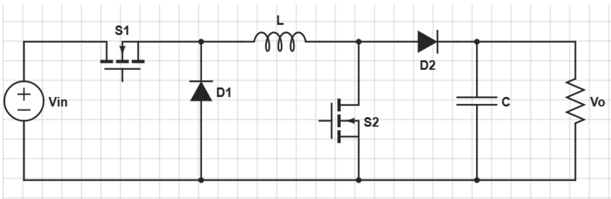

Fig. 2. The circuit diagram of the non-inverting buck-boost converter

According to Fig. 2, there are different operating situations for power electronic switches. The mathematical correlation which is described the input and output voltage relation is attained through the subsequent equation [5]:

$$\frac{V_O}{V_{in}} = \frac{D_1}{(1 - D_2)} \begin{cases} D_1 + D_2 > 1 \rightarrow Boost \\ D_1 + D_2 < 1 \rightarrow Buck \end{cases} \tag{1}$$

Which D_1 is the duty cycle of *S1* and D_2 is the duty cycle of *S2*. To stay away from a short circuit of the input source, the nominal values of D_1 is always bigger than D_2.

To establish the state space model of power electronic converter, the differential equations of the DC-DC converter in different circumstances based on the suitable switching scheme should be described. In this converter, three sets of circumstances are given as follows.

Both S_1 and S_2 are active ($0 < t<D_2T$)

S_1 is active and S_2 is inactive ($D_2T < t<D_1T$)

Both switches are inactive.

$$\begin{cases} \frac{dv_C}{dt} = \frac{1}{C}\left(-\frac{v_C}{R}\right) \\ \frac{di_L}{dt} = \frac{1}{L}(v_{in}) \end{cases} \quad 0 < t < D_2T$$
$$\begin{cases} \frac{dv_C}{dt} = \frac{1}{C}\left(i_L - \frac{v_C}{R}\right) \\ \frac{di_L}{dt} = \frac{1}{L}(v_{in} - v_C) \end{cases} \quad D_2T < t < D_1T \tag{2}$$
$$\begin{cases} \frac{dv_C}{dt} = \frac{1}{C}\left(i_L - \frac{v_C}{R}\right) \\ \frac{di_L}{dt} = \frac{1}{L}(-v_C) \end{cases} \quad D_1T < t < T$$

Where i_L is the current of an inductor, v_C is the voltage of output capacitor, v_{in} is the voltage of DC source and R is the resistance of the load. The variables which are presented by uppercase; are the equilibrium of the power electronic converter [3–5].

By merging the differential equations and then linearization around the equilibrium operating point, the average state space model of the non-inverting DC-DC converter is established. By taking into account the converter always works in the buck-boost mode and the duty cycles of S1 and S2 are equal, consequently, the average model of the DC-DC converter is written in state space form as following [6]:

$$\begin{pmatrix} \frac{d\hat{v}_C}{dt} \\ \frac{d\hat{i}_L}{dt} \end{pmatrix} = \begin{pmatrix} -\frac{1}{RC} & \frac{(1-D)}{C} \\ -\frac{(1-D)}{L} & 0 \end{pmatrix} \begin{pmatrix} \hat{v}_C \\ \hat{i}_L \end{pmatrix} + \begin{pmatrix} -\frac{I_L}{C} \\ \frac{V_{in}+V_c}{L} \end{pmatrix} \hat{d} + \begin{pmatrix} 0 \\ \frac{D}{L} \end{pmatrix} \hat{v}_{in} \tag{3}$$

3 Control Design

Designing sliding mode control for power electronic converter is always challenging. In the classic sliding mode control, the control signal is determined as follows which is calculated from Lyapunov stability theory:

$$u = u_{eq} + k_w.sgn(s) \tag{4}$$

Where k_w is the switching gain and s is sliding surface.

The sign function will make the chattering phenomenon on the global control signal u. For this reason, in this paper, the incorporating of fuzzy control method and sliding mode control is advocated to get rid of the chattering issue in control loops of the DC-DC converter and the robustness of the controller is fulfilled. Moreover, the control system performance is enhanced. Thus, the total control command of robust controller is described as follows:

$$u = u_{eq} + k_{fs}.u_{fs} \tag{5}$$

$$u = -f(\mathrm{X(t), t}) + \dot{X}_{ref}(\mathrm{t}) + k_{fs}.u_{fs} \tag{6}$$

To gain proper dynamic response and control accuracy, seven fuzzy rules are taken in the described control system. For scaling the input membership functions, the boundary of −1 and 1 with an equal extent is considered for all fuzzy variables.

Furthermore, designing of the decision rules for the fuzzy controller is established. The fuzzy rules satisfy the stability of the power electronic system. These rules hold the input/output correspondences and each control input has seven fuzzy sets so that there are around 49 fuzzy rules [14]. Furthermore, to reach the adaptivity characteristic of the controller, the global output of the fuzzy controller is calculated as follow:

$$u_{Fuzzy} = \frac{\sum_{l}^{m} \mu^j . U^j}{\sum_{l}^{m} \mu^j} = \frac{\sum_{l}^{m} \mu^j . C^j}{\sum_{l}^{m} \mu^j} \tag{7}$$

Then, the method based on the gradient descent is employed for tuning the C^j which is adaption parameter

$$C_{k+1}^j = C_k^j - \eta \frac{\partial S_k}{\partial C_k^j} \tag{8}$$

The character η is the learning factor, and k specifies the learning iterations quantity which is performed through the procedure. The Lyapunov function is built by the sliding surface to fulfill the stability of the learning process, which is described as following [14]:

$$\begin{aligned} V_k &= \frac{1}{2} S_k^2 \\ \Delta V_k &= V_{k+1} - V_k = \frac{1}{2}\left(S_{k+1}^2 - S_k^2\right) \\ &= \frac{1}{2}(S_{k+1} - S_k)(S_{k+1} + S_k) \end{aligned} \tag{9}$$

From Eq. (9), the following equations are extracted which are sued for learning procedure:

$$\begin{aligned} \Delta S_k &= S_{k+1} - S_k = \frac{\partial S_k}{\partial C_k^j} \Delta C_k^j \\ \Delta C_k^j &= C_{k+1}^j - C_k^j = \eta \frac{\partial S_k}{\partial C_k^j} \end{aligned} \tag{10}$$

After substituting the Eqs. (10) and (9), it is re-arranged:

$$\begin{aligned}
\Delta V_k &= \frac{1}{2}(S_{k+1} - S_k)(S_{k+1} + S_k) = \frac{1}{2}(\Delta S_k).(S_{k+1} + S_k) \\
&= \frac{1}{2}(\Delta S_k)(2S_k + \Delta S_k) \\
&= \frac{1}{2}\frac{\partial S_k}{\partial C_k^j}\eta S_k \frac{\partial S_k}{\partial C_k^j}\left(-2S_k + \frac{\partial S_k}{\partial C_k^j}\eta S_k \frac{\partial S_k}{\partial C_k^j}\right) \\
&= \frac{1}{2}\left(S_k \frac{\partial S_k}{\partial C_k^j}\right)^2 \left[\left(\frac{\partial S_k}{\partial C_k^j}\right)^2 \eta^2 - 2\eta\right]
\end{aligned} \tag{11}$$

Finally, to gratify the Lyapunov stability, the following conditions need to be confirmed:

$$\begin{aligned}
&\Delta V_k < 0 \rightarrow \left(\frac{\partial S_k}{\partial C_k^j}\right)^2 \eta^2 - 2\eta < 0 \\
&0 < \eta < \frac{2}{\left(\frac{\partial S_k}{\partial C_k^j}\right)^2}
\end{aligned} \tag{12}$$

4 Computer Results

With the purpose of validating the established model of the power train of fuel cell electric vehicle, the entire structure has been executed in the software of MATLAB. The sizing of each component has been listed in Table 1.

Table 1. Sizing of each component

Fuel cell power	50 kW
Fuel cell current	80 A
DC bus voltage	400 V
Battery capacity	50 KWh

For examining the power train system with a developed control method, the case studies for simulation is conducted which is described as continue. For this purpose, a typical load is assumed as in Fig. 3. Then by the implementation of the controller, some simulations results are obtained.

If the requested power is low, the battery bank delivers the required power to the power train. As a result, the SOC is reduced. While the request is growing, the fuel cell power is raised smoothly, and the rest of the demanded power is provided by the battery bank. Normally battery response during load fluctuations is fast and it can

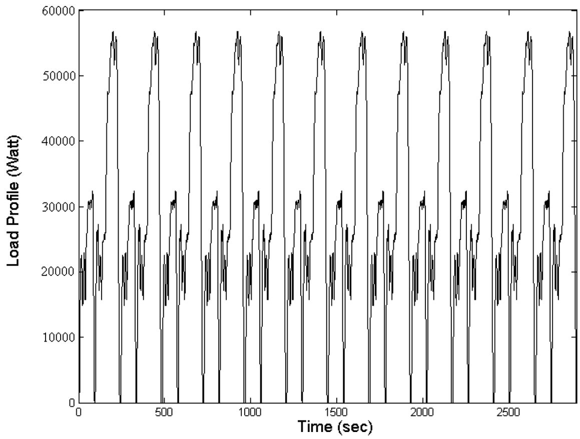

Fig. 3. Power demand profile of fuel cell electric vehicle

provide power to satisfy the load transient and fuel cell power changes gradually to fulfill a safe and durable operation. From Figs. 4 and 5, it is apparent that the load profile is distributed between fuel cell stack and battery bank. During peak load, the load power is requested more than the nominal power of fuel cell system. Thus, the demanded power is provided by the fuel cell power source and the battery bank concurrently. The voltage of battery is influenced by the load variations as seen in Fig. 6. In this situation, the controller stabilizes the voltage of non-inverting DC-DC converter as illustrated in Fig. 7, it varies in an acceptable range and the chattering effect is observable on it. Moreover, during the load power variation, by the implementation, the fuzzy sliding mode control the power balance in the power train is guaranteed. As a result, the SOC is sustained at a practical level as observed in Fig. 8.

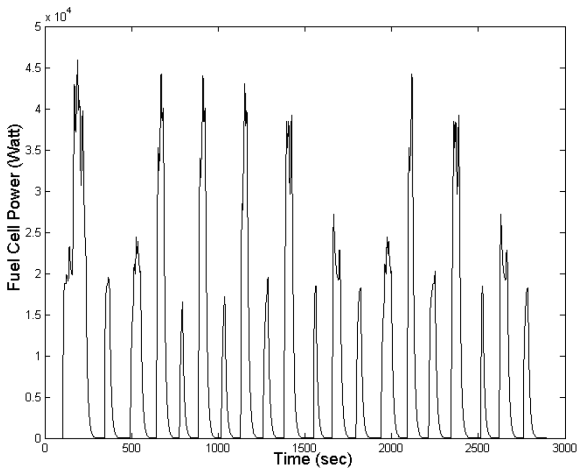

Fig. 4. The power of fuel cell during load variation.

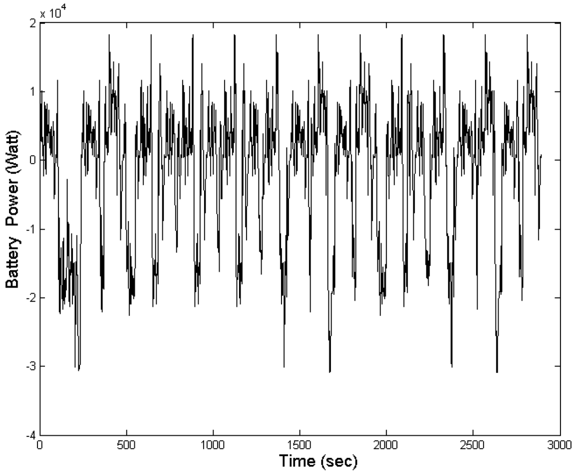

Fig. 5. Battery output power during load variation.

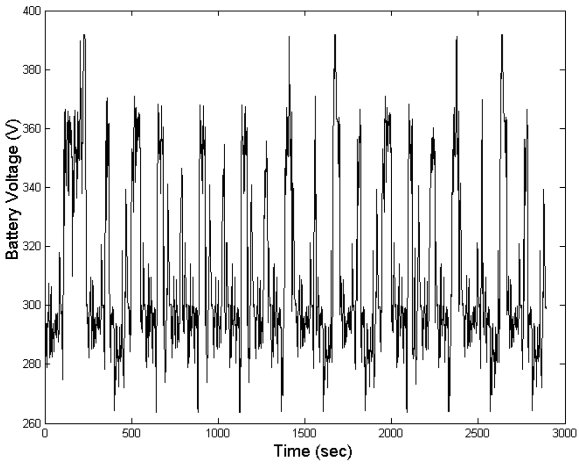

Fig. 6. Battery output voltage during load variation.

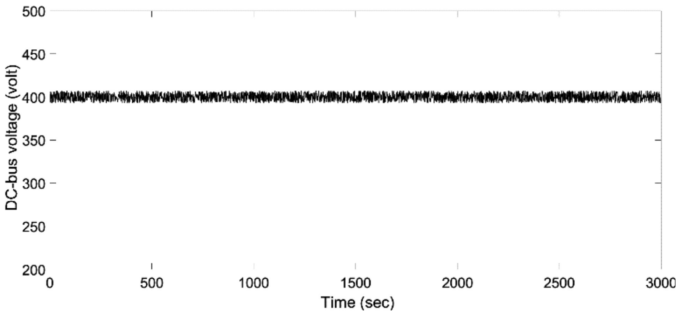

Fig. 7. Voltage of non-inverting DC-DC converter during load variation.

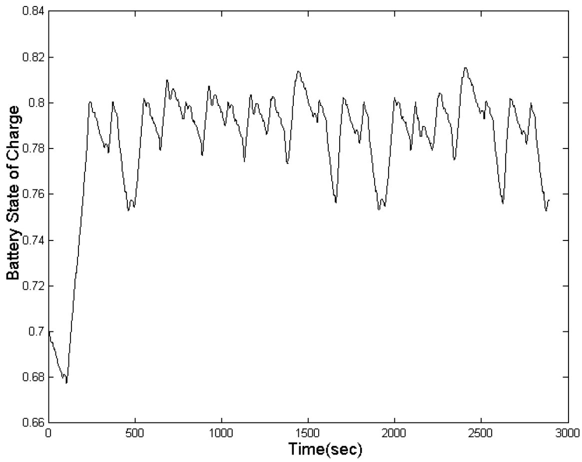

Fig. 8. State of charge during load variation

5 Conclusion

A control method employing fuzzy and sliding mode approaches was introduced in this paper for the power electronic converter of fuel cell power train system. The controller adjusts the response of non-inverting DC-DC converter when its operating point varies throughout the changes in input voltage or current fluctuation. The proposed robust control strategy synthesizes the gains of both fuzzy and sliding mode controllers. The obtained computer results demonstrate the ability of the control system.

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