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A Review of Hybrid Energy Storage System for Heavy-Duty Electric Vehicle

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Abstract

The driving range of electric vehicles is one of the major concerns to be addressed today. The cruising range of electric vehicles mainly depends on the energy storage system (ESS). The current energy storage system for small electric vehicles is mainly batteries. But for heavy-duty electric vehicles as well as high-performance electric sports cars, a hybrid energy storage system (HESS) has offered a better solution. A hybrid energy storage system usually consists of two complementary storage devices which are coordinated through an energy management system; these devices could be batteries, supercapacitors, fuel cells flywheels and others where each has different advantages and disadvantages and is suitable for different application scenarios. This paper reviews major energy storage system combinations and presents different energy storage system topologies. At the same time, different control methods of the hybrid energy storage system are reviewed in this paper, although some of which are based on the storage system available at the grid side.

Keywords: Hybrid Energy Storage System ; Heavy-Duty Electric Vehicle; Powertrain; Power electronic control

1. Introduction

Electric cars have demonstrated their effectiveness in addressing present energy and environmental concerns. Heavy-duty electric vehicles and high-performance electric sports cars require larger and different kinds of energy storage systems to provide more energy than ordinary household based small to medium electric vehicles. Hybrid energy storage system (HESS) has offered one solution for powering heavy-duty vehicles.

So far, the most prevalent arrangement employed in e-buses and trucks adopts this concept, which involves a solitary motor producing the necessary torque. The torque is subsequently transformed via a fixed-ratio gearbox and

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a differential, as illustrated in Figure 1 (Arora, et al., 2021). To ensure optimal performance, the rated speed of the chosen motor must align with the highest attainable vehicle speed based on the final reduction gears. The solid lines depict HV lines, while the dashed lines indicate the communication area network (CAN) bus layout.

Hybrid configurations typically employ a "main energy system" (MES) with high energy storage capacity, and an "auxiliary energy system" (AES) with high power capability and reversibility. The MES allows for a longer driving distance, whereas the AES enables quick acceleration and regenerative braking. The MES includes battery, fuel cell, biofuel, etc. The AES includes supercapacitor, flying wheels, etc. By combining the MES and AES, hybrids can achieve extended range, strong power, excellent regenerative braking, and improved efficiency (Etxeberria, et al., 2010).

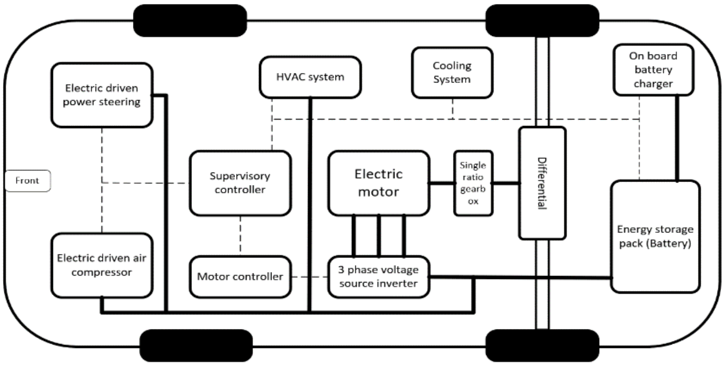

Figure 1: Schematic of Powertrain of Heavy-Duty Electric Vehicle

2. Power Sources for Heavy-Duty Electric Vehicles

Battery + Super Capacitor: The HESS that sees the most frequent usage in hybrid electric vehicles applications consists of a combination of a battery and a supercapacitor (SC) bank (Etxeberria, et al., 2010). The combination of battery pack and super capacitor seems to be a better solution for hybrid energy storage system compared to the systems with Li-ion battery only. The power density and energy storage capacity for the former is higher than the latter. Moreover, the volume and quality of such combinations will be relatively small (Zandi, et al., 2011). Batteries and supercapacitors complement each other where the former provides extra power for longer time while in terms of the number of charge and discharge cycles, supercapacitors exhibit a longer lifespan (Marshall & Kazerani, 2005) (Burke, 2007). The combination of batteries and supercapacitors can deliver outstanding performance and fuel efficiency (Schupbach, et al., 2003) (Schupbach & Balda, 2003) (Gao, 2005) (Pede, et al., 2004) (Baisden & Emadi, 2004).

Fuel Cell + Super Capacitor: Fuel cell-ultracapacitor vehicles are not a currently recommended combination. The powertrain price will be higher, the fuel economy will be lower, and the energy density of supercapacitors are lower compared to commonly used Li-ion batteries (Kazerani, 2008) while the total vehicle mass will be large.

Fuel Cell + Battery: Both fuel cell-battery and fuel cell-battery-supercapacitor are proposed hybrid energy storage system solutions. Of the two, fuel cell-battery vehicles cost less, but have lower fuel economy. Moreover, in a fuel cell-battery vehicle, the stress on the battery is higher, resulting in a lower battery life (Kazerani, 2008).

Battery + Superconducting magnetic energy storage (SMES): Energy storage based on superconducting magnetism has a few distinctive characteristics such as high power density, almost infinite charge and discharge cycles, and high peak current handling capability (Kita, 2005) (Li, et al., 2015). Superconducting magnetic energy storage can be used in railway systems to compensate fluctuating loads (Kita, 2005). Superconducting magnetic energy storage can also be used in wind energy applications.

The high cost of superconducting materials is the main reason that hinders the use of SMES (Li, et al., 2016). The main disadvantage of superconducting magnetic energy storage is the need for cooling below the critical temperature of the superconducting material used. When the electric vehicle is running, a closed-loop cooling system needs to be used. But when the electric car is stopped, the system does not work. It can only be obtained by the evaporation of cryogenic liquids, and the operational temperature of the SMES superconducting material should be compatible with the cooling temperature offered by the cryogenic fuel (Trevisani, et al., 2009). It is possible to increase the battery lifespan in the SMES-battery hybrid system in a measurable manner (Li, et al., 2015).

Battery + Flywheels: Flywheels have a unique characteristic of being able to undergo a vast number of charge/discharge cycles, sometimes exceeding hundreds of thousands, regardless of the depth of discharge (DOD). As a result, their lifespan can extend to 20 years or more, surpassing that of other energy storage devices. Additionally, monitoring the state of charge in flywheels is a straightforward and dependable process since it only requires the measurement of rotational speed (Hebner, et al., 2002). FES systems have several advantages. Firstly, they have long lifetimes and can last for decades with minimal maintenance. Secondly, FES systems have high specific energy, typically ranging from 100 to 130 W·h/kg or 360-500 kJ/kg and can produce a large maximum power output. Thirdly, the energy efficiency of flywheels, also known as round-trip efficiency, can be as high as 90% (Vere, 2008) (Täubner, 2010)

3. Powertrains of Hybrid Energy Storage System

3.1 Power Electronic Topology

Although there are different power sources, the topologies of hybrid energy storage systems include passive, semi-active, and active hybrid. The following introduction includes not only the energy storage system in EV but also the storage system connected to power grid. They share a lot of similarities.

3.1.1. Passive Hybrid

Passive hybrid systems are by far the most common, with a battery bank and a supercapacitor bank connected in parallel with each other and with the load. The advantage is that there is no power electronics and control circuit, which reduces the cost and weight. The disadvantage is that the load current is hardly controlled and is determined only by the internal resistance (Kuperman & Aharon, 2011) (Kouchachvili, et al., 2018). In (Smith, et al., 2002) (Dougal, et al., 2002), the energy storage system (ESS) is configured by directly connecting two storage devices - a battery and a supercapacitor (SC) bank - in parallel, using a passive setup. This simple arrangement falls short in terms of fully harnessing the storage system's control capabilities. The current flowing through the system is divided between the two devices based on their internal resistances, resulting in an unregulated power flow. In addition, the battery's fixed voltage limits the effective utilization of the SC, whose voltage is constrained by the battery. The battery's voltage also imposes a restriction on the selection of SC array sizes, since they must match the battery's voltage.

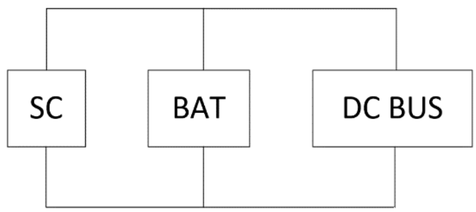

Figure 2: HESS Passive configuration

3.1.2. Semi-active hybrid

This type of hybrid energy storage systems is considered semi-active, as one of the system components, either load, battery, or supercapacitor, is connected with a DC-DC converter giving rise respectively to load-based (parallel), battery-based and supercapacitor-based semi-active hybrid systems. A parallel is shown in topology. The Power Conversion System (PCS) is typically used to connect short-term storage to the DC bus in most applications. An example of this topology can be found in (Li & Joos, 2008), although it is for power grid application where a battery is for long-term storage and a SC for short-term storage while smoothing the wind power fluctuation. The

DC bus voltage will fluctuate based on the SOC of the battery, which must be kept within a specific range so that the inverter operates properly. This topology eliminates the need for a separate PCS for the battery, which reduces power losses and becomes an attractive choice for ESSs. The system operation is, however, restricted because the bus voltage must fall within a specific range that is dependent on the battery's SOC.

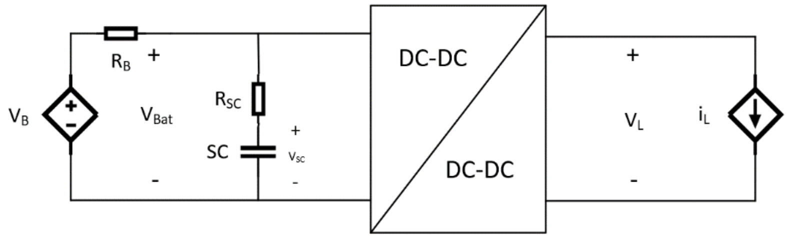

Figure 3: Parallel semi-active hybrid topology.

In (Ise, et al., 2005), a similar topology is presented with a different ESS. This HESS consists of a Battery and SMES device. The research shows that the utilization of a single Power Conversion System (PCS) as an interface for the SMES, together with an appropriate Energy Management System (EMS), can effectively maintain the State of Charge (SOC) of both storage devices within their specified ranges. However, like the work in [23] the DC bus voltage fluctuation based on the SOC of the Battery could also potentially lead to issues with the inverter's operation.

In (Etxeberria, et al., 2010), the authors suggest that in order to optimize the system, a PCS is required to directly manage the power flow of at least one storage device in the ESS when it is in a parallel configuration. In (Palma, et al., 2003), it was demonstrated that utilizing a combination of batteries and supercapacitors can lead to a battery runtime extension of 4% to 12%. Furthermore, by integrating a DC-DC converter that links the supercapacitor bank to the battery, it is possible to attain a cost-efficient method for prolonging runtime with a reduced number of supercapacitors. The topology employed in almost all cases involves connecting the Supercapacitor (SC) to the DC bus via a PCS, while the battery is directly connected to the DC bus (Ozatay, et al., 2004) (Ortuzar, et al., 2007) (Awerbuch & Sullivan, 2008) (Camara, et al., 2006) (Camara, et al., 2009).

3.1.3. Active Hybrid

In an active hybrid energy storage system, all components have a DC-DC converter. Active hybrid energy storage systems include capacitor series active systems, battery series active systems, and parallel active systems. Among all these, the parallel active hybrid system is the best. A parallel active is shown in Figure 4:Parallel active hybrid topology. This topology combines the advantages of a semi-hybrid system of batteries and supercapacitors. Whether the energy is from the battery to the load or from the supercapacitor to the load, there is always one-stage power conversion in one DC-DC converter, so the conversion efficiency will not decrease.

The types of storage devices are mentioned in (Abbey, et al., 2009), (Li, et al., 2009) where a HESS consists of a battery and a supercapacitor bank. The two storage devices are under direct control to keep the DC bus voltage constant, enabling the battery to discharge more extensively and make full use of its energy capacity. In (Yoo, et al., 2008) (Thounthong', et al., 2009), the power control system manages both storage devices, thereby demonstrating the workability of this configuration for electric vehicle implementation.

In (Pay & Baghzouz, 2003) (Gao, et al., 2005) (Palma, et al., 2003), different simulations are built to compare the advantages and disadvantages of active and passive topologies. In (Pay & Baghzouz, 2003), based on the findings, the power converter decreases the battery's maximum current by 40%, and optimizes the utilization of supercapacitor characteristics. In (Gao, et al., 2005), the result shows that the active topology has a power density that is 3.2 times greater than the passive topology, resulting in a significant reduction in battery current and a more stable DC bus voltage. The PCS accounts for half of the power losses in the active HESS which mainly due to the switching of transistors so it is critical to choose the best switching strategy.

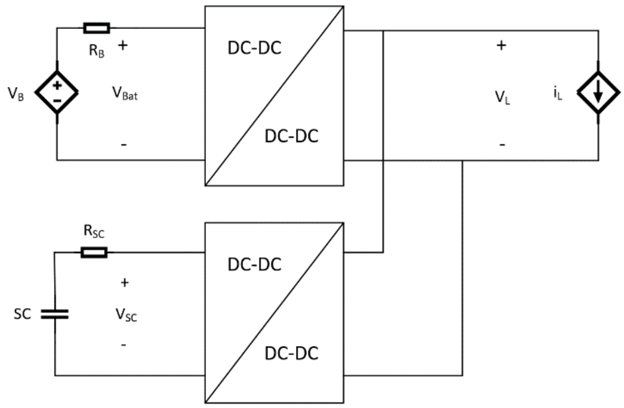

Figure 4:Parallel active hybrid topology

4. Control Method for Hybrid Energy Storage System

The main challenge in implementing hybrid energy storage units for vehicle electrification is to efficiently distribute energy demand among different power sources in real-time. To achieve this, energy management strategies must be developed with real-time implementable techniques and predictions based on a range of information systems (Mohammed, et al., 2023).

There are many control methods for hybrid energy storage systems. In general, it can be divided into two categories, namely conventional control and intelligent control. Some examples of controlling method are shown below.

4.1 Conventional Control

Conventional controls include filter based, droop control-based methods, rule-based control, bang-bang control etc. In (Allègre, et al., 2013),the control scheme of the system is derived from the inversion of its EMR. A “bang-bang” control strategy is used, which requires the use of supercapacitors as much as possible. The supercapacitor is employed solely if its state of charge surpasses a specific threshold. The battery is used only when the supercapacitor voltage reaches the limit.

A rule-based control approach is used in (Fakham, et al., 2011) (Teleke, et al., 2010) (Zhou & Francois, 2010) (Ongaro, et al., 2012). In (Su, et al., 2023), Su et al. proposed a decentralized power distribution strategy that adds a power buffer between multiple hybrid energy storage systems consisting of batteries and capacitors. Current-voltage droop control (I-V) is applied to decompose the power mismatch into high frequency and low frequency parts. The low frequency component is compensated by the battery, while the high frequency component is compensated for by the supercapacitor, as shown in Figure 5.

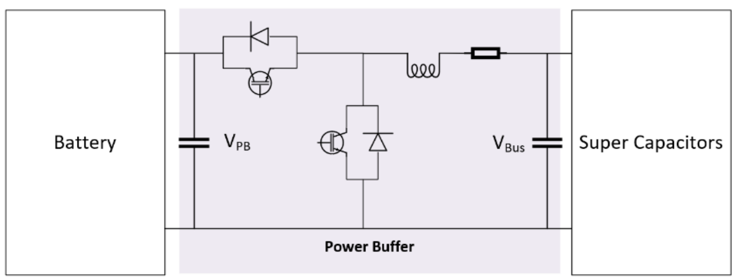

Figure 5:Multiple HESSs configuration with power buffers

4.2 Intelligent Control

Intelligent control includes neural network, fuzzy logic, model predictive control, etc. In (Hredzak, et al., 2015), an explicit model predictive control (EMPC) system for a hybrid battery-supercapacitor power supply is proposed. The main advantage of EMPC systems is that for low-order systems, their implementation is less computationally demanding than classical MPC systems. Compared to traditional (implicit) model predictive controllers, explicit MPC controllers demand a reduced number of computations during run-time.

The fuzzy logic control method suggested in (Ferreira, et al., 2008) has undergone experimental verification where none of the fuzzy-based approaches have been thoroughly evaluated as far as the restrictions of battery state of charge (SOC) and/or current are concerned. The work by (Erdinç, et al., 2009) (Hajizadeh & Golkar, 2009) (Melero-Perez, et al., 2009) and (Kisacikoglu, et al., 2007) presented various control methods, including fuzzy, wavelet-fuzzy, and fuzzy-neural, for managing a hybrid power source. In (Ortuzar, et al., 2007), the neural network is combined with the control system. The load current is used as the input of the neural network, and the output is the current of the required supercapacitor and power electronic system.

5. Conclusions

Single devices such as batteries, supercapacitors, and fuel cells cannot alone meet all the requirements of advanced electric vehicle drive systems. Most current commercial electric vehicles do not involve on-board hybrid energy storage systems. This paper has reviewed the types of hybrid energy storage systems used in heavy-duty electric vehicles, the power electronic structure, and different control methods.

Researchers in the field of heavy electric vehicles are currently focused on integrating various management strategies to improve power distribution and management efficiency among different power sources such as fuel cells, batteries, and supercapacitors, while minimizing computational efforts. The battery must still provide support to the supercapacitor to meet the power demand. A hybrid energy storage system that combines the characteristics of large capacity, fast charging and discharging, long life cycle and low cost will be a more viable solution for heavy-duty electric vehicles.

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