Energy Conversion and Management 151 (2017) 562–572

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Implementation of an estimator-based adaptive sliding mode control strategy for a boost converter based battery/supercapacitor hybrid energy storage system in electric vehicles

Bin Wang*, Jun Xu, Dan Xu, Zhen Yan

State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University, Xi'an 710049, China

A R T I C L E I N F O

Keywords:
Energy management
Hybrid energy storage system
Adaptive sliding-mode control
Boost converter
Supercapacitor
Electric vehicles

A B S T R A C T

For the energy management of the boost converter based battery/supercapacitor (SC) hybrid energy storage system (HESS) in electric vehicles, a robust current control should be achieved for the battery such that the battery safety can be guaranteed. In this paper, an estimator-based adaptive sliding-mode control (estimator-based ASMC) strategy is proposed for the current tracking control of the boost converter based battery/SC HESS. By considering the unmodeled dynamics of the SC and the unknown disturbances, the equivalent circuit and the state-space average model are established for the boost converter based battery/SC HESS. To achieve the current tracking control, a sliding surface is defined based on the estimated tracking current error. The average control factor is designed according to the sliding-mode control (SMC) strategy. Furthermore, the adaptation laws are designed based on the state observers and the Lyapunov function, which can be used to estimate the load variations and unknown external input voltage. Finally, the adaptive control factor is recalculated based on the estimator-based ASMC strategy. In practical application, a hysteresis control strategy and an average filter method are developed to guarantee the smooth SMC for the boost converter based battery/SC HESS. Simulations and experiments are established to verify the estimator-based ASMC strategy. Compared to the conventional total SMC (TSMC) and PI strategies, the estimator-based ASMC strategy has over 37% and 50% settling-time improvement of current adjustment to deal with the load variation, respectively. The estimator-based ASMC strategy can improve the operating stability of the boost converter based battery/SC HESS under different operating modes. The battery can provide a constant or optimal current to the load. Therefore, the boost converter based battery/SC HESS with the proposed estimator-based ASMC strategy can effectively ensure the system stability and extend the battery life, simultaneously.

1. Introduction

Energy storage systems (ESSs) with batteries are of critical importance in electric vehicles (EVs) [1–3]. For the ESSs in EVs, there is no doubt that the cost of maintenance can be saved by extending the battery life. So it is very important to guarantee the battery safety [4,5]. However, the ESSs in the EVs often suffer from frequent charge and discharge operations. As a result, unexpected battery degradation and damage could not be avoided in the battery-based ESSs [6,7]. On the other hand, another energy storage device, i.e., supercapacitor (SC) has an incomparable cycle life than the battery. It can be used as an auxiliary equipment to deal with the current surges and the high frequent charge-discharge [3,8,9]. Combining with the SCs, batteries only need to provide constant or optimal current/power to the load such that the energy management system can guarantee the battery safety [4,10–12]. For these reasons, hybrid energy storage system (HESS) including batteries and SCs has been considered as one of the most suitable ESS options for EVs [8,13].

The boost converter based battery/SC HESS has been widely utilized to extend the battery life and improve the power performance of the ESSs in EV applications [8,10]. To deal with the unknown disturbances or load variations and ensure that the battery can provide the constant or optimal power, the key is to design a reliable control strategy for the HESS [14–16]. It has been successfully demonstrated that sliding-mode control (SMC) strategies can deal with the unknown disturbances and reduce the current/voltage fluctuation of the boost converter [8,17]. However, the obvious drawbacks of the conventional SMC (CSMC) are the uncontrollable infinite switching frequency and chattering phenomena when the CSMC is implemented in the direct current converter [18–20]. To suppress the switching frequency into a suitable range, the

* Corresponding author.
E-mail address: wb8751@163.com (B. Wang).

http://dx.doi.org/10.1016/j.enconman.2017.09.007
Received 22 May 2017; Received in revised form 9 August 2017; Accepted 5 September 2017

hysteresis control (HC) strategy can be utilized to limit the switching frequency [8,21]. Moreover, to alleviate the chattering phenomena caused by the sign function of the control factor in the CSMC, the control gain of the sign function should be conservatively designed [8].

The load uncertainties and parameter variations of the boost converter should be effectively estimated to design a suitable control gain of the sign function in the SMC [20,22]. In previous studies, the input voltage of the DC-DC converter should be known to implement the SMC strategy [18,23]. Unfortunately, for the boost converter based battery/SC HESS, the input voltage of the DC-DC converter is related to the nonlinear internal resistance of the battery, which cannot be accurately calculated [8,24,25]. Besides, unknown disturbances are coupled with load variations, which also cannot be accurately estimated [17]. In the literature [8], the adaptive law was designed to deal with the lumped system uncertainties. So the closed-loop control system designed for the boost converter could be asymptotically stable despite large system uncertainties. But when this adaptive SMC (ASMC) was implemented, the lumped system uncertainties should be accurately estimated. The implementation of the ASMC might be more complex since the lumped system uncertainties should be distinguished with the actual value.

In EV applications, the white noise and random disturbance should be noticed in the implementation of the estimator-based ASMC strategy for the boost converter based battery/SC HESS. Voltage and current signals involve with random noise such that they are not smooth and accurate [26,27]. So the real-time sampling signals of the voltage and current will lead to uncontrollable phenomenon. Real-time average filter method has been used to deal with the white noise and random disturbance of the collected signals [27–29]. By using the average filter method to update the sampling values, the collected signals are filtered and the filtered output becomes smooth. So the battery can provide the constant or optimal power/current according to the filtered output. For the boost converter based battery/SC HESS in EVs, the power demands from the motor inverters also need to be filtered. The real-time average filter method will be very beneficial to make the SC act as a low-pass filter such that the battery safety can be well guaranteed [4,7].

In this paper, an estimator-based ASMC strategy is proposed for the boost converter based battery/SC HESS. The primary average control factor (i.e., the duty-ratio) is designed according to the SMC strategy. The estimated state observers of the proposed ASMC are designed by considering the unknown external input voltage and load variations. The final average control factor is designed based on the state estimator, the Lyapunov function and the primary average control factor. The originality of the proposed ASMC strategy is that the adaptation laws are designed by the estimated error rather than the real-time test error, thereby achieving the valid estimate of the unknown disturbances and load variations in practical applications. In addition, the smooth SMC can be assured by the hysteresis control and the average filter method. So the system stability of the boost converter based battery/SC HESS can be effectively ensured no matter the load uncertainties and parameter variations exist or not. This paper is organized as follows. In Section 2, the equivalent circuit and the equivalent state-space average model of the boost converter based battery/SC HESS are established. Section 3 presents the design of the estimator-based ASMC strategy and its implementation method. Simulation results are discussed in Section 4. Experimental results and evaluation of the estimator-based ASMC strategy for the boost converter based battery/SC HESS are presented in Section 5. Finally, conclusions are given in Section 6.

2. Model of the boost converter based battery/SC HESS

For the boost converter based battery/SC HESS, the SC and the load are directly paralleled. Since the SC can directly provide peak power to the motor inverter or the load, the battery pack can be isolated from high frequency power and provide a constant power to the load. In addition, the boost converter can be designed with a smaller power level [2]. It should be noticed that the SC voltage can be changed within a wide range. When the boost converter based battery/SC HESS is directly paralleled with the motor inverter, the motor inverter should have a wide operating voltage range. Otherwise, a voltage stabilizing circuit (VSC) should be added to maintain a high and stable voltage for the motor inverter. Although it can increase the energy loss in the VSC, the stable high-voltage of the VSC can effectively improve the overall efficiency of the electric drive system and make up the energy loss in the VSC [31].

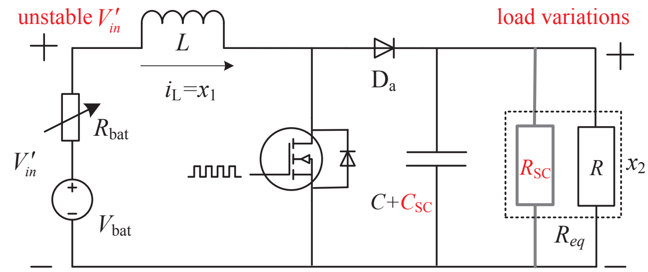

Fig. 1. Equivalent circuit of the boost converter based battery/SC HESS.

The equivalent circuit of the boost converter based battery/SC HESS is shown in Fig. 1. By considering the electric resistance and capacitance characteristics of the SC, the SC could be equivalent to a variable load impedance ($R_{SC}//C_{SC}$) [8,30]. On the other hand, the filter capacitor in the output side of the boost can be expressed as C, while the load can be expressed as R. The equivalent state-space average model of the boost converter based battery/SC HESS can be written as

$$\dot{x}_1 = -\frac{(1-d)}{L}x_2 + \frac{V'_{in}}{L} \tag{1}$$

$$\dot{x}_2 = \frac{(1-d)}{(C+C_{SC})}x_1 - \frac{1}{R_{eq}(C+C_{SC})}x_2 \tag{2}$$

where x_1 represents the average inductor current (i_L); x_2 represents the output voltage (V_0) of the boost converter; d is the average control factor (i.e., the duty-ratio); V'_{in} is the input voltage of the boost converter; L, C are the nominal values of the input inductor and the output capacitor, respectively; R_{eq} is the equivalent load paralleled with the output side of the boost converter.

$$R_{eq} = RR_{SC}/(R+R_{SC}) \tag{3}$$

From Fig. 1, it can be known that the external input voltage (V'_{in}) of the boost converter is unstable since it is related to the open circuit voltage (V_{bat}), internal resistance (R_{bat}) and the output current (i_{bat}) of the battery. In this paper, different discharge experiments are implemented for testing the internal resistance of the battery pack, as shown in Fig. 2.

$$V'_{in} = V_{bat} - R_{bat}i_{bat} \tag{4}$$

In addition, the unmodeled load variations exist since the equivalent resistance ($R_{eq} = RR_{SC}/(R+R_{SC})$) is related to the SC voltage and the power demands from the motor inverter. Different from the single reference current/voltage control strategy of the boost converter, the control strategy of the boost converter based battery/SC HESS should deal with the unknown external input voltage and the unmodeled load variations. What's more, the reference current of the boost converter based battery/SC HESS might be changed according to the SC voltage or the power demand from the motor inverter. Therefore, to achieve the robust current tracking control, the estimator-based ASMC strategy will be designed for the boost converter based battery/SC HESS by considering the unknown disturbances and the unmodeled load variations in the next section.