Battery, Ultracapacitor, Fuel Cell, and Hybrid Energy Storage Systems for Electric, Hybrid Electric, Fuel Cell, and Plug-In Hybrid Electric Vehicles: State of the Art

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***Abstract*—The fuel economy and all-electric range (AER) of hybrid electric vehicles (HEVs) are highly dependent on the onboard energy-storage system (ESS) of the vehicle. Energy-storage devices charge during low power demands and discharge during high power demands, acting as catalysts to provide energy boost. Batteries are the primary energy-storage devices in ground vehicles. Increasing the AER of vehicles by 15% almost doubles the incremental cost of the ESS. This is due to the fact that the ESS of HEVs requires higher peak power while preserving high energy density. Ultracapacitors (UCs) are the options with higher power densities in comparison with batteries. A hybrid ESS composed of batteries, UCs, and/or fuel cells (FCs) could be a more appropriate option for advanced hybrid vehicular ESSs. This paper presents state-of-the-art energy-storage topologies for HEVs and plug-in HEVs (PHEVs). Battery, UC, and FC technologies are discussed and compared in this paper. In addition, various hybrid ESSs that combine two or more storage devices are addressed.**

***Index Terms*—Battery, energy storage, fuel cell (FC), hybrid electric vehicles (HEVs), plug-in HEVs (PHEVs), ultracapacitor (UC).**

I. Introduction

It IS ESTIMATED that current global petroleum resources could be used up within 50 years if they are consumed at present consumption rates. The U.S. Energy Information Administration stated that the United States consumed 18.7 million barrels of petroleum per day in the first half of 2009. Most petroleum is used by various ground vehicles. The global number of vehicles will increase from 700 million to 2.5 billion in the next 50 years [1]. Thus, methods of improving vehicular fuel economy have gained worldwide attention.

A hybrid power train utilizes an electric motor to supplement the output of an internal combustion engine (ICE) during acceleration and recovers the energy during braking [2]–[4]. In hybrid topologies, since the vehicle is no longer dependent on only one type of fuel, they have many benefits for the vehicle, from emission reduction to performance and efficiency improvements. The efficiency and all-electric range (AER) of hybrid electric vehicles (HEVs) depend on the capability of their energy-storage system (ESS), which not only is utilized to store large amounts of energy but also should be able to release it quickly according to load demands [5]. The important characteristics of vehicular ESSs include energy density, power density, lifetime, cost, and maintenance. Currently, batteries and ultracapacitors (UCs) are the most common options for vehicular ESSs. Batteries usually have high energy densities and store the majority of onboard electric energy. On the other hand, UCs have high power densities and present a long life cycle with high efficiency and a fast response for charging/discharging [8], [9]. A fuel cell (FC) is another clean energy source; however, the long time constant of the FC limits its performance on vehicles. At present, no single energy-storage device could meet all requirements of HEVs and electric vehicles (EVs). Hybrid energy sources complement drawbacks of each single device [6]–[8].

This paper reviews state-of-the-art ESSs for advanced hybrid vehicular applications. Section II presents the battery technologies for automotive applications. Section III addresses ultracapacitors (UCs) as another ESS for future hybrid vehicles. Applications of FCs in vehicular systems are presented in Section IV. In addition, topologies of hybridized ESS are addressed in Section V. Finally, Section VI presents the summary and conclusions.

II. Batteries for Hybrid Electric Vehicles, Electric Vehicles, and Plug-In Hybrid Electric Vehicles

Batteries have widely been adopted in ground vehicles due to their characteristics in terms of high energy density, compact size, and reliability [5].

A. Lead–Acid Batteries

The spongy lead works as the negative active material of the battery, lead oxide is the positive active material, and diluted sulfuric acid is the electrolyte. For discharging, both positive and negative materials are transformed into lead sulfate [10]. The lead–acid battery presents several advantages for HEV applications. They are available in production volumes today, yielding a comparatively low-cost power source. In addition,

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lead–acid battery technology is a mature technique due to its wide use over the past 50 years [11]. However, the lead–acid battery is not suitable for discharges over 20% of its rated capacity. When operated at a deep rate of state of charge (SOC), the battery would have a limited life cycle. The energy and power density of the battery is low due to the weight of lead collectors [12], [13]. Research efforts have found that energy density can be improved by using lighter noncorrosive collectors [14].

B. Nickel–Metal Hydride (NiMH) Batteries

The NiMH battery uses an alkaline solution as the electrolyte. The NiMH battery is composed of nickel hydroxide on the positive electrode, and the negative electrode consists of an engineered alloy of vanadium, titanium, nickel, and other metals. The energy density of the NiMH battery is twice that of the lead–acid battery. The components of NiMH are harmless to the environment; moreover, the batteries can be recycled [15]. The NiMH battery is safe to operate at high voltage and has distinct advantages, such as storing volumetric energy and power, long cycle life, wide operation temperature ranges, and a resistance to over charge and discharge [16].

On the other hand, if repeatedly discharged at high load currents, the life of NiMH is reduced to about 200–300 cycles. The best operation performance is achieved when discharged 20% to 50% of the rated capacity [17]. The memory effect in NiMH battery systems reduces the usable power for the HEV, which reduces the usable SOC of the battery to a value smaller than 100% [18].

C. Lithium-Ion Batteries

The lithium-ion battery has been proven to have excellent performance in portable electronics and medical devices [19]. The lithium-ion battery has high energy density, has good high-temperature performance, and is recyclable. The positive electrode is made of an oxidized cobalt material, and the negative electrode is made of a carbon material. The lithium salt in an organic solvent is used as the electrolyte. The promising aspects of the Li-ion batteries include low memory effect, high specific power of 300 W/kg, high specific energy of 100 Wh/kg, and long battery life of 1000 cycles [20]. These excellent characteristics give the lithium-ion battery a high possibility of replacing NiMH as next-generation batteries for vehicles.

NiMH batteries were priced at about $1500/kWh in 2007. Since the price of nickel is increasing, the potential cost reduction of NiMH batteries is not promising. Li-ion batteries have twice energy density of NiMH batteries, which are priced at $750 to $1000/kWh. Table I demonstrates the characteristics of commercially available lead-acid, NiMH, and Li-ion batteries for vehicles [3].

D. Nickel–Zinc (Ni–Zn) Batteries

Nickel–zinc batteries have high energy and power density, low-cost materials, and deep cycle capability and are environmentally friendly. The operation temperature of Ni–Zn batteries ranges from −10 °C to 50 °C, which means that they can be used under severe working circumstances. However, they suffer from poor life cycles due to the fast growth of dendrites, which prevents the development of Ni–Zn batteries in vehicular applications [21].

TABLE I
CHARACTERISTICS OF COMMERCIAL BATTERIES FOR HEV APPLICATIONS

	Capacity (Ah)	Voltage (V)	Resistance (mΩ)	W/kg 95%eff	Usable SoC
NiMH					
Panasonic	6.5	7.2	11.4	207	40%
Ovonic	12	12	10	195	30%
Saft	14	1.2	1.1	172	30%
Li-ion					
Saft	12	4	7.0	256	20%
Shin-kobe	4	4	3.4	745	18%
Lead-acid					
Panasonic	25	12	7.8	77	28%

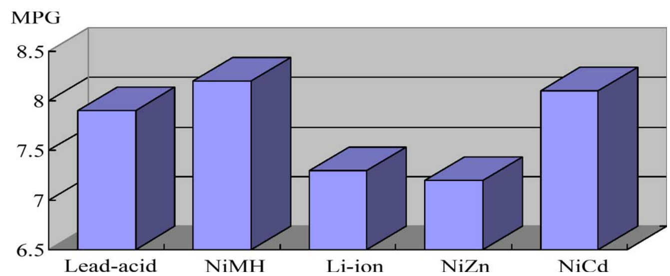

Fig. 1. Fuel economy (in miles per gallon) comparison on different batteries.

E. Nickel–Cadmium (Ni–Cd) Batteries

Nickel–cadmium batteries have a long lifetime and can be fully discharged without damage. The specific energy of Ni–Cd batteries is around 55 Wh/kg. These batteries can be recycled, but cadmium is a kind of heavy metal that could cause environmental pollution if not properly disposed of. Another drawback of Ni–Cd batteries is the cost. Usually, it will cost more than $20 000 to install these batteries in vehicles [22], [23].

Fig. 1 shows the comparison of fuel economy of different batteries for a diesel-fueled transit bus in Indian urban driving cycles [6]. As shown in Fig. 1, the NiMH battery has the best fuel efficiency. Currently, all available HEVs, such as the Toyota Prius, use NiMH as the ESS. Ni–Zn and Li-ion batteries show considerable potential but still need much work to make them suitable for HEV use.

III. ULTRACAPACITORS

The UC stores energy by physically separating positive and negative charges. The charges are stored on two parallel plates divided by an insulator. Since there are no chemical variations on the electrodes, therefore, UCs have a long cycle life but low energy density. Fig. 2 shows the structure of an individual UC cell [24]. The applied potential on the positive electrode attracts the negative ions in the electrolyte, whereas the potential on the negative electrode attracts positive ions.

The power density of the UC is considerably higher than that of the battery; this is due to the fact that the charges are physically stored on the electrodes. Low internal resistance gives UC high efficiency but can result in a large burst of output currents if the UC is charged at a very low SOC [25], [26].

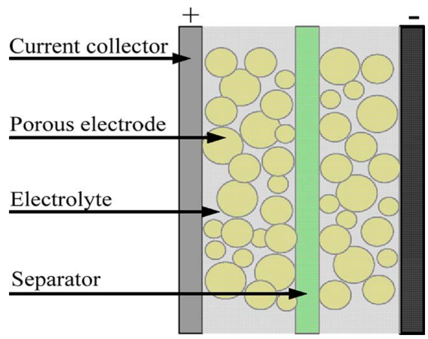

Fig. 2. Individual UC cell.

TABLE II
COMPARISON OF THE ZEBRA BATTERY AND UC PRODUCTS

	ZEBRA Batt Pack	Thunderpack II Ultracap Pack
Usable energy (kWh)	23.5	0.3
Max discharge current (A)	224	400
Specific energy (Wh/kg)	113	4
Specific power (W/kg)	174	1500
Life cycle (year)	2.5-5	10-12
System cost ($/kW)	400	100
Life cycle cost ($/kW)	1200	100

Another feature of the UC is that the terminal voltage is directly proportional to the SOC. The development of interface electronics allows the UC to operate throughout its variable voltage range. Researchers are investigating various methods to increase the surface area of the electrodes to further improve the energy-storage capability of UCs [27].

UCs can be used as assistant energy-storage devices for HEVs. In urban driving, there are many stop-and-go driving conditions, and the total power required is relatively low. UCs are very appropriate in capturing electricity from regenerative braking and quickly delivering power for acceleration due to their fast charge and discharge rates. Table II presents a comparison of battery and UC packs. In this table, the ZEBRA battery is a kind of high-energy battery made from common salt, ceramics, and nickel. The Thunderpack UC pack uses Maxwell's BOOSTCAP products [28]. Batteries have high energy density, whereas UCs have higher power densities. Long lifetime and low maintenance lead to cost savings. In HEV applications, both batteries and UCs could be combined to maximize the benefits of both components. It is estimated that over 30 000 UCs are at work in hybrid drives, delivering over 75 000 000 F of electric drive and regenerative braking power.

There are five UC technologies in development: carbon/metal fiber composites, foamed carbon, a carbon particulate with a binder, doped conducting polymer films on a carbon cloth, and mixed metal oxide coatings on a metal foil. Higher energy density can be achieved with a carbon composite electrode using an organic electrolyte rather than a carbon/metal fiber composite electrode with an aqueous electrolyte [5].

IV. FUEL CELLS

The FC generates electricity from the fuel on the anode and the oxidant on the cathode and reacts in the electrolyte. During the generation process, the reactants flow into the cell,

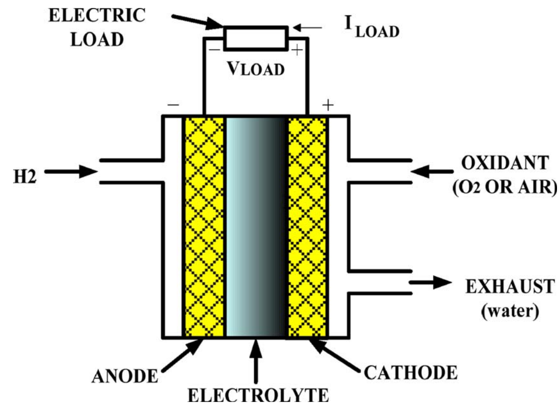

Fig. 3. Configuration of a hydrogen FC.

whereas the products of reaction flow out. The FC is able to generate electricity as long as the reactant flows are maintained. Advantages of the FC include high conversion efficiency of fuel to electrical energy, quiet operation, zero or very low emission, waste heat recoverability, fuel flexibility, durability, and reliability.

Different combinations of fuels and oxidants are possible for FCs. Hydrogen is an ideal nonpolluting fuel for FCs, since it has the highest energy density than any other fuel, and the product of cell reaction is just water. Fig. 3 shows the configuration of a hydrogen FC [1]. Other fuels include hydrocarbons and alcohols, and other oxidants include chlorine and chlorine dioxide [29]. Table III summarizes typical characteristics of FCs.

Unlike electrochemical batteries, the reactants of FCs must be refilled before they are used up. In vehicular applications, a specific fuel tank should be included on board. Due to the relatively low energy density (2.6 kWh/L for liquid hydrogen compared with 6 kWh/L for petrol), large fuel tanks are required.

The efficiency of the FC is dependent on the amount of power drawn from it. Generally, the more power drawn, the lower the efficiency. Most losses manifest as a voltage drop on internal resistances. The response time of FCs is relatively longer compared with that of batteries and UCs. Another drawback of FCs is that they are expensive. FCs currently cost five times more than ICEs, the major cost components being the membrane, the electrocatalyst, and the bipolar plates. New research is in progress to develop hydrocarbon membranes to replace the current per fluorinated membranes [20].

V. HYBRID ENERGY-STORAGE SYSTEMS FOR VEHICULAR APPLICATIONS

A. HEVs

The ESS of most of the commercially available HEVs is composed of only battery packs with a bidirectional converter connected to the high-voltage dc bus. The Toyota Prius, Honda Insight, and Ford Escape are examples of commercially available HEVs with efficiencies around 40 mi/gal in the market.

Topologies to hybridize ESSs for EVs, HEVs, FC hybrid vehicles (FCHVs), and PHEVs have been developed to improve miles per gallon efficiency. Various topologies can be introduced by combining energy sources with different characteristics. Most of these combinations share one common feature,

TABLE III
TYPICAL CHARACTERISTICS OF FCs

	PAFC	MCFC	AFC	SOFC	DMFC	SPFC
Temp (°C)	150-210	600-700	60-100	900-1000	50-100	50-100
Density (W/cm^2)	0.2-0.25	0.1-0.2	0.2-0.3	0.24-0.3	0.04-0.23	0.35-0.6
Life (kh)	40	40	10	40	10	40
Cost ($/kW)	1000	1000	200	1500	200	200

PAFC-phosphoric acid fuel cell.
MCFC-molten carbonate fuel cell.
AFC-alkaline fuel cell.
SOFC-solid oxide fuel cell.
DMFC-direct methanol fuel cell.
SPFC-solid polymer fuel cell also known as proton exchange membrane fuel cell.

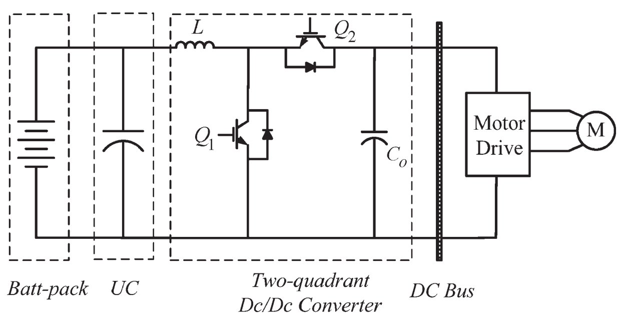

Fig. 4. Passive cascaded battery/UC system.

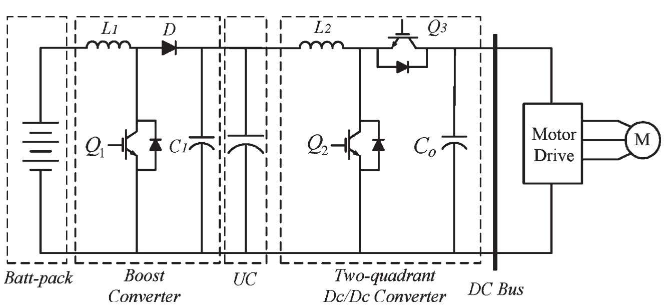

Fig. 5. Active cascaded battery/UC system.

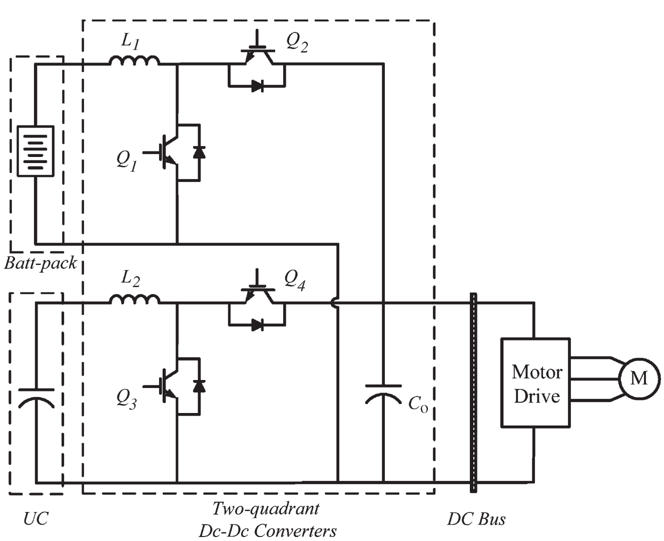

Fig. 6. Parallel active battery/UC system.

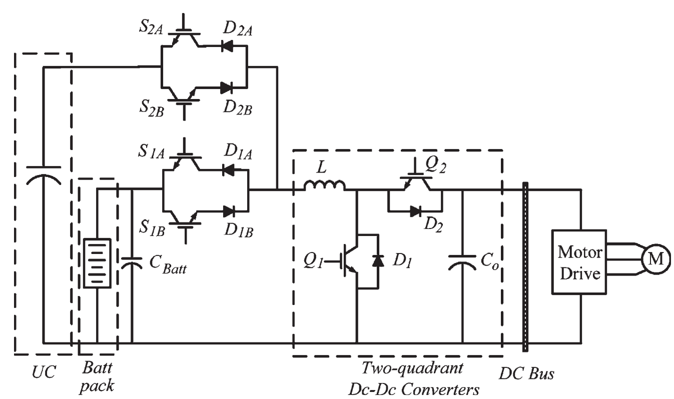

Fig. 7. Multiple-input battery/UC system.

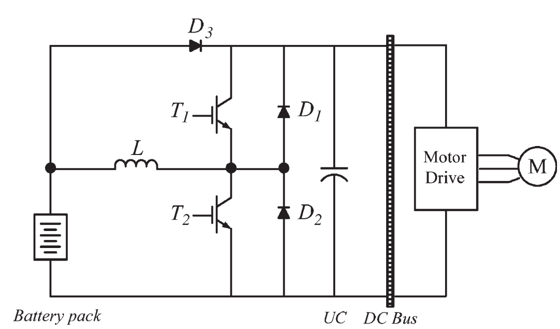

Fig. 8. Proposed hybrid ESS.

which is to efficiently combine fast response devices with high power density and slow response components with high energy density. For battery/UC systems, bidirectional dc/dc converters are widely used to manage power flow directions, either from the source to the load side for acceleration or from the load side to sources during regenerating periods [30]–[36]. In addition, researchers have introduced hybrid FC and battery or UC ESSs to improve the fuel efficiency of vehicles [37]–[40].

In [40], the battery pack is directly paralleled with the UC bank. A bidirectional converter interfaces the UC and the dc link, controlling power flow in/out of the UC, as shown in Fig. 4. Despite wide voltage variation across UC terminals, the dc-link voltage can remain constant due to regulation of the dc converter. However, in this topology, the battery voltage is always the same with the UC voltage due to the lack of interfacing

TABLE IV
ESSs FOR HEVs

Topology	ESS type-Battery/UC		Cost / Weight	Specific energy	Specific power
Passive cascaded system [Fig. 4]	Battery (NiMH) 192 V	UC (Maxwell) 48V, 80F	Approximately $ 5,000/ 40 kg	Approximately 35 Wh/kg	Approximately 750 W/kg
Active cascaded system [Fig. 5]	Battery (NiMH) 144V	UC (Maxwell) 75V, 94F	Approximately $ 4,000/ 40 kg	Approximately 35 Wh/kg	Approximately 750 W/kg
Parallel active system [Fig. 6]	Battery (NiMH) 168 V	UC (Maxwell) 75V, 94F	Approximately $ 5,000/ 50 kg	Approximately 30 Wh/kg	Approximately 600 W/kg
Multiple-input system [Fig. 7]	Battery (NiMH) 168 V	UC (Maxwell) 75V, 94F	Approximately $ 5,000/ 55 kg	Approximately 30 Wh/kg	Approximately 550 W/kg
Hybrid ESS [Fig. 8]	Battery (NiMH) 144 V	UC (Maxwell) 125V, 63F	Approximately $ 5,000/ 40 kg	Approximately 35 Wh/kg	Approximately 750 W/kg
ESS output power is rated at 30kW in HEV topologies.					
Vehicle	ESS type	MPG	ESS Cost/ Weight	Specific energy	Specific power
Toyota Prius 4 door sedan	Battery (NiMH) 201.6 V, 1.3 kWh	City 51mpg Hwy 48mpg	Approximately $ 2,500/ 30kg	Approximately 44 Wh/kg	Approximately 1310 W/kg
Honda Insight 5 door hatchback	Battery (NiMH) 144 V, 0.9 kWh	City 40mpg Hwy 43mpg	Approximately $ 1,900/ 22kg	Approximately 42.55 Wh/kg	Approximately 450 W/kg
Ford Escape 4 door SUV	Battery (NiMH) 330 V, 1.8 kWh	City 34mpg Hwy 31mpg	Approximately $ 5,000/ 50kg	Approximately 36.6 Wh/kg	Approximately 600 W/kg

control between the battery and the UC. The battery current must charge the UC and provide power to the load side.

The passive cascaded topology in Fig. 4 can be improved by adding a dc/dc converter between the battery pack and the UC, as shown in Fig. 5. This configuration is called an active cascaded system [42]. The battery voltage is boosted to a higher level; thus, a smaller sized battery can be selected to reduce cost. In addition, the battery current can more efficiently be controlled compared with the passive connection. Due to the existence of the boost converter, the battery current is smoothened, and the stress on the battery is reduced. The battery supplies average power to the load, and the UC delivers instantaneous power charge and recovers fast charging from regenerative braking. The drawback of this topology is that the battery can neither be charged by braking energy nor by the UC due to the unidirectional boost converter.

A parallel active battery/UC system, as shown in Fig. 6, has been analyzed by researchers at the Energy Harvesting and Renewable Energy Laboratory (EHREL), Illinois Institute of Technology (IIT), and Solero at the University of Rome [30], [33]. The battery pack and the UC bank are connected to the dc link in parallel and interfaced by bidirectional converters. In this topology, both the battery and the UC present a lower voltage level than the dc-link voltage. The voltages of the battery and the UC will be leveled up when the drive train demands power and stepped down for recharging conditions. Power flow directions in/out of the battery and the UC can separately be controlled, allowing flexibility for power management. However, if two dc/dc converters can be integrated, the cost, size, and complexity of control can be reduced.

In the multiple-input bidirectional converter shown in Fig. 7, both the battery and the UC are connected to one common inductor by parallel switches [31], [34]. Each switch is paired with a diode, which is designed to avoid short circuit between the battery and the UC. Power flow between inputs and loads is managed by bidirectional dc/dc converters. Both input voltages are lower than the dc-link voltage; thus, the converter works in boost mode when input sources supply energy to drive loads and in buck mode for recovering braking energy to recharge the battery and the UC. Only one inductor is needed, even if more inputs are added into the system. However, the controlling strategy and power-flow management of the system are more complicated.

A hybrid topology, where a higher voltage UC is directly connected to the dc link to supply the peak power demand, is demonstrated in Fig. 8 [36]. A lower voltage battery is interfaced by a power diode or a controlled switch with the dc link. This topology can be operated in four modes of low power, high power, braking, and acceleration. For light duty, the UC mainly supplies the load, and the battery will switch in when the power demand goes higher. Regenerative energy can directly be injected into the UC for fast charging or into both the battery and the UC for a deep charge. Table IV summarizes structures, characteristics, and costs of ESS topologies for HEV, as well as comparisons of ESSs of typical market-available HEVs.

B. PHEVs and EVs

The PHEV is defined as any HEV containing a battery storage system of 4 kWh or more, a means of recharging a battery from an external electric source, as well as being able to drive at least 10 mi in all-electric mode [43]. Available PHEVs include Fisker Karma, Chevy Volt, and BYD F3DM. However, none of these automobiles are in mass production as of December 2009.

Despite PHEVs, EVs have a pure electrical propelling system, which completely replaces ICEs. The ESS of EVs should be able to supply all power demands of the vehicle [44]. To extend the driving range of EVs, the capacity of the battery pack must be increased to store enough energy. In Fig. 9, the ESS system integrates the battery pack and the UC to meet higher energy requirements and satisfy fast charging and discharging responses. The battery pack can be recharged from a grid charger or a specific high-voltage charger. Tesla Motors has developed commercially available EVs with a driving range of 300 mi per charge, using Li-ion batteries as energy-storage devices [45].

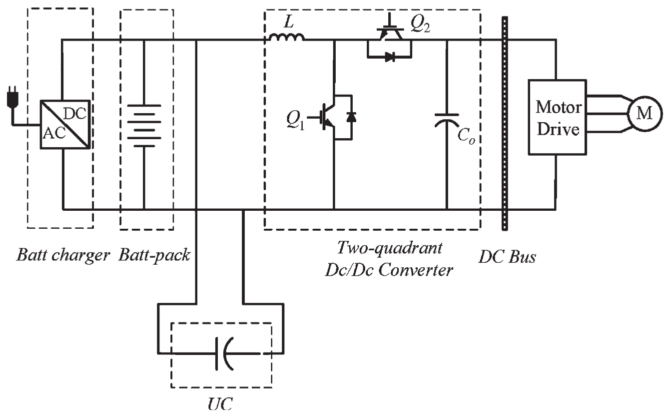

Fig. 9. ESS topology of a pure EV.

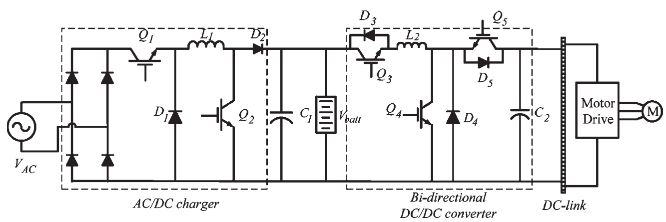

Fig. 10. Topology of PHEVs with a cascaded converter.

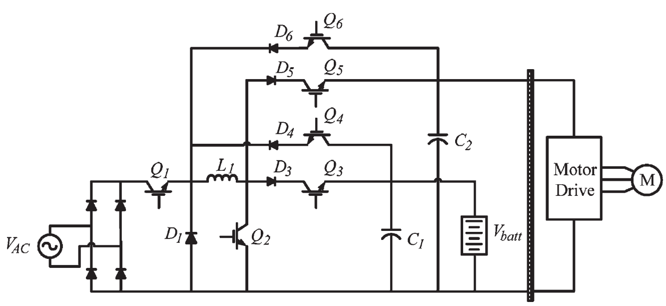

Fig. 11. Topology of PHEVs with an integrated converter.

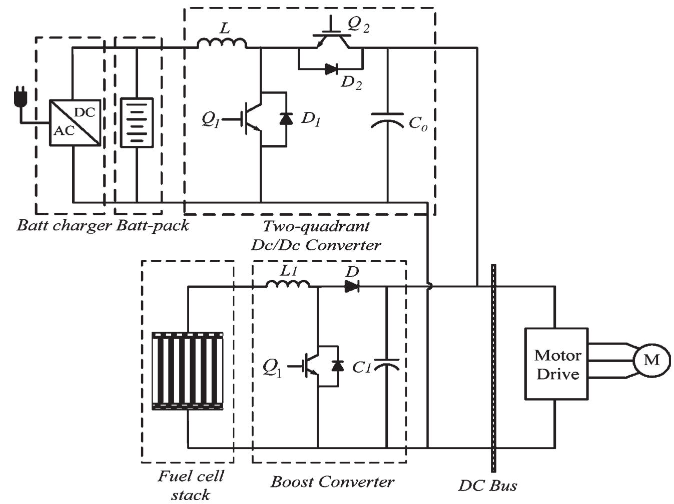

Fig. 12. Plug-in FC vehicle topology.

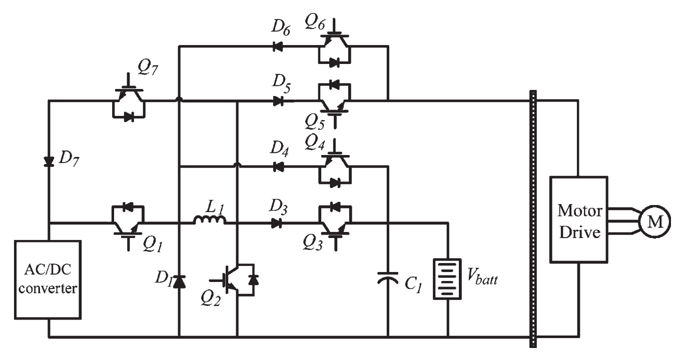

Fig. 13. Bidirectional dc/dc converter integrated with an ac/dc converter.

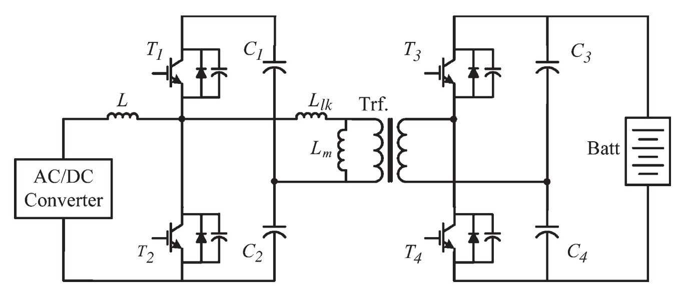

Fig. 14. Dual-active-bridge dc/dc converter.

Fig. 10 shows a full-bridge charger with two noninverting converters for PHEVs [51]. In this topology, a grid charger, a battery pack, and dc converters are cascaded. One of the issues of this topology is the conduction loss of switches, which limits the efficiency.

Researchers at IIT have proposed an integrated bidirectional converter for PHEVs [51]. In the proposed converter, as shown in Fig. 11, six switches and five diodes are utilized, where their combination enables the buck or boost modes of operation. Only one inductor is employed in this integrated converter, which allows reducing the number of high-current transducers. This helps reduce cost and weight.

A plug-in FCHV topology is shown in Fig. 12 [52]. Due to the grid connection capability and the size of the battery pack, this topology would not depend only on hydrogen. In this system, the FC is interfaced by a boost converter with the dc link, which boosts the FC voltage to a higher level. Batteries are connected to the dc link via a bidirectional converter to supply and absorb regenerative energy.

PHEVs have been proposed to extend the all-electric driving range of HEVs [53]–[58]. According to the study of the Pacific Northwest National Laboratory, the existing U.S. power grid is sufficient to supply 70% of America's passenger vehicles, if they charged after midnight. This could potentially reduce gasoline consumption by 85 gal/yr, saving $270 billion in gasoline [59]. Therefore, a lot of research is being conducted to configure the most efficient ESSs for PHEVs.

Researchers are investigating the novel topology of the battery integrated with the bidirectional ac/dc–dc/dc converters for PHEVs [60]–[62]. The proposed topology in Fig. 13 could be operated in four modes: charging/discharging the battery from/to the grid and bidirectional power flow between the battery and the dc link.

Adding UCs to ESSs of EVs, HEVs, and PHEVs will help reduce battery size and extend battery life. Currently, no commercial vehicles use UCs in their ESSs. The hybridized ESSs are being investigated for a future generation of PHEVs, EVs, and HEVs. Combining UCs with batteries would also improve

TABLE V
ESSs FOR EVs AND PHEVs

Topology	Type	Output power	Cost/ Weight	Specific energy	Specific power
ESS of EV [Fig. 9]	EV	150 kW	Approximately $ 10,000/ 300 kg	Approximately 120 Wh/ kg	Approximately 500 W/ kg
Cascaded converter for PHEV [Fig. 10]	PHEV	85 kW	Approximately $ 6,000/ 150 kg	Approximately 133 Wh/ kg	Approximately 720 W/ kg
Integrated converter for PHEV [Fig. 11]	PHEV	85 kW	Approximately $ 6,000/ 150 kg	Approximately 133 Wh/ kg	Approximately 720 W/ kg
Plug-in fuel cell topology [Fig. 12]	PHEV	100 kW	Approximately $ 75,000/ 500 kg	Approximately 110 Wh/ kg	Approximately 200 W/ kg
Bi-direc. converter for PHEV [Fig. 13]	PHEV	85 kW	Approximately $ 6,500/ 160 kg	Approximately 125 Wh/ kg	Approximately 700 W/ kg
Dual active bridge converter [14]	PHEV	85 kW	Approximately $ 7,500/ 200 kg	Approximately 115 Wh/ kg	Approximately 700 W/ kg
Vehicle	ESS Type	All Elec.Range/MPG	ESS Cost/Weight	Specific energy	Specific power
Tesla Model S EV/4 door Sedan	Battery (Li-ion) 42 kWh	26 kWh/100 mile 300 miles/charge	Approximately $ 12,000/340 kg	Approximately 123 Wh/ kg	Approximately 470 W/ kg
Fisker Karma PHEV/4 door Sedan	Battery (Li-ion) 22.6 kWh	Claims 100 mpg 50 all-electric miles	Approximately $ 8,000/200 kg	Approximately 113 Wh/ kg	Approximately 760 W/ kg
Chevy Volt PHEV/5 door Liftback	Battery (Li-ion) 16 kWh	Estimated 48 mpg 40 all-electric miles	Approximately $ 5,000/150 kg	Approximately 107 Wh/ kg	Approximately 740 W/ kg
Data of MPG and driving range in Table 4 and Table 5 are obtained from manufactures' official websites and based on optimal estimations [45]-[50].					

fuel efficiencies, extend all electric driving ranges, decrease greenhouse gas emissions, and improve the life of the battery packs.

Researchers have designed an isolated converter with a transformer to charge/discharge PHEV batteries. A dual-active-bridge converter consisting of two active full bridges linked by a transformer is shown in Fig. 14. When delivering energy from the ac/dc converter to the battery, the left bridge acts as an inverter, whereas the internal diodes of the switches on the right bridge rectify ac power to dc. When discharging the battery, the right bridge inverts dc power to ac, and an ac voltage is induced on the left bridge through a transformer. The internal diodes of the left bridge rectify the current back to dc that is usable by the bidirectional ac/dc converter [63].

When operated in a high frequency, a fairly small transformer can be used. Zero-voltage switching is achieved by operating the two half-bridges with a phase shift. This operation allows a resonant discharge of lossless snubber capacitances of switching devices. Each antiparallel diode is conducted before the conduction of the switching device. The circuit operation uses the transformer leakage inductance as an interface and energy transfer element between the two half-bridge converters. This topology provides high power density and fast control. Table V summarizes structures, characteristics, and costs of ESS topologies for PHEV, as well as comparisons of ESSs of typical market-available PHEVs.

VI. Conclusion

EVs, HEVs, FCHVs, and PHEVs have proven to be an effective solution for current energy and environment concerns. With revolutionary contributions of power electronics and ESSs, electric drive trains totally or partially replace ICEs in these vehicles. Advanced ESSs are aimed at satisfying the energy requirements of hybrid power trains. Currently, most commercially available EVs and hybrid vehicles do not involve hybrid ESSs on board. Single ESS devices such as batteries, UCs, and FCs could not meet all the requirements of advanced hybrid electric drive trains individually. Researchers are investigating hybrid ESSs with large capacity, fast charging/discharging, long lifetime, and low cost.

Various hybridized topologies for EVs, HEVs, FCHVs, and PHEVs have been investigated in this paper. For the purpose of making HEVs and PHEVs competitive with conventional vehicles in the market, additional research efforts should be focused on decreasing cost, improving efficiency, and increasing electric driving range of future advanced vehicles by introducing transformational ESSs. Therefore, low-cost, high-efficiency hybrid ESSs with extended AER would make EVs and plug-in hybrid vehicles more feasible to compete with conventional vehicles in the near future.

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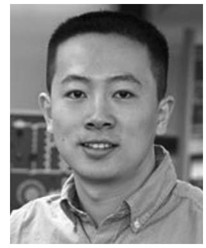

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