Energy Storage Systems for Automotive Applications

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***Abstract*—The fuel efficiency and performance of novel vehicles with electric propulsion capability are largely limited by the performance of the energy storage system (ESS). This paper reviews state-of-the-art ESSs in automotive applications. Battery technology options are considered in detail, with emphasis on methods of battery monitoring, managing, protecting, and balancing. Furthermore, other ESS candidates such as ultracapacitors, flywheels and fuel cells are also discussed. Finally, hybrid power sources are considered as a method of combining two or more energy storage devices to create a superior power source.**

***Index Terms*—Capacitors, energy storage, flywheels, fuel cells (FC), land vehicle, transportation.**

I. Introduction

GROWING consumer expectations, legislation pushing for lower emissions and higher fuel economy, and the realization that petroleum is a finite resource are leading to groundbreaking changes in the automotive industry, including drivetrain electrification and a push for fuel cell vehicle (FCV) commercialization. Depending on the degree of electrification, the combination of the internal combustion engine (ICE) with an electric motor in the hybrid drive train offers a wide range of benefits, from reduced fuel consumption and emission reduction to enhanced power performance and the introduction of power-hungry hotel loads [1]–[3]. Hybrid electric drive trains may also facilitate the introduction of FCs. Progress anticipated in the development of both energy storage systems (ESSs) and electric drivetrains will benefit FC/electric hybrids. The major hurdle to the widespread usage of advanced vehicles is the unavailability of an adequate storage system to supply the power and energy demands posed by drivetrain electrification [1]–[4].

The remainder of this paper is organized as follows. In Section II, we review the status and trends in the automotive industry. Degrees of electrification are classified into sub groups, namely, micro, mild, power assist, and plug-in hybrid electric vehicles (HEVs). In Section III, candidate battery technologies (lithium ion (Li-ion), nickel metal hydride (NiMH), and lead acid) for drivetrain electrification are discussed in detail. It is shown that valve-regulated lead-acid (VRLA) batteries may be considered for micro and mild hybrids, while NiMH and Li-ion have to be considered for higher electrification levels. Furthermore, the need and methods to monitor, manage, protect, and balance the packs will be examined. State-of-charge (SoC) monitoring algorithms and cell balancing methodologies will be covered in detail.

Ultracapacitors (UCs), FCs, and flywheels are considered in Sections IV–VI, respectively. Principle of operation as well as technical challenges to the widespread introduction of these systems will be presented. In Section VII, hybrid power sources are considered as a method of combining two or more ESSs to create a superior power source. Summary and conclusion are presented in Section VIII.

II. Review of the Status and Trends in the Automotive Industry

Due to the high energy density (6 kWh/L) and low cost of petroleum, ICE has been the power source of choice for vehicle propulsion. An acceptable range and performance are achieved even with peak tank to wheel efficiency of less than 30%. However, rising prices and environmental concerns about the impact of petroleum combustion have led to a push for the development of more efficient and less polluting vehicles. Drivetrain electrification is seen as the short-term means to reduce oil consumption. Simultaneously, the number and electric power draw of "convenience" hotel loads are increasing, leading to larger energy consumption. Both of these competing requirements make a larger energy storage unit necessary.

As the long-term solution to eliminating oil consumption for transportation, researchers are developing advanced vehicles which use other sources of energy, such as FCVs and battery electric vehicles (BEVs).

Electric vehicles can broadly be defined as vehicles with electric propulsion capability [3], [5]. Such vehicles include HEV, BEV and FCV. In this section, we look at these technologies in more detail.

In a HEV, power from the ICE and electric motor is combined to propel the vehicle. The electric motor is powered by sources which provide electric energy, including batteries, UCs, flywheels, or FCs. The fuel economy improvement comes from efficient operation of a smaller engine as well as regenerative breaking energy.

HEVs can be categorized by their mechanical connections as parallel, series, or parallel/series. In parallel HEVs, both the electric motor and the engine can provide power directly to the drivetrain. In a series HEV, all the propulsion power comes from the electric motor. The engine is used only to recharge the

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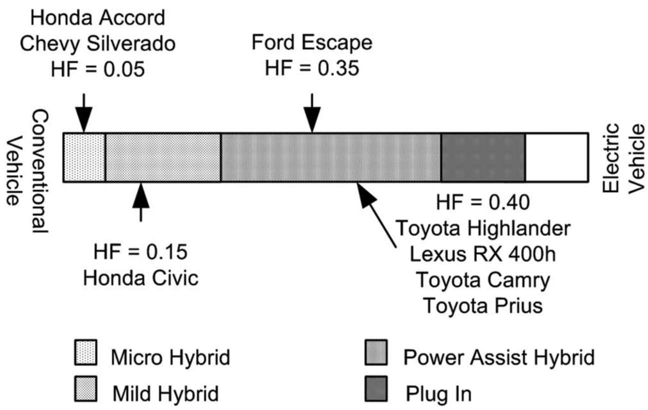

Fig. 1. HEV classification using HF.

TABLE I
FEATURES IN HEVs [6]

Feature	Conv.	Micro	Mild	Pwr. Assist	Plug In
Cranking	Yes	Yes	Yes	Yes	Yes
Engine off at idle	No	Yes	Yes	Yes	Yes
Mild regen	No	Yes	Yes	Yes	Yes
Regen	No	No	Yes	Yes	Yes
Mild assist	No	No	Yes	Yes	Yes
Acceleration assist	No	No	No	Yes	Yes
Extended EV oper.	No	No	No	No	Yes

energy storage unit; FCVs and EVs belong to this group. Some mechanical setups allow the vehicle to behave both as a series and a parallel hybrid (usually via a planetary gear). Vehicles in this group are called parallel/series HEVs. Most commercially produced passenger cars belong to this group.

Parallel and parallel/series HEVs can be further categorized by their level of hybridization. To facilitate categorization, we introduce the concept of hybridization factor (HF) [2]

$$\mathrm{HF} = \frac{P_{\mathrm{EM}}}{P_{\mathrm{EM}} + P_{\mathrm{ICE}}} \tag{1}$$

where P_{EM} is the peak power of the electric motor, and P_{ICE} is the peak power of the ICE. Fig. 1 shows the classification of HEVs using the HF. On the extreme left is the conventional vehicle with $\mathrm{HF} = 0$, and on the extreme right is the electric vehicle with $\mathrm{HF} = 1$. It is interesting to note that Toyota has chosen HF of 0.4 for all their power assist HEVs. HEVs can also be grouped by the functions they perform, as shown in Table I. In the following, the properties of each category are described in more detail.

Micro-HEVs combine the automatic engine stop/start operation with regenerative braking to improve vehicle fuel economy. Due to the higher power requirements imposed by the hotel loads and drivetrain electrification, the introduction of a higher voltage (42 V) level was considered. The system allows the starter and the alternator to be combined into one unit and also provides a fast start for the engine as well as limited propulsion assist. Advanced lead acid batteries are considered to be sufficient to supply this limited power requirement (Table II).

TABLE II
FREEDOMCAR ENERGY STORAGE TARGETS

Vehicle Type	Energy		Power		Oper. Temp	Life
	kWh	Wh /kg	kW	W/kg		
42V start-stop	0.25	10	6	240	-30-52	15
42V M-HEV	0.3	12	13	520	-30-52	15
42V P-HEV	0.7	20	18	520	-30-52	15
HEV-min	0.3	7.5	25	625	-30-52	15
HEV – max	0.5	8.3	40	667	-30-52	15
EV – current	40	150	80	300	-40-50	10
EV - long term	40	200	80	400	-40-85	10

Mild-HEVs are fitted with a more powerful electric propulsion system—up to 0.25 HF. They are capable of moving the vehicle at low speeds as well as capturing more regenerative braking energy. Many mild HEVs are performance HEVs where the electric system is geared toward boosting performance rather than increasing fuel economy. Due to the higher power capabilities of the electrochemical system, the energy throughput in the batteries is much higher than in micro-HEVs. This implies the use of more advanced battery technology, typically NiMH. The larger generator also allows for more hotel loads such as a 110-V ac outlet to be introduced.

Power-assist HEVs offer substantial electric propulsion assistance and also limited electric-only range. Electric drive and battery typically operate at voltages above 200 V.

Plug-In HEVs are full hybrids characterized by batteries that can be recharged from the residential power grid. The vehicles provide a much longer all electric range and, therefore, higher overall fuel economy. These vehicles are essentially BEVs with an on-board generator in the form of an ICE.

BEVs use the energy stored in the battery to propel the vehicle. These vehicles have had some degree of success in the past, such as with the GM EV1. The issue with these vehicles is the limited range due to the inadequate amount of energy stored in the batteries. The energy density of the batteries needs to be improved substantially for the BEVs to have a larger impact (see Table II). Other issues are battery recharge time and recharging infrastructure.

FCs are electric vehicles which produce electricity on board by releasing energy stored in hydrogen gas, or a compound from which hydrogen is extracted (via a reformer). After 30 years of research, these vehicles are still in a developmental stage. There are some major obstacles to their commercial introduction, including price, hydrogen energy density, and refueling infrastructure. No FCVs are currently available for purchase.

III. BATTERIES

Batteries are the prevalent ESS in the market due to their low cost, portability, and ruggedness. They produce electricity by releasing the potential energy stored in the chemicals of the battery.

A battery typically consists of an electrolyte, two electrodes (positive and negative), and a separator (electrically insulating porous material). The two electrodes are made of different materials, both of which chemically react with the electrolyte in

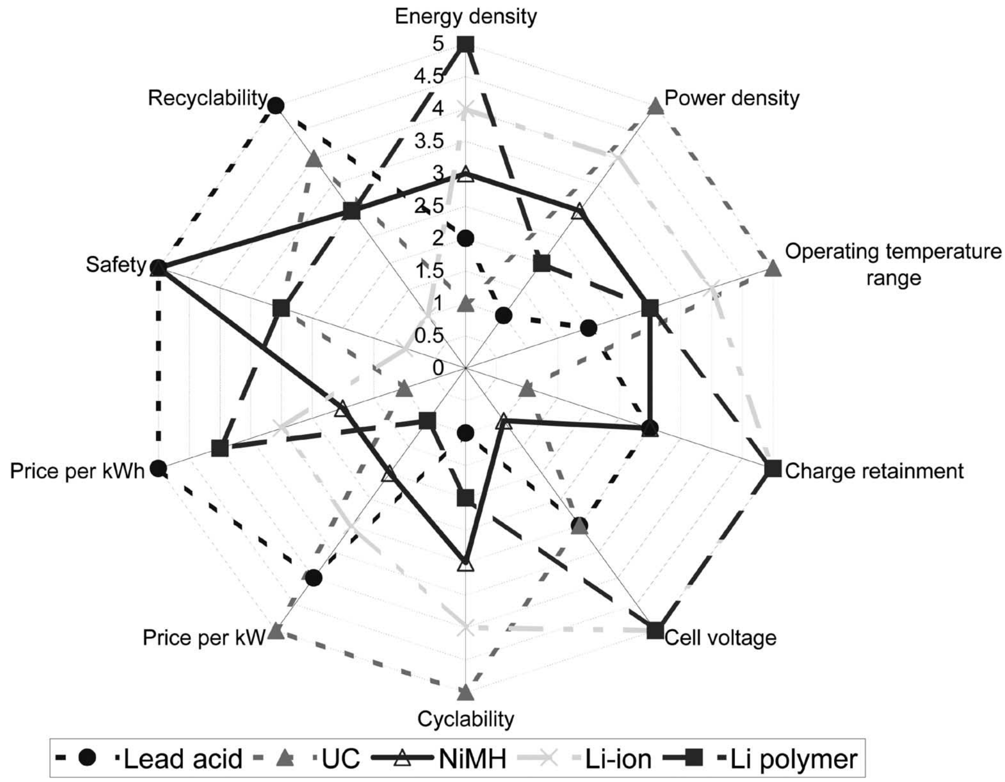

Fig. 2. Comparison of attributes of various battery and UC technologies.

some form of ionic bonding. The most important characteristics of interest in automotive applications are the life, specific power, specific energy, cost, and safety of the technology. Requirements from the ESS for various automotive applications have been developed by the FreedomCAR initiative and are summarized in Table II. Even though lead acid batteries have been traditionally used in automotive applications, Li-ion and NiMH batteries are the main contenders to achieve FreedomCAR goals. To ensure that the battery will perform as expected, the battery pack needs to monitored, managed, and protected. There may be a need to charge balance the cells as well. This section describes the properties of lead acid, NiMH, and Li-ion batteries in detail, and also outlines monitoring, managing, and protection methods.

A. *Overview of Battery Chemistries*

Lead acid batteries have been in use since the 1900s. Interestingly, the system has not changed dramatically since then. The system consists of a lead current collector, spongy lead as the negative active material, lead oxide as the positive active material, and diluted sulfuric acid as the electrolyte. During discharge, the active material on both the positive and the negative plates is transformed into lead sulfate.

Lead acid batteries are the energy storage choice for many applications due to their ruggedness, low cost, inherent safety, and temperature tolerance (see Fig. 2). The VRLA battery is maintenance-free and has good cyclability even at deep discharge. The specific energy and power of the battery is low due to the weight of lead and its use as the current collector. Power density can be boosted by increasing the surface area of the electrodes, which raises the rate of corrosion and thus reduces battery life. More importantly, lead acid batteries face additional life cycle limitations when operated at a high rate partial SoC (HRPSoC) mode typical of HEV applications [15]. It has been shown that large nonconductive sulfate crystals are formed when the battery is not fully recharged periodically. The sulfate crystals reduce porosity and limit access to the active material, and therefore limit the battery capacity.

Research efforts have focused on addressing both the poor energy density as well as the limited life at HRPSoC. Energy density is improved by using lighter noncorrosive collectors [16], while the HRPSoC issues are addressed by adding conductive carbon to the active material to mitigate the sulfation issue.

Alkaline batteries are nickel-based and use an alkaline solution as the electrolyte. In this group, only NiMH is a serious contender for automotive applications. In fact, all currently available HEVs use NiMH technology as the ESS. Nickel cadmium batteries have been ruled out due to the high cost and environmental concerns associated with cadmium, while nickel zinc batteries suffer from short life due to fast dendrite growth.

NiMH batteries are composed of nickel hydroxide on the positive electrode and a multicomponent, engineered alloy consisting of vanadium, titanium, nickel, and other metals on the negative electrode. This technology has experienced great advances in the past 15 years, as evidenced by a threefold increase in energy and tenfold increase in specific power. The distinct advantages of the technology include: safe operation at high voltage; excellent volumetric energy and power; tolerance to abusive overcharge and overdischarge; and excellent thermal properties [17].

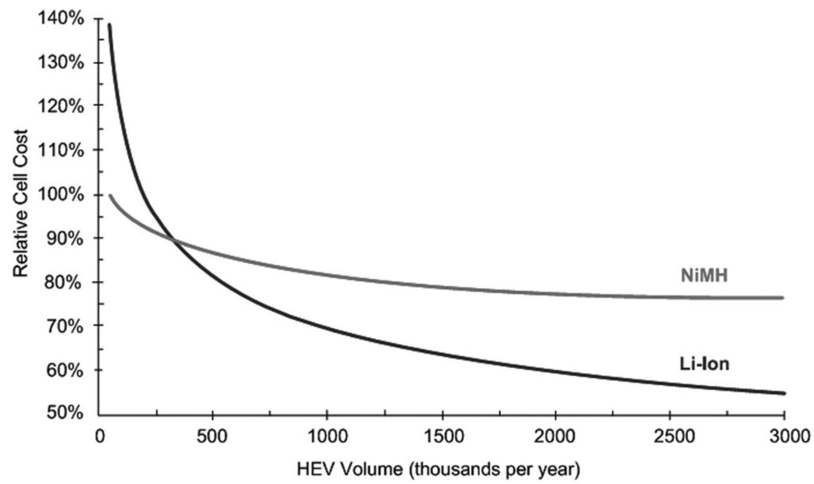

Fig. 3. NiMH and Li-ion HEV cell cost as a function of vehicle production volume [18].

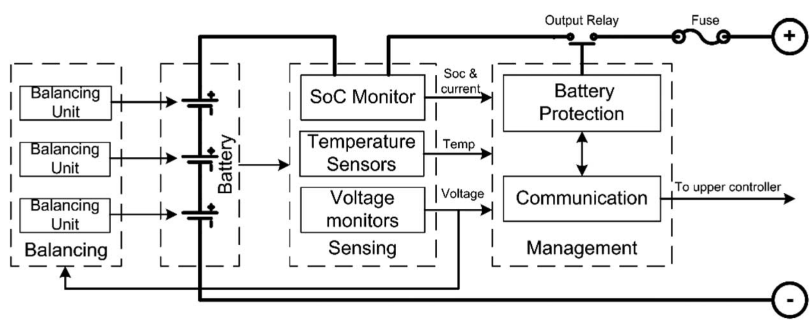

Fig. 4. Block diagram of a generic BMS.

In the past, main hurdles to widespread use of the technology were limited capacity at low temperatures and limited charge acceptance at elevated temperatures. Progress has been made in improving the performance of the batteries at temperature extremes. On the other hand, the issue with price is a more serious one. The raw materials used are very expensive and will not become much cheaper in mass production as evidenced by Fig. 3. To keep NiMH technology competitive in the long term, more frugal use of precious metals or the use of cheaper substitutes is a must.

Li-ion batteries: Due to their high specific energy and potential to be produced at low cost (see Fig. 3), Li-ion is expected to replace NiMH batteries in automotive applications. The battery consists of oxidized cobalt material on the positive electrode, carbon on the negative electrode, and lithium salt in an organic solvent for the electrolyte. Even though use of the chemistry is fairly novel, it is interesting to note that processes in the battery are fairly simple compared to other chemistries, and therefore lend themselves to detailed modeling. Li-ion battery models have been instrumental in increasing the performance of the battery, and more recently even in predicting battery deterioration. The promising aspects of the chemistry are its low memory effect, high specific energy of 100 Wh/kg, high specific power of 300 W/kg, and battery life of 1000 cycles. The key barriers are the following: calendar life, cost, operation at temperature extremes, and abuse tolerance. A breakthrough in the development of advanced electrodes is needed to further increase the specific energy [19].

B. Battery Management

The goal of the battery management system (BMS) is to achieve maximum system performance, while minimizing power consumption to extend battery life [1], [7], [25]. To achieve these objectives, it is critical for the BMS to accurately communicate the state of the battery to the system controller. The most basic BMS performs the following functions:

1) undervoltage protection;
2) overvoltage protection;
3) short-circuit protection (maximum current limit);
4) thermal protection.

Additional functions which may be performed by the management system include the following:

1) SoC, state-of-health (SoH), and state-of-function (SoF) monitoring;
2) cell equalization (balancing) on cell/module level.

Fig. 4 shows the block diagram of a generic BMS. The voltage information gathered by the sensing subsystem is sent to the balancing circuit, which uses the information to ensure that all cell voltages are within the allowed limit. The balancing is typically done on the module level, rather than on the cell-to-cell level. The sensing block also records temperature and current. Voltage, current, and temperature information (along with the battery history) are then used to determine the state of the battery charge.

TABLE III
TECHNIQUES FOR MEASURING THE CONDITION OF BATTERY. THE (+, −) SYMBOLS SHOW IF THE METHOD IS ABLE TO ESTIMATE A PARTICULAR FIGURE OF MERIT

Technique	SoC	SoH	SoF	Advantages	Disadvantages
Discharge Test	+	+	+	Easy, Accurate and independent of SoH	Offline; time Intensive; modifies battery state
Current Integration [7]	+	-	-	Online; accurate is recalibrated often	Needs a model for the losses; sensitive to parasitic reactions, and their changes; processing power required; needs recalibration
Electrolyte Measurements[8]	+	+	+	Online	Sensitive to acid stratification; slow dynamics; temperature sensitive
Model [8, 9]	+	+	+	Online and flexible	Processor intensive
Impedance Spectroscopy [10]	+	+	+	Online; little processing required	Temperature sensitive; expensive
DC Resistance [10]	+	+	+	Cheaper than Impedance measurement; online	Requires resistance changes that are substantial
Kalman Filter [11]	+	+	+	Online; precise in dynamic situations	Needs Computing Capacity; needs a suitable battery model
Voltage at zero current	+	-	-	No Current Sensor required	Limited precision especially in dynamic situations; needs many zero current situations
Artificial Neural Network [1, 12]	+	+	+	Online; has the potential to be very precise	Needs training on similar battery; complex and expensive to implement
Fuzzy Logic [13, 14]	+	+	+	Online	Complex and expensive to implement

C. Battery State Monitoring

A good knowledge of the state of the battery is essential for meaningful energy management [1], [7], [26]. Difficulty in measuring the condition of a battery in an operating system stems from the fact that the rate and efficiency of the chemical reaction that produces the current depends on a number of factors, including the temperature, age, and manufacturing conditions [7]. Therefore, various figures of merit have been used to define the state of the battery.

SoC is defined by

$$\mathrm{SoC} = \frac{\text{Actual Amount of Charge}}{\text{Total Amount of Usable Charge at a given C - rate}}. \tag{2}$$

The issue with this metric is that the actual amount of charge is very difficult to measure. For instance, the total amount of charge available for utilization changes as the battery ages. The capacity scatter due to manufacturing variations also makes the total amount of charge hard to determine, even for a new cell.

SoH measures the ability of a battery to store energy, source and sink high currents and retain charge over extended periods, relative to its initial or nominal capability. This quantity is closely related to battery age and SoC.

SoF is the capability of the battery to perform a specific duty, which is relevant to the functionality of a system powered by the battery. The SoF is a function of the battery SoC, SoH, and operating temperature. For example, a new battery (high SoH) at a lower SoC and higher operating temperature may perform better (higher SoF) than an older battery (low SoH) at a higher SoC and lower temperature.

There are a number of methods that allow for the determination of the SoC, SoH, and SOF, as outlined in Table III. The simplest and most commonly used method is measuring the open circuit voltage of the battery and relating it to the SoC. In a dynamic application, this method will be very imprecise when the battery has been under a load for a longer period of time. A simple equivalent circuit model that uses the cell voltage and current to estimate the open circuit voltage can be implemented (this requires a current sensor). Alternatively, a comparator can be used to identify points where the current is zero, and measure only these points. More complex processor intensive procedures that give much higher precision can be used. For example, a more complex equivalent circuit model that also uses information from impedance and resistance measurements can be used. Other options include the use of fuzzy logic, neural networks, or Kalman filters. A discharge test is the only certain way of determining the values of all three figures of merit.

NiMH batteries present a bigger challenge for the determination of figures of merit because the voltage versus SoC plot is not linear. In fact, the voltage is almost flat throughout the 20%–80% SoC range. The batteries also exhibit a memory effect. The most common way of determining the SoC is by current integration. However, this method does not consider charge inefficiencies or the effect of temperature. Fuzzy logic method has been used with success for monitoring NiMH SoC [1], [27].

D. Cell Balancing

Cell balancing is critical for systems which consist of long strings of cells in series [1]. Since the cells are exposed to different conditions within the pack, the individual states of charge and therefore cell voltages will gradually drift apart without equalization. In the worst case scenario, this leads to a catastrophic event such as ignition in the case of Li-ion batteries and, at best, the degradation of pack life. The sources of cell imbalance stem from manufacturing variance leading to variations in internal impedance and differences in the self-discharge rate. Another source of variation is the thermal differential across the pack, which results in differing thermodynamics in the cells. Variations in the SoC can be minimized by designing a good thermal management system, and with tight manufacturing controls.

The equalization methods can be considered active or passive. Passive methods are effective for lead acid and NiMH batteries which can be overcharged safely. However, overcharge

TABLE IV
CELL BALANCING STRATEGIES

Name	Description	Advantages	Disadvantages
Dissipative Resistor [20]	Dissipate power in accordance with voltage	Cheap, simple to incorporate	Not very effective; inefficient
Analog Shunting Circuit [20]	Current shunted around the cell in proportion to cell voltage	Cheap; can be operated in both charging and discharging	Dissipative; not very effective; only works during charging
PWM+ Inductor Shunting [21]	By applying a PWM square wave on the gating of a pair of MOSFETS, the circuit controls the current difference of the two neighboring cells	Soft switching makes balancing highly efficient	Needs accurate voltage sensing; could be operated in charging mode only
Buck-Boost Shunting [21]	By using a buck-boost converter the circuit shunts the current from single cell to the rest of cells	Control strategy relatively easy; relatively low cost; easy for modular design; also need intelligent control unit.	Voltage sensing needed
Complete Shunting [22]	Complete shunting when cell reaches max voltage	Simple and effective	Can be only used in charging; special mass charger is needed when string is long
Switched Capacitors	Balance adjacent cells by equalizing their voltages via adjacent capacitor	Simple control; operates in all modes; only two switches and one capacitor needed for each cell	Needs large capacitor bank large switched because of capacitor inrush current
Single Capacitor	Balance adjacent cells by equalizing their voltages via single capacitor	Simple control; operates in all modes; many switches, but only one capacitor	Long time to balance cells
Step-up converter [22]	Each cell is equipped with a step up converter for cell balancing	Easy for modular design	Intelligent control needed; high cost
Multi-winding transformer [23]	A shared transformer has a single magnetic core with secondary taps for each cell. The secondary with the least reactance will have the most induced current	Possible integration of trickle charging and equalization	High cost; inability to modularize the system; requires transformers
Multiple transformer	Several transformers can be used with the same core	Can be modularized	High cost; requires transformers
Multilevel Converters [24]	Each cell/module has a dedicated converter. The resulting topology can act as the motor driver.	Ideal for transportation applications	High Cost

equalization is only effective on a small number of cells in series, because equalization problems grow exponentially with the number of cells in series, and extensive overcharge leads to cell degradation.

Many active methods are available, ranging from the minimally effective to the exorbitantly expensive. An example of a cheap minimally effective system is the use of shunt resistors. This system is used for low cost equalization solutions in small scale systems. On the expensive side, separate chargers can be used for each cell. This system is typically used for large standby batteries in UPS systems.

Table IV gives an extensive list of available cell balancing methods. Dissipative resistors in continuous mode, buck-boost shunting, and switched capacitors are the three most effective methods for different applications. Dissipative resistors in continuous mode are good for low power applications. Because the resistors are operating in continuous mode, they can be small and do not need much thermal management. Another advantage of this method is the low price. Buck-boost shunting is appropriate for either high or low power applications, has relatively low cost and is simple to control. The switched capacitor method is suitable for HEV applications because it is effective in both charging and discharging regimes.

E. Practical Systems

A complete battery system should include the following three subsystems: 1) balancing system; 2) monitoring system; and 3) management system. However, in most HEV battery packs, the balancing system is not available to reduce the cost. Thermal management, tight cell manufacturing, and limited use of the pack in a narrow SoC range minimize the need for cell balancing. The battery system on both Toyota Prius and Honda Civic can be described by Fig. 4, excluding the balancing circuits. The hardware layout is summarized as follows:

1) every six cells as a module (7.2 V);
2) sense the voltage of every two modules (14.4 V);
3) circuit breaker or switch in series in the middle of battery pack.

IV. UCs

Capacitors store electric energy by physically separating and accumulating unlike charges. The charges are stored on two parallel plates divided by an insulator. The energy stored in a capacitor is measured in Coulombs or amp-seconds as follows:

$$Q = CV = \frac{A\varepsilon}{d}V. \tag{3}$$

The energy storing capability of a capacitor (its capacitance) is proportional to the area A of the plates and the permittivity of the dielectric ε and inversely proportional to the distance d between the plates. UCs are special capacitors which are able to store a substantial amount of energy at a low voltage. This

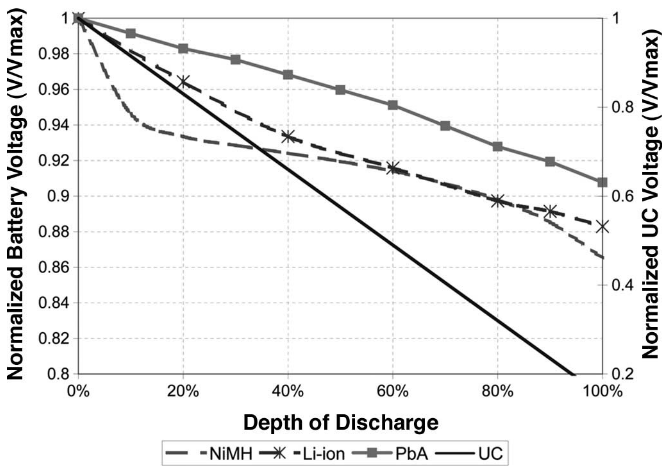

Fig. 5. Normalized open circuit voltage change (Voc/Vmax) for various battery chemistries and typical UC.

is achieved by having a high surface area and high permittivity dielectric. These design parameters lead to a low-voltage withstand capability [28]. There are five UC technologies in development:

1) carbon/metal fiber composites;
2) foamed (aerogel) carbon;
3) carbon particulate with a binder;
4) doped conducting polymer films on carbon cloth;
5) mixed metal oxide coatings on metal foil.

Current trends indicate that higher energy densities are achievable with a carbon composite electrode using an organic electrolyte rather than carbon/metal fiber composite electrode devices with an aqueous electrolyte.

UC stores energy physically separating unlike charges. This has a major implication on the properties of UCs such as cycle life, efficiency, energy and power density, and voltage (as a function of SoC). UCs have a long cycle life due to the fact that (ideally) there are no chemical changes on the electrodes in normal operation. Efficiency is superior: it is only a function of the ohmic resistance of the conducting path. Power density is exceptional, since the charges are physically stored on the electrodes. Conversely, energy density is low since the electrons are not bound by chemical reactions. This lack of chemical bonding also implies that the UC can be completely discharged, leading to larger voltage swings as a function of the SoC (Fig. 5).

UCs also have the unique feature that their voltage is directly proportional to their SoC. The voltage of a UC under a constant current load can be calculated as

$$V_{(t=T)} = V_{(t=0)} - i \cdot \frac{T}{C_{\mathrm{TOT}}} - i \cdot R_{\mathrm{TOT}} \tag{4}$$

where the second term on the right side of (4) is the effect of the change in SoC, and the last term is the effect of the internal resistance.

One of the keys to UCs for vehicle applications is the development of interface electronics that allow the UCs to operate throughout their variable voltage range. There is also research regarding increasing the surface area of the electrodes to further improve energy storage capability. Finally, researchers are making efforts to combine the properties of a capacitor and a battery into one device [29].

V. FCs

Proton exchange membrane FCs have the potential to fundamentally change the automotive industry by fully displacing ICEs as the primary power source. FCs are powered by hydrogen, which could be produced remotely as a part of the hydrogen economy [30]. Currently, however, there are major hurdles to the commercial introduction of FCVs, with the most important being the price and durability of the system. FCs currently cost five times more than ICEs after considering economies of scale. The major cost contributors are the membrane, the electrocatalyst (due to the platinum content), and the bipolar plates. The issue of durability is exemplified when the environment and the mode of operation of the ICE are considered. FC would be required to operate over a wide temperature and humidity range, as well as an extensive range of operating points, all of which have a detrimental effect on the catalyst layers and cause tears or pin-holes and membrane failure. Finally, the on-board storage of hydrogen is an issue due its relatively low energy density (2.6 kWh/L for liquid hydrogen compared to 6 kWh/L for petrol), which requires large storage tanks for the target 300-mi range. Research activities are in progress to address all of the issues mentioned. Another approach to reduce costs is to develop hydrocarbon membranes, which should be less expensive to manufacture than the current state-of-the-art perfluorinated membranes [19].

VI. FLYWHEELS

The concept of using flywheels to store energy has been implemented with some success [31]. However, the application of this ESS to the automotive industry is novel. A flywheel stores energy in the kinetic form, which can then be transformed into electricity. A flywheel consists of a large rotating disk where the kinetic energy is stored and a motor/generator which is coupled to the flywheel to convert kinetic to electrical energy. The electric motor is used to increase the energy stored in the flywheel, while the generator is used to supply energy to the load. The kinetic energy of a rotating flywheel is derived as

$$E = \frac{1}{2} I \omega^2 \quad \text{and} \quad I = \frac{1}{2} M r^2 \tag{5}$$

where E is the kinetic energy stored in the flywheel, I is the moment of inertia, ω is the rotational speed of the flywheel rotor, r is the radius of the rotor, and M is the mass of the rotor. Based on (5), the energy storage capability of flywheels can be improved either by increasing the moment of inertia of the flywheel, or by increasing rotational velocities. Higher rotational speed flywheels seem more attractive for automotive applications due to the smaller size and the fact that the stored energy increases as the square of its rotational speed [see (5)]. However, these systems need to be operated at a partial vacuum

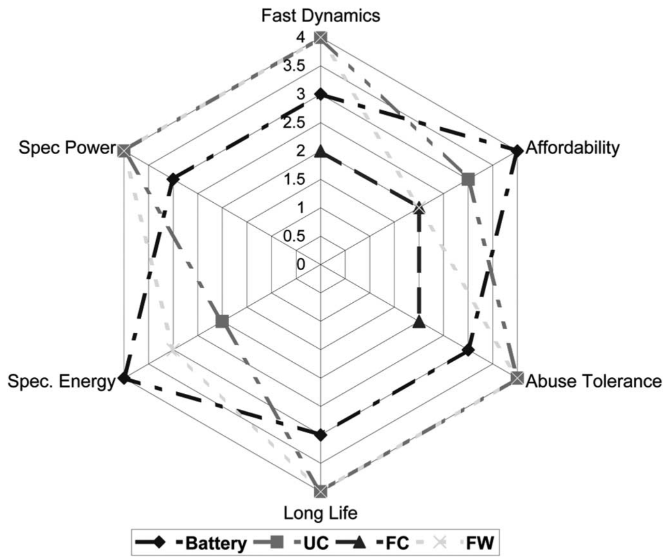

Fig. 6. Comparison of attributes of energy storage technologies for the purpose of source hybridization.

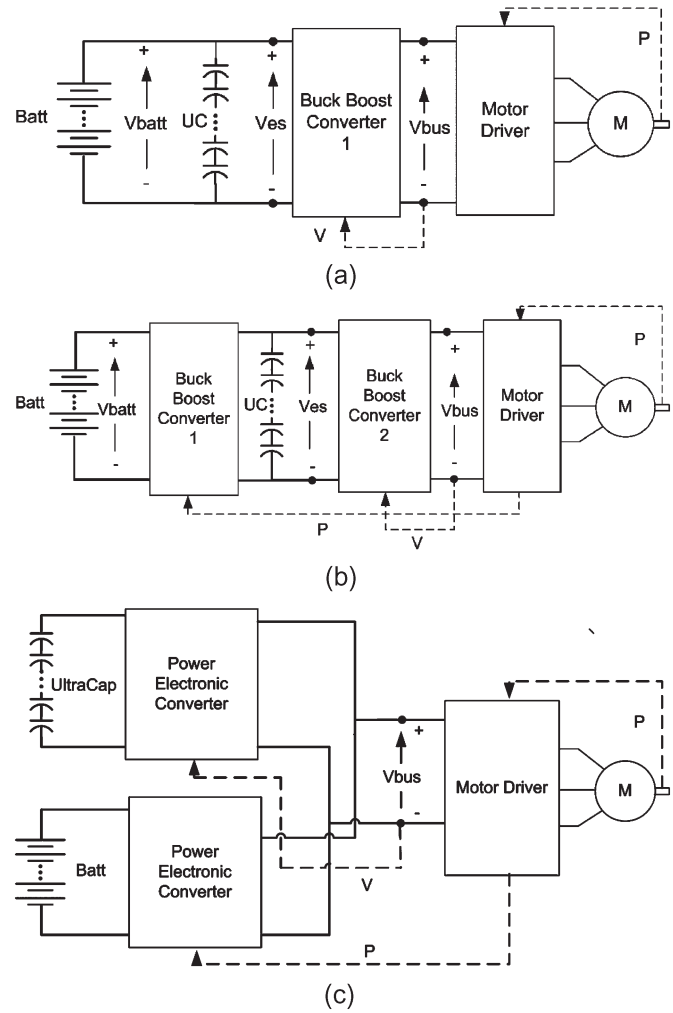

Fig. 7. Topology of the (a) passive parallel connection, (b) bidirectional dc/dc converter, and (c) two-input bidirectional dc/dc converter.

to ensure acceptable losses due to windage. Another source of losses is the bearings. The use of magnetic noncontact bearings [32] has been investigated to mitigate this problem.

As with other energy sources, safety is a major concern when using flywheels. To address safety, containment vessels are used in case the rotor fails mechanically, the flywheel is designed not to fail by flying apart, and the dynamic behavior of the flywheel is monitored.

A flywheel battery has a long life, is free from depth-of-discharge effects, and can accept and deliver large amounts of energy in a very short time (limited by the size of the electric machine). Because of the current cost of flywheels, they are initially being considered for large vehicles where the battery costs are inherently high [33].

VII. Hybrid Power Sources

As previously outlined, there is a tradeoff among energy, power, cost, and life cycle when choosing an ESS for automotive applications. A kind of superdevice can be constructed by combining power sources which have complementary characteristics [34], [35]. Fig. 6 shows that combining batteries and UCs leads to a superior system. These hybrid devices come in many variations, but all share a common trait of combining high specific power devices (fast response) and high energy devices (usually slow response). An example would be to combine the slow dynamics of the FCs, with either batteries or more likely with UCs. Another example would be to combine batteries (relatively slow responding) with UCs (high power, fast response) to improve the life and performance of the system. In this investigation, we focus on a battery/UC hybrid power source.

As shown in Fig. 4, there are many potential methods of pairing a battery and UC. Researchers [36], [37] have considered a direct parallel connection of the two sources [Fig. 7(a)]. This setup keeps the same voltage over both sources, which in turn limits the power delivered from the UC.

Alternatively, a bidirectional dc/dc converter placed between the batteries and the UCs may be used [34], [36] [Fig. 7(b)]. Buck-boost 1 controls the current output of the battery, while the UC supplies the remaining power requirement to the load. This system allows decoupling of the battery and UC voltages. However, there is a large voltage swing on the input to Buck-Boost 2, which reduces efficiency due to larger IR losses at low UC voltages.

Finally, some researchers [36], [38], [39] have looked at using a two-input bidirectional dc/dc converter [Fig. 7(c)]. This gives the highest flexibility and provides the same functionality as the bidirectional dc/dc converter. The two-input bidirectional converter topology is superior from both a stability and efficiency point of view due to the decoupling of the power supplying paths. The stability is also improved since a failure of one source still allows the operation of the other.

VIII. Conclusion

Power electronics have revolutionized motor drives, bringing within the realm of possibility electric drive-trains with extremely high performance. The motors themselves have been improved, offering higher reliability and better performance with reduced cost. Unfortunately, the weak link in the electric drivetrain development chain remains—energy storage. There are some advancements in energy storage device development which offer good promise in terms of energy density and power density, but none has the desired combination of all the following features: fast charging/discharging (high power density), large storage capacity (high energy density), low cost, and long life.

Since no existing device is able to achieve all of the requirements of various vehicular applications, the concept of combining devices to obtain their best traits is also considered. The notion of hybrid power sources is introduced, and the various topologies are presented.

This paper also briefly discusses the possibility of FC technology replacing the ICE. It was shown that there are still many issues with the FC technology. In addition, vehicles utilizing the current FC technology will use many of the components developed for electric vehicles. Of most importance is the need for an energy storage unit which will limit stresses on the FC.

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