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Adaptive mode switch strategy based on simulated annealing optimization of a multi-mode hybrid energy storage system for electric vehicles

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HIGHLIGHTS

- An AMSS based on SA optimization is integrated with the rule-based strategy.
- The proposed AMSS focusing on selecting the most suitable operating mode.
- The optimization of the reference SC SOC and battery power is realized with the SA algorithm.
- The proposed strategy can achieve the global energy management optimization.

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ABSTRACT

This paper proposes an adaptive mode switch strategy (AMSS) based on simulated annealing (SA) optimization of a multi-mode hybrid energy storage system (HESS) for electric vehicles. The proposed SA-AMSS is derived from a rule-based strategy to achieve the adaptive mode selection and energy management optimization. To improve the overall system efficiency of the multi-mode HESS, the state of charge (SOC) level of the supercapacitor (SC), the power level and the component efficiencies are discussed. On this basis, the objective function for the AMSS is established, focusing on selecting the most suitable mode. Furthermore, to accomplish a global energy management optimization based on the driving cycles, the SA approach is introduced into the optimizations of the reference SC SOC and battery power, rather than the direct power distribution optimization between the battery and SC. The AMSS is implemented based on the SA optimization. Simulations and experiments are presented to verify the effectiveness of the SA-AMSS for the multi-mode HESS. Results show that the SA-AMSS can not only reduce the frequency of the mode switching, but also avoid the sudden excessive power output of the battery. The SC can respond to all peak power demands and absorb all the braking energy. So the SA-AMSS is very flexible and effective, and the battery safety can be guaranteed. Compared with the rule-based strategy, the overall system efficiency of the multi-mode HESS is significantly improved.

1. Introduction

Nowadays, electric vehicles (EVs) have been considered as one of the most potential ecological transportation tools due to their high efficiency and low emission [1–5]. However, the energy storage systems (ESSs) in the EVs need both high power density and energy density, leading to oversizing of the ESSs [3,4,6]. Moreover, the batteries in the EVs often suffer inconstant current surges due to start-stop, acceleration, deceleration, etc. As a result, unexpected battery degradation could not be avoided [7–9]. For the high power density characteristics, Supercapacitor (SC) can be used as an auxiliary equipment to prevent batteries from being subjected to peak power or current surges [10–13]. In this case, hybrid energy storage system (HESS), which includes the batteries and SC, has been widely used to extend battery lifetime [14–17]. The HESS has complementary advantages of the battery and SC, guaranteeing high power density and energy density simultaneously.

To achieve a coordinated usage between the battery and SC, different topologies and control strategies have been studied [11,18–20]. In previous studies, the literatures [6,20,21] have

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classified the conventional topologies for the HESS, including passive-parallel, multiple converter or cascade, Battery/SC and SC/Battery topologies. Some improved variants based on the Battery/SC or SC/Battery topologies have been also proposed to improve the operating efficiency or the system stability of the HESSs, e.g., improved semi-active, multi-mode (or compound-type), series–parallel connection topologies [13,14,19]. The most suitable topology for EV applications should be an open discussion. However, those HESSs with more operating modes might be more flexible to become more efficient [13,22]. For example, the improved semi-active HESS directly connects the SC to the load such that the SC can be utilized as a low-pass filter [7,11]. So the advantage of the Battery/SC topology could be inherited. In addition, the battery could directly provide the power to the load with a passive mode selection, such that it could have a slight advantage of the SC/Battery topology. To make the best coordination between the battery and the SC in the improved semi-active HESS, the unique advantages of both the Battery/SC and the SC/Battery topologies should be inherited.

The multi-mode HESS has been proposed to achieve the unique advantages of both the Battery/SC and the SC/Battery topologies [13,14]. For the multi-mode HESS, the energy management involves the mode selection and power distribution [13]. The major challenge of the energy management is that it needs a more efficient but practical way to select the most suitable mode and to achieve the power distribution optimization at the same time. The rule-based strategies were usually used to accomplish the energy management for the HESSs [13,14,16]. However, the reference SC voltage needs to be defined in the rule-based strategy to accomplish the mode selection [14,23–25]. The overall system efficiency of the multi-mode HESS might be influenced by the preset reference SC voltage. As a result, the optimization is difficult to be obtained with the rule-based strategy. The optimization of the reference SC voltage should be considered carefully in the real-time energy management for the HESS [26,27].

Many optimization approaches have been adopted for improving the performance of the HESSs [24,25,28]. Besides improving the overall system efficiency, the optimization has been focused on extending the battery lifetime [22,29]. As a branch of intelligent control, fuzzy control strategy has been widely used for the power distribution optimization in different HESSs [29,30]. Other intelligent control approaches such as model predictive control [31–33], neural networks [34,35], particle swarm optimization (PSO) [36] have been also used in the Battery/SC HESS, the SC/Battery HESS and the hybrid renewable energy systems, respectively. Favorable control performances could be obtained with these approaches. However, the multi-mode HESS has more operating modes and switching schemes. Although it could improve the flexibility of the mode selection, the energy management optimization of the multi-mode HESS might be complex. Especially, the jumping parameters might appear during the mode switching, such that a single fuzzy control system is not completely suitable to the multi-mode HESS. The computation is complex for the neural networks and PSO approaches. Besides, the model predictive control strategy needs to establish accurate models for different operating modes of the multi-mode HESS.

The adaptive control has a special advantage to achieve an energy management optimization for the multi-mode HESS, which can adaptively adjust control models according to the jumping parameters during the mode switching [37]. The adaptive optimization has been successfully used in the hybrid EV and the HESS based tramway [29,38]. It can be also introduced into the adaptive mode switch strategy (AMSS) of the multi-mode HESS. In addition, other intelligent control methods could be integrated with the rule-based strategy to further improve the system performance for the HESS. In literatures [25,26], a simulated annealing (SA) optimization approach is developed for the power distribution between the battery and SC. The SA as a stochastic search approach has been initially proposed to deal with the combination optimization problems. It could find a new optimal or sub-optimal result with random and comparative ways [16]. Better yet, the computational efficiency of the SA is fast and the power distribution based on the SA is easy to be implemented [25]. The HESS with the SA also presented a perfect real-time performance when responding to the peak-power demands [26].

In this paper, the AMSS is developed for selecting the most suitable mode. Different from the literatures [25,26], the SA approach is introduced into the optimizations of the reference SC SOC and battery power, rather than the direct optimization of the power distribution between the battery and SC. Based on the optimizations of the two key factors, the SA-AMSS is integrated with the rule-based strategy so that the global energy management optimization of the multi-mode HESS can be well realized. This paper is organized as follows. Section 2 introduces the specific topology of the multi-mode HESS and its operating modes. The rule-based strategy is designed in Section 3. The SA-AMSS is developed in Section 4. Simulation and experimental results are discussed in Section 5. Finally, conclusions are given in Section 6.

2. Multi-mode HESS and its operating modes

The multi-mode HESS is shown in Fig. 1. Compared to the Battery/SC and SC/Battery HESS, the multi-mode HESS adds only one switch and one power diode. The main originality of the multi-mode HESS is that the operating modes can be actively switched [13]. In addition, the battery is isolated from being directly charged. By using the averaging concept [11], a much small size DC–DC (buck–boost) converter is installed between the battery and the SC. So the multi-mode HESS can reduce the energy losses in the DC–DC converter.

By controlling the buck/boost mode of the DC–DC converter and the ON/OFF state of the switch S, the multi-mode HESS can realize six operating modes. Fig. 2 shows these operating modes. When the switch S is ON, the pure SC mode or the Battery/SC mode can be implemented. When the switch S is OFF, the pure battery mode or the SC/Battery mode can be implemented. When the multi-mode HESS meets negative power demands, the switch S is also OFF, the pure SC recycle mode or the hybrid recycle mode can be implemented.

To select the most suitable mode according to the EV's driving modes and obtain a high operating efficiency of the EMS, the rule-based strategy will be introduced. On this basis, the SA-AMSS will be integrated with the rule-based strategy to achieve the global energy management optimization.

3. Rule-based strategy of the multi-mode HESS

The different driving modes of the EV are in accordance with different power demands. Besides the power demands, the battery SOC [39,40], the SC voltage and the operating modes should be considered to design the rule-based strategy. In this study, the SC

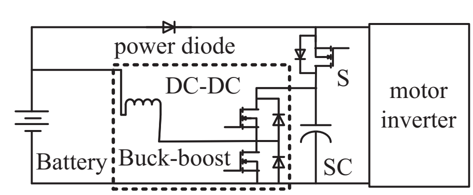

Fig. 1. The multi-mode HESS.