Hybrid Energy Storage System (HESS) in Vehicular Applications: A Review on Interfacing Battery and Ultra-capacitor Units

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***Abstract*—One of the key components of every Electric Vehicle (EV)/Hybrid Electric Vehicle (HEV) is the Energy Storage System (ESS). The most widely-used ESS in electric drivetrains is based on batteries. As the specific power of batteries is normally low, they are hybridized with high -specific power storage elements such as ultra-capacitors in a Hybrid Energy Storage System (HESS) to meet harsh power requirements of the vehicle during acceleration and regenerative braking. This paper provides a thorough literature review on various configurations for interfacing battery and ultra-capacitor units to the DC bus forming a HESS in EV/HEV applications. It also reviews the energy management mechanisms used to split the power demand between battery and ultra-capacitor units.**

***Keywords*—Hybrid Energy Storage System (HESS), Specific Energy, Specific Power, Battery, Ultra-capacitor, Power Electronics, DC Bus, EV/HEV, energy management.**

I. Introduction

Concerns about environmental pollution, rapid increase in fuel cost, and depletion of fossil fuel reserves have been the main motivations behind the efforts made by the automotive industry towards electrification of transportation. Along with research sectors in the industry, universities have been playing a considerable role in studying electric vehicles (EVs) and hybrid electric vehicles (HEVs) and coming up with new topologies and ideas. Although EVs and HEVs present many advantages, there are some difficulties associated with these types of transportation. The main issue is energy storage devices in the vehicle. Statistical analysis shows that consumers are reluctant to purchase EVs and HEVs unless the performance and reliability of these types of vehicles match or go beyond that of traditional combustion-engine-based vehicles at a competitive price [1].

II. Hybrid Energy Storage System (HESS)

One of the key components of every EV/HEV is the Energy Storage System (ESS). ESS is a source or a combination of two or more sources, which provide electric power to the drive train in an EV/HEV. Two of the most well-known types of ESS components are batteries and ultra-capacitors (also known as super-capacitors) [2], [3]. Battery is an electrochemical storage device which is mainly composed of two electrodes (Anode and Cathode), an electrolyte, and a conducting separator. To power the battery, anions are oxidized at the anode and cations receive the free electrons if the circuit is closed. Batteries are known as sources with very high specific energy. However, the specific power of a battery cell is normally low. If the ESS in an EV/HEV is only structured by the battery cells, in harsh conditions where the vehicle undergoes significant variations of power, the battery cells may not be able to supply the required power demand or absorb the power available from regenerative braking. Even if the power demand is supplied or the available regenerative braking power is absorbed, due to the huge fluctuations of charge/discharge current, the efficiency and consequently, the lifetime of the battery cells are compromised. The concept behind an ultra-capacitor is similar to the electrolytic capacitor in which charge separation creates an electric potential between the plates. However, due to special structure of the ultra-capacitors which have larger equivalent surface areas on the electrodes and thinner layers of dielectric,

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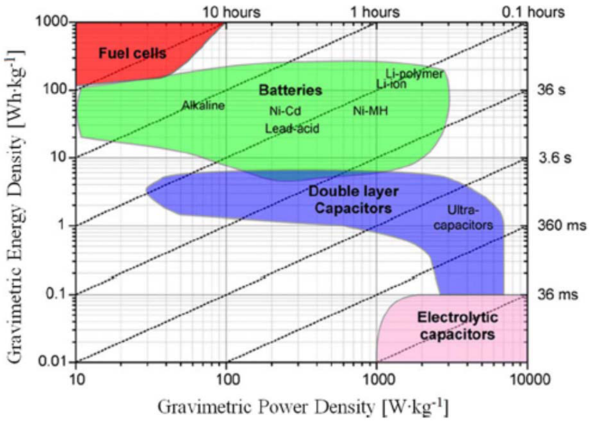

Fig. 1. Specific energy versus specific power for various ESSs [5]

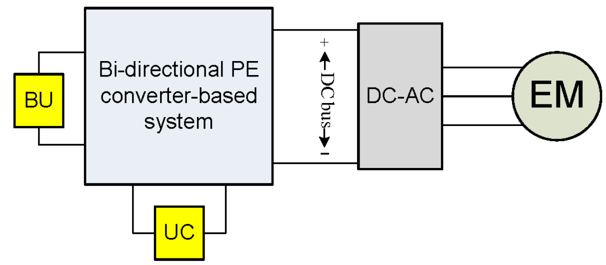

Fig. 2. Schematic diagram of a HESS structure built from BU and UC

their capacity is much bigger than that of conventional capacitors [2], [4]. Despite conventional batteries, ultra-capacitors have high specific power levels. This makes ultra-capacitors a very favorable choice for relieving the electrical systems having storage elements in conditions of harsh power fluctuations.

Ragone curve, shown in Fig. 1, demonstrates the specific energy of fuel cells, batteries, ultra-capacitors, and conventional capacitors, versus their corresponding specific power levels [5]. As depicted in this figure, batteries with high specific energy and low specific power are placed more towards top left of the figure while ultra-capacitors approach the opposite corner due to their high specific power and low specific energy. There have been ongoing efforts by ESS manufacturers to bridge the gap between different storage devices by developing products featuring both high specific energy and high specific power. Despite these efforts, the gap remains wide due to the difference in the nature of energy storage mechanisms. A viable, intermediate solution, before high specific-energy and high specific-power devices hit the market, would be combining the best of the two worlds and developing a Hybrid Energy Storage System (HESS) by combining two or more storage units and modules to realize the required energy and power characteristics, while working on development of innovative structural designs for ESS [6].

III. Interfacing Battery Unit (BU) and Ultra-Capacitor Unit (UC) to the DC Bus in a Drive Train

One of the main challenges in a HESS configuration is how to interface battery and ultra-capacitor units to the DC bus. This issue has been extensively addressed in the literature. Figure 2 shows a general schematic diagram for interfacing BU and UC to the DC bus. The bidirectional power electronic (PE) converter-based system represents either a single DC-DC converter or a combination of DC-DC converters. Different converters such as Buck-Boost, Cúk, SEPIC, Half-Bridge, and Full-Bridge may be utilized as the interface in a HESS for vehicular applications [2], [7]-[11]. Figure 3 depicts different topologies of HESS in more detail. Every topology has its own pros and cons. In the following subsections, these topologies are briefly studied.

A. Direct connection of BU and UC to the DC bus

Figure 3(a) shows the direct connection of BU and UC to the DC bus. This is the simplest way of connecting battery and ultra-capacitor units to the DC bus. The characteristics of this configuration are as follows [1], [2], [7], [12], [13]-[18]:

- The DC bus voltage experiences very small and slow variations as the bus is directly clamped to the

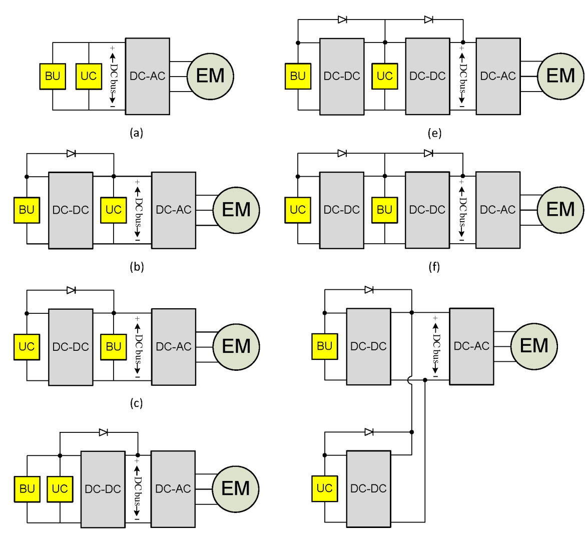

Fig. 3. Different configurations of interfacing BU and UC to the DC bus in a drive train: (a) Direct connection of BU and UC to the DC bus, (b) Partially-decoupled configuration, type I, (c) Partially-decoupled configurations, type II, (d) Fully-decoupled configuration of parallel-connected BU and UC, (e) Cascaded configuration, type I, (f) Cascaded configuration, type II, (g) Parallel converter configuration

terminals of the BU. This is a favourable feature for the input voltage of the DC-AC converter.
- The control system is significantly simple as the magnitude and direction of power components associated with the BU and UC are determined by their corresponding internal impedances and instantaneous value of the DC bus voltage.
- This configuration is considerably easy to build and very cost-effective.
- Since the BU is directly connected to the DC bus, it can be exposed to large and fast variations of discharge/charge currents during acceleration/regenerative braking. This extensively deteriorates the functionality of the battery, causes considerable losses, and reduces the battery life.
- As the terminal voltage of the UC is clamped to that of the battery, the terminal voltage of the UC cannot vary freely and therefore, functionality of the UC remains very limited, especially during acceleration and regenerative braking. This reduces the efficiency of the system.
- System optimization is not achievable as there is no power management mechanism to govern the power sharing between the BU and UC.

B. Partially-decoupled configurations

In partially-decoupled configurations, either BU or UC is decoupled from the DC bus using a DC-DC converter. Although the DC-DC converter adds to the cost of the system and complexity of the control, this type of HESS configuration offers several important features. Depending on whether BU or UC is connected directly to the DC bus, two topologies exist in this category. In topology I, shown in Fig. 3(b), the UC is connected directly to the DC bus. This configuration offers three major advantages compared to the configuration of Fig. 3(a). These advantages are [6], [12], [15], [17]-[19]:

- As the BU is decoupled from the DC bus, it is immune to highly-fluctuating charge/discharge currents.
- Through the use of DC-DC converter, power input to/output from the BU can be controlled.
- Sharp rises and falls of the power demand during acceleration and regenerative braking are picked up by the UC at the DC bus. This increases the efficiency of the system.

One of the drawbacks of this configuration is that the DC bus voltage may be exposed to large voltage fluctuations due to the direct connection of the UC across the DC bus. This can add considerably to the losses of the converter, especially in harsh driving condition where the UC may experience significant voltage variations over the drive cycle. However, proper control of the DC-DC converter when DC bus voltage regulation is required, can resolve this issue very effectively. In topology II of partially-decoupled configurations, shown in Fig. 3(c), the BU is directly connected to the DC bus while the UC is interfaced to the bus via the DC-DC converter. Some of bold features of this topology are [6], [8], [15], [18]-[20]:

- The DC bus does not undergo significant voltage fluctuations as it is clamped to the BU terminals.
- Using the DC-DC converter, the UC can operate over a wide voltage range which improves the functionality of UC.
- Being installed directly on the DC bus, the BU is exposed to high charge/discharge current fluctuations. This can result in reducing the life time of BU.
- The DC-DC converter is rated according to the power rating of UC which is supposed to take care of sharp and large power demand variations. This means the converter's power rating must be higher than that of topology I, leading to a higher cost.

C. Fully-decoupled configurations

In fully-decoupled configurations, BU and UC are completely decoupled from the DC bus using a power electronic system. Through implementing a power management algorithm, power demand is shared between the BU and the UC in such a way that the objectives of the system are fulfilled. This offers full control on the operation of BU and UC. Consequently, the performance of the system is improved and the life of BU will be longer. However, due to existence of a complex power electronic structure and its corresponding control circuitry, the system is normally more expensive than in the previous cases. Besides, the system losses may increase considerably due to the existence of a large number of semiconductor devices and passive elements.

Several topologies lie under the category of fully-decoupled configurations. The simplest one is shown in Fig. 3(d) where the parallel-connected BU and UC are decoupled from the DC bus by a DC-DC converter [1], [2], [7], [13], [14], [16]. Although this conguration allows some control over the output power of BU-UC combination compared to the one in Fig. 3(a), it still suffers from low level of functionality of the UC as it is clamped to the terminals of the BU. In addition, battery life may be shortened due to harsh driving conditions specifically when HESS is installed in an EV.

Cascaded topologies are shown in Figs. 3(e) and 3(f) where two cascaded converters decouple the BU and the UC from the DC bus [1], [2], [6], [7], [13], [14], [18]. A crucial drawback of the cascaded topologies is potential stability problems as they can represent a DC-DC converter with a constant power load, thus requiring significant amount of care [21], [22]. In the topology type I, shown in Fig. 3(e), the BU is connected to the lowest voltage terminals and the UC is installed at the intermediate voltage level. This is a favorable topology as balancing the battery cells at lower voltage levels is easier than that at higher voltage levels [23], [24]. In addition, the first DC-DC converter which interfaces the BU to the UC is rated at around the power rating of the BU. However, as the UC voltage is free to fluctuate, it can create more losses for the higher-rating converter which is between the UC and the DC bus [13]. Besides, with more fluctuating voltage conditions at the intermediate level, the problem of instability due to constant power load is more serious. To solve these problems, the positions of BU and UC can be exchanged as shown in Fig. 3(f). This way, the BU is connected to the intermediate voltage level and provides a more stable voltage at the terminals of the higher-rating converter. However, this topology has its own drawbacks as cell balancing of the BU at higher voltage levels is a difficult task. In addition, the latter topology requires a bigger DC-DC converter which adds to the cost of system. The other fully-decoupled configuration is the parallel-converter topology shown in Fig. 3(g). This is a favorable and commonly-used topology in this category [1], [2], [6], [7], [13], [15], [16], [25]. The stability problems associated with cascaded topology are taken care of to a great extent in this configuration. Besides, the converters are required to be rated separately for the BU and the UC, implying lower converter costs when compared with cascaded configurations.

IV. Energy Management Mechanisms in Vehicular Applications

The literature reports two types of control strategies for energy management among different sources in HEV applications: (i) rule-based approaches and (ii) optimization-based approaches [26]-[28].

A. Rule-based energy management approaches

Rule-based algorithms are very effective for real-time energy management in a hybrid drive train. The rules can be made based on intuition, expertise, and mathematical models. The output of the rule-based schemes determines the mode of operation for each of the storage devices. Rule-based approaches can be of deterministic or fuzzy type.

In deterministic rule-based methods, modes of operation are determined normally based on the power demand, SOC of the batteries, or velocity of the vehicle [29]. Reference [30] proposes a power management scheme for a HESS configuration composed of battery and ultra-capacitor cells installed in a waste-collection vehicle. The power management is simply based on the current limits defined for the battery during discharge conditions. Based on this scheme, if the current at the DC bus was less than the maximum discharge current of the battery unit, all the power demand would be supplied by the battery; otherwise, the battery would be discharged at its maximum current rate and the rest of power would be provided by the super-capacitors. In charging mode, all of regenerative power would be absorbed by the super-capacitors.

In [1], design of a battery - ultra-capacitor HESS for installing in a Chrysler Pacifia with a parallel drive train has been discussed. A rule-based procedure using simulation results has been used to determine the specifications of different components of the drive train. Power management between batteries and ultra-capacitors is based on the power demand and percentage of the maximum power deliverable by the cells. In [31], sizes of the battery and ultra-capacitor units in a HESS installed in an HEV have been determined using the set points of the upper and lower voltage limits defined for the ultra-capacitors and the peak power demand.

The other type of rule-based approach is based on fuzzy logic. In fuzzy-based techniques, two or more operating modes are used to control power management among different sources of the drive train in a fuzzy logic manner. Therefore, transition between one mode and another does not occur at a specific moment of time (deterministic rule-based method), but in a continuous manner. Reference [32] discusses implementation of a power management system used for controlling the sharing of power between battery and ultra-capacitor units in a HESS configuration. The authors divide the system into energy management shell, power management shell, and power electronic shell. In energy management shell, long-term (in seconds) variations such as SOC of the battery cells are monitored and using the conditions of the vehicle on the road in terms of speed and required torque, as well as fuzzy rules, the limits on the power of the battery cells are determined. In the power management shell, short-term decisions (in milliseconds) for splitting the load power between battery and ultra-capacitor units are made. Determination of the power reference for the battery unit was in such a way that the thresholds on the cell power capability and its rate of change are respected.

B. Optimization-based energy management approaches

In optimization-based strategies, well-known optimization techniques are used to optimize the system for a given drive cycle. The drive cycle can be a standard one, available in the public domain, or one generated by combining a number of standard drive cycles or a custom-made one. A rule (such as low-pass filtering) for splitting of the power demand among available sources can be fixed prior to optimization. Alternatively, the optimization algorithm can determine the power management rule during optimization process [33]. If a fixed power management rule is used for optimization over a certain drive cycle, the system is claimed to be optimum for the chosen power management law and the selected drive cycle. When the optimization algorithm determines the power management rule, the optimization process will be much more complex, requiring a significantly large search space and computation time.

The optimization problem can be solved using different algorithms such as Linear Programming (if the system is convex and can be represented by a set of linear functions), Dynamic Programming (both deterministic and stochastic), and Evolutionary methods such as Genetic Algorithm (GA), Simulated Annealing (SA), and Particle Swarm Optimization (PSO) [26], [28], [34].

Optimization-based approaches are divided into two general categories: (i) global optimization and (ii) real-time optimization. In the global optimization approach, the complete drive cycle is known in advance and optimization techniques are utilized to find the best energy management scenario. In [35] and [36], general supervisory controls have been used to take care of power managements in a hybrid system to minimize the fuel consumption while sustaining the SOC at a specified threshold. The optimization problem is solved at various instants during the drive cycle.

References [37] and [38] use a Quadratic Programming approach to implement an energy management algorithm for splitting the power between the battery unit and the ICE. The cost function includes flow rate of the fuel, emissions of the ICE, and the losses in the battery unit. Dynamic programming is also a powerful tool to tackle the problem of energy management for finding the global optimum point. Reference [39] used a stochastic Dynamic Programming technique to implement an energy management platform for sharing the power between the ICE and battery unit in an HEV. The stochastic approach models the stochastic behaviour of the drive cycles to have a more realistic optimization scenario.

Reference [40] uses optimal control theory to enhance fuel economy in a parallel HEV. The optimal control strategy determines the torque provision by ICE over a priori known drive cycle and the optimum gear ratio taking the dynamics of the battery cells into consideration. The constraints of the problem are the limits on the SOC and the torque and speed of the ICE.

In [33], Linear Programming is used to solve the optimization problem of minimizing fuel consumption in an HEV. It is assumed that the objective functions and constraints are convex over a priori known drive cycle and the convex optimization problem can be converted to a Linear Programming problem. The optimum point found using Linear Programming technique is the global optimum of the system. Several simplifications are considered for solving the problem, such as having a fixed DC bus voltage, a constant efficiency for the battery cells, and no dynamics on the storage elements, to reduce the level of complexity of the problem.

Fuzzy logic-based control strategies can be combined with optimization-based algorithms to solve the optimal power management problem in a HESS. Reference [41] uses fuzzy logic controllers to control outputs of battery and ultra-capacitor units in a lift truck. The fuzzy controllers are implemented based on the velocity of the truck, the terminal voltages and currents of the ultra-capacitor cells, and the load current on the DC bus without considering the dynamics of the battery cells during power management process. It is assumed that the battery unit is installed directly on the DC bus and the ultra-capacitor unit is interfaced to the DC bus via a DC-DC converter. To optimize the parameters of the fuzzy logic controllers, Genetic Algorithm (GA) is used. Reference [42] uses Genetic Algorithm (GA) to optimize power management in a Fuel Cell (FC) vehicle, with fuel cell stack as the main energy source and a battery unit as the auxiliary power source. The result of optimization determines the gear ratio of the transmission system, the output power of the FC, and SOC threshold of the battery cells.

Reference [43] presents a detailed analysis on sizing an HEV which has battery units as the electric energy storage system. Stochastic Dynamic Programming is used to determine the sizes of the battery unit and fuel economy of the ICE. The duration of the drive cycle is modeled by a normal (Gaussian) distribution function. The drive cycle is generated randomly using Markov chain to take stochastic variations of an unknown drive cycle into considerations. In [44], Sequential Quadratic Programming (SQP) is used for designing the powertrain components in a combat vehicle. Different scenarios in terms of vehicle weight and harshness of the mission are considered during design of components.

Reference [45] uses Genetic Algorithm (GA) to determine the ratings/sizes of powertrain components including the maximum powers of ICE and electric machine (EM) and the number of battery cells in an HEV. Charge sustaining strategy is used for keeping the SOC within predefined limits. Different objectives such as fuel economy and reduction of various types of emissions form a multi-objective optimization problem. A deterministic approach, in which the drive cycle is known ahead of time, is implemented for solving the optimization problem. Reference [46] addresses the problem of optimal sizing of a HESS in HEV applications using Genetic Algorithm (GA). The author uses a sigmoid function as a power management tool between the ICE, the battery unit, and the ultra-capacitor unit. The sigmoid function was formulated in such a way that the limits on the SOC of the battery and ultra-capacitor cells, power capability of the battery unit, and rate of power change defined for battery cells are taken into account. Depending on the number of occurrences of certain velocities and accelerations over the drive cycle, the optimization algorithm is run several times to find a suboptimal power management profile based on the chosen sigmoid function.

V. Conclusions

This paper makes a critical literature review of the topologies for interfacing components of a Hybrid Energy Storage System (HESS) composed of battery and ultra-capacitor units to the DC bus of an HEV/EV. Batteries have been the traditional building block of every electric drive train. However, low specific power of batteries necessitates using high specific-power storage elements such as ultra-capacitors with batteries. There are numerous ways of interfacing the battery and ultra-capacitor units to the DC bus in an electric drive train. Although the simplest and most cost-effective method is to directly connect both storage units to the DC bus, this scheme suffers from several drawbacks regarding the life time of the batteries and efficiency of the system. To overcome these problems, power electronic (PE) converter-based structures can be utilized to facilitate interfacing and implementation of efficient energy management algorithms. Qualitative analysis through literature review reveals that the partially-decoupled configuration with the ultra-capacitor unit directly-connected to the DC bus and battery unit connected via a bidirectional DC-DC converter is the most promising interfacing topology in EV/HEV applications.

A complete review of different energy management mechanisms in vehicular applications is included in the paper as well. Rule-based and optimization-based techniques are used in the design of energy management systems. Choice of a specific energy management mechanism depends on the available information on the driving pattern, expected performance of the vehicle, and complexity and cost of the management system.

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