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A novel multimode hybrid energy storage system and its energy management strategy for electric vehicles

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HIGHLIGHTS

- A novel topology of multimode HESS is proposed for EVs.
- The rule-based control strategy and the power-balancing strategy are developed for the mode selection and the power distribution.
- The energy management strategy is proposed to reduce energy losses in the DC–DC converter.
- The proposed multimode HESS could extend the batteries life and improve the operation efficiency of the HESS.

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ABSTRACT

This paper proposes a novel topology of multimode hybrid energy storage system (HESS) and its energy management strategy for electric vehicles (EVs). Compared to the conventional HESS, the proposed multimode HESS has more operating modes and thus it could in further enhance the efficiency of the system. The rule-based control strategy and the power-balancing strategy are developed for the energy management strategy to realize mode selection and power distribution. Generally, the DC–DC converter will operate at peak efficiency to convey the energy from the batteries to the UCs. Otherwise, the pure battery mode or the pure ultracapacitors (UCs) mode will be utilized without the DC–DC converter. To extend the battery life, the UCs have the highest priority to recycle the energy and the batteries are isolated from being recharged directly during regenerative braking. Simulations and experiments are established to validate the proposed multimode HESS and its energy management strategy. The results reveal that the energy losses in the DC–DC converter, the total energy consumption and the overall system efficiency of the proposed multimode HESS are improved compared to the conventional HESS.

1. Introduction

To meet the power demands of an electric vehicle (EV), the design of an energy storage system (ESS) with high power and high energy density is of greatest importance [1,2]. There are some power batteries today with high specific power density [3,4], but volume or size problems could not be ignored. Moreover, a massive source of heat will be created when the batteries meet peak power demands, leading to a short battery life [5,6]. Even worse, a single-battery ESS also causes an increase in cost compared to a multi-power sources [1,5]. To solve the problems listed above, ultracapacitors (UCs) can be utilized in the ESS to meet the high power demand [5,7–9]. Furthermore, the UCs can be recharged or discharged more efficiently and quickly, which can reduce energy losses and recycle braking energy quickly, thus prolong the battery life [2,7]. In this regard, the hybrid energy storage systems (HESSs) of EVs, which include batteries and UCs, have been widely studied in recent years [7,8,10–12].

To achieve low cost of power conversion, the conventional HESS design usually uses a bidirectional DC–DC converter. The HESSs with single DC–DC converter can be divided into UC/battery configuration [1,7], battery/UC configuration [1,13], and the improved configuration based on both UC/battery and battery/UC HESS [5]. However, the UC/battery and the battery/UC HESS fail to achieve the goal that both the batteries and the UCs can provide power directly to the motor inverter without DC–DC converter, which might result in energy losses in DC–DC converter. Although the improved configuration [5] achieves that both the batteries and

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the UCs can provide power directly, the UCs voltage must drop below the battery voltage when only the batteries provide power directly. So the improved configuration is a passive configuration and may fail to achieve the highest efficiency of the HESS. To solve problems discussed above, a novel topology of multimode HESS is proposed in this paper. An N-mosfet is connected to the UCs and a P-mosfet is connected to the batteries. The two energy sources are directly connected to the two ends of the bidirectional DC–DC converter respectively. A power diode is used to avoid the batteries being recharged directly. Thus the UCs can provide peak power directly to the motor inverter and the goal to isolate the batteries from providing peak power is achieved. Besides, the batteries are able to provide the power directly to the motor inverter to reduce energy losses of the DC–DC converter.

To achieve the high efficiency of the whole system, the configuration and topology of HESS is not enough. Energy management and control is also crucial to the HESS [2,11,14–16]. Many control methods have been used for HESS energy management [17–20]. However, if different operating modes are considered, the HESS may work better. Multimode transmission technology has been successfully used in most hybrid electric vehicles (HEVs) and EVs, [21–23], but few has been reported in HESS. This paper introduce multimode technology to improve the efficiency of the whole system.

In the proposed multimode HESS, the pure battery mode would be selected to meet low power demands while the hybrid output mode would be selected to meet peak power demands. Since the HESS has pure battery mode, pure UCs mode, hybrid output mode and recycle mode, etc. Thus, different modes of energy flows need to be analyzed and properly chosen. Otherwise, the batteries may suffer from frequent charge and discharge operations, leading to short battery life [7,24]. In addition, improper mode selection may cause a voltage fluctuation. As a result, the energy losses of the HESS could be increased, and even the efficiency of the motor inverter could be reduced [25]. In this case, the switch rules of mode selection should be reasonable to ensure the high efficiency of energy management strategy. Based on the discussion above, the mode switching strategy will be developed and analyzed.

In this paper, a novel topology of multimode HESS is proposed and its energy management strategy is developed. Section 2 presents the configuration of the proposed multimode HESS and its operating modes. Section 3 is the energy management strategy of the proposed HESS. Section 4 focuses on the simulation and its results. Section 5 is the experimental verification. The main conclusion is given in Section 6.

2. Proposed multimode HESS configuration and its operating modes

Batteries have a relatively high energy density [26] and UCs have a significantly higher power density [27]. To prolong the battery life, the UCs are suggested to be connected to the dc link directly so that the batteries could be isolated from providing peak power and being recharged directly [8]. The bidirectional DC–DC converter in the HESS has buck mode and boost mode, and the conversion efficiency in different modes is always considered as the most important factor. However, since the energy loss cannot be avoided in both buck mode and boost mode, to improve the efficiency of the whole system, the UCs and the batteries should provide the power directly without DC–DC converter if possible.

Based on the aforementioned discussion, this paper proposes a novel multimode HESS configuration. The proposed circuit structure is illustrated in Fig. 1. The main feature of the proposed multimode HESS is that the N-mosfet (SW1) is connected to the UCs and the P-mosfet (SW2) is connected to the batteries. In addition, the two energy sources are directly connected to each the two ends of the bidirectional DC–DC converter respectively. A power diode is used to avoid the batteries being recharged directly. What's more, the SW1 and the SW2 are controlled by the same electrical signal. In this configuration, the UCs can provide peak power directly to the motor inverter when the SW1 is ON (the SW2 is OFF). The batteries provide energy through the DC–DC converter only when the SW1 is ON. Thus the goal to isolate the batteries from providing peak power is achieved. When power demands of the motor inverter are not so very high (referred to as “low power demands” in this paper), the SW2 is ON (the SW1 is OFF), and the batteries provide the power directly to the motor inverter to reduce energy losses of the DC–DC converter.

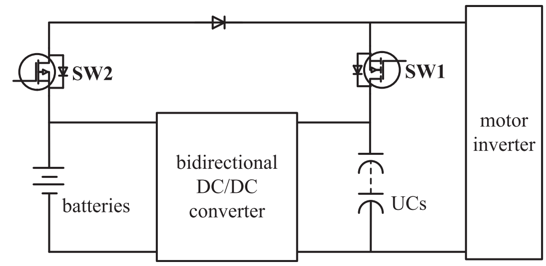

Fig. 1. Circuit structure of the proposed multimode HESS.

The UCs voltage and battery voltage are important factors for the design of HESS. In this paper, the proposed multimode HESS is designed for a SD-EV which is a pure EV developed in our laboratory. The nominal voltage of the batteries is 288 V; the effective operating voltage range of the batteries is from 252 V to 324 V. On the other hand, the effective operating voltage range of the motor inverter is from 190 V to 380 V. Considering the configuration of UCs module, the maximum voltage of the UCs is designed as 375 V. To ensure enough energy from the UCs, the minimum voltage of the UCs is designed as 190 V. The energy stored in UCs is a function of its voltage as shown in (1). It is noted that the actual energy available of the UCs is less than 25% when its voltage is less than 50%. So the lower limit of the UCs voltage is designed as 50% of the maximum voltage.

$$E_{cap} = \frac{1}{2}CV_{UC}^2 \quad (1)$$

To improve the efficiency of the HESS, the DC–DC converter should be properly designed. Since the DC–DC converter could boost or buck the battery voltage, the configuration of the DC–DC converter is designed as Fig. 2. In this configuration, the DC–DC converter could also buck the UCs voltage to recharge the batteries, which ensures the safety of the batteries during regenerative braking.

Based on the design above, four operation schemes are proposed as follows: (a) the batteries boost scheme, (b) the batteries buck scheme, (c) the UCs buck scheme, (d) the regenerative braking scheme, as shown in Fig. 3. To avoid damages to batteries, the UCs

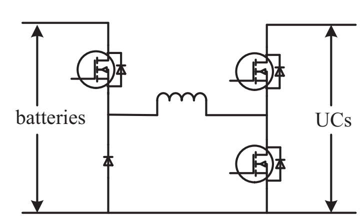

Fig. 2. Configuration of the DC–DC converter.