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Energy storage devices for future hybrid electric vehicles

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Abstract

Powertrain hybridization as well as electrical energy management are imposing new requirements on electrical storage systems in vehicles. This paper characterizes the associated vehicle attributes and, in particular, the various levels of hybrids. New requirements for the electrical storage system are derived, including: shallow-cycle life, high dynamic charge acceptance particularly for regenerative braking and robust service life in sustained partial-state-of-charge usage. Lead/acid, either with liquid or absorptive glass-fibre mat electrolyte, is expected to remain the predominant battery technology for 14 V systems, including micro-hybrids, and with a cost-effective battery monitoring system for demanding applications. Advanced AGM batteries may be considered for mild or even medium hybrids once they have proven robustness under real-world conditions, particularly with respect to cycle life at partial-states-of-charge and dynamic charge acceptance. For the foreseeable future, NiMH and Li-ion are the dominating current and potential battery technologies for higher-functionality HEVs. Li-ion, currently at development and demonstration stages, offers attractive opportunities for improvements in performance and cost. Supercapacitors may be considered for pulse power applications. Aside from cell technologies, attention to the issue of system integration of the battery into the powertrain and vehicle is growing. Opportunities and challenges for potential "battery pack" system suppliers are discussed.

Keywords: Hybrid electric vehicles (HEV); Micro-hybrid; Energy management; Batteries; Supercapacitors

1. Introduction

Requirements for automotive batteries have been increasing significantly for a number of years, particularly due to the integration of more and larger loads into vehicle electrical systems. In addition, fuel saving measures are being considered that actively utilize the battery. On the one hand, these are energy management strategies that decouple electric generation and load operation during key-on; at least partly. The battery is used as a buffer, and continuous overcharge is avoided. On the other hand, such measures involve different levels of powertrain hybridization, including micro, mild/medium, and power-assist/full hybrid electric vehicles (HEV). The requirements associated with any of these HEV system configurations necessarily involves a fundamental shift in the nature of the energy storage system requirements away from those traditionally considered for lead/acid SLI battery application usage.

This paper will characterize the novel vehicle attributes that drive battery usage. It will not focus on the "classical" functions of starting/lighting/ignition (SLI) batteries, which impose requirements regarding both high-rate discharge power capability (e.g. cold-cranking current, CCA) and lower-rate capacity [1]. Instead, it will analyze newly emerging requirements that reflect the aforementioned novel battery functions. We will focus on functional requirements rather than on other important constraints, including: packaging, cooling, ventilation, or electric system integration.

2. Vehicle attributes

2.1. Energy management

The expanding functions of the vehicle electric/electronic system call for significant improvements of the power supply system. A couple of years ago, broad introduction of a higher system voltage level, 42 V, initially in a dual-voltage

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14/42 V system, was considered as a viable solution. However, the cost/benefit ratio associated with this type of configuration in systems operating at 42 V or less turned out to be too low for widespread implementation. Furthermore, the electric propulsion that can be generated at this voltage level is generally considered too low to make mild-hybrid electric vehicles attractive. At the same time, several hardware components for the conventional 14 V system experienced significant technological progress. For example, enhanced 14 V clawpole (Lundell) alternators were developed that can continuously generate an electric power output of 3 kW or more. AGM batteries demonstrated at least three-fold longer shallow-cycle life, compared to conventional SLI batteries. Finally, the introduction of high-level energy management control strategies can ensure system robustness and optimal energy efficiency and thus help stretch the boundaries of the 14 V system.

Energy management functions can be separated into two groups:

- Power Supply Management (PSM): Control of the on-board electric generation, i.e. control of the alternator setpoint in conventional electrical systems, aiming at optimizing all of the following: electrical function availability, battery life, vehicle performance (e.g. reduced alternator load when maximum acceleration is demanded), or fuel consumption (e.g. reduce alternator output at idle to allow for lower idle speed). Whereas many of these functions can be considered state-of-the-art in modern voltage regulation, particularly the latter has garnered growing attention recently. Electric generation contributes significantly to fuel consumption, at least in real-world conditions. An average alternator output of 1 kW involves as much as 1–1.4 l gasoline fuel consumption per 100 km, depending on vehicle parameters and driving conditions. Decoupling the electric generation from the loads' demands can significantly reduce this specific fuel consumption contribution by optimizing the system efficiency of engine and alternator at any point in time. This will introduce supply voltage fluctuations into the electrical system and systematically exploit the battery as a short-term energy buffer. Significantly more advanced strategies of PSM are of course needed for HEVs, where electric generation plays a more vital role.
- Power Distribution Management (PDM) is used to schedule the allocation of available power and energy to electric loads on a subsystem or component level. Effectively, it must ensure the controlled function delivery of individual electric features by prioritization. Whenever a power deficiency occurs, the PDM algorithm aims at ensuring rail voltage stability, charge balance and robustness, as well as minimizing battery charge throughput in the case of peak loads. Depending on the definition of electric feature priorities, a PDM strategy can dictate a temporary functional degradation under appropriate conditions. Here, a careful balancing of priorities is required, especially for functions that are directly perceivable by the customer. Advanced PDM algorithms will schedule electric feature functionalities dynamically rather than statically.

Electric energy management actively uses the energy storage system (battery, supercapacitor, etc.) and hence relies on precise status information about this device. A battery monitoring system (BMS) has to deliver these essential inputs to the energy management control system.

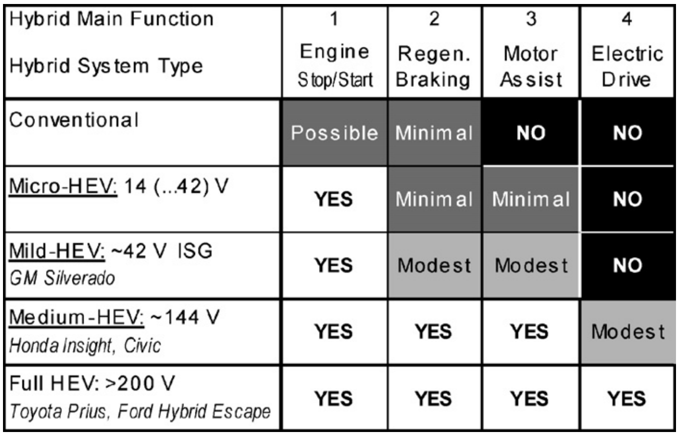
2.2. *Powertrain hybridization*

In recent years, a number of new hybrid electric vehicle propulsion systems for passenger cars and light trucks have been developed and brought to the market by automotive manufacturers. By adding an electromechanical component to the driveline, improvements in propulsion efficiency and reduced exhaust gas emissions could be shown. Different levels of hybridization can be distinguished, implementing the following hybrid functions to different extents, cf. Fig. 1 and Table 1: engine stop/start operation, regenerative braking, modification of engine operating points and various levels of hybrid electric propulsion assist. Fig. 2 shows Ford examples, a Micro-HEV technology demonstrator and a full hybrid in series production.

The lowest level of hybridization, the *Micro-HEV*, combines automatic engine stop/start operation with regenerative braking. Several electrical drive systems can deliver the stop/start function, e.g. an enhanced starter motor or an integrated starter generator (ISG), either belt-driven (B-ISG) or crankshaft-mounted (C-ISG). The benefit of regenerative braking depends on the power level of the electromechanical component. For Micro-HEVs, with typical generator capacity in the range of 2–4 kW and corresponding conventional 12 V battery technology, the limited maximum torque minimizes the need for modifications of the brake system. Fuel consumption and CO_2 emissions can be reduced by 1.5–4%, depending on vehicle, drivetrain, and driving conditions [2].

At higher voltage levels ($\geq$42 V), limited electric propulsion assist becomes possible, and here larger B-ISG and C-ISG systems with hybrid electric propulsion functionality are known. *Mild-HEVs* offer propulsion assist at lower engine speeds only, whereas *Medium-HEVs* can support the engine at higher engine speeds, too. The higher electromechanical power level also enables higher fuel saving benefits from regenerative braking. As

Table 1
Hybrid types and functionalities



Hybrid Main Function	1	2	3	4
Hybrid System Type	Engine Stop/Start	Regen. Braking	Motor Assist	Electric Drive
Conventional	Possible	Minimal	NO	NO
Micro-HEV: 14 (...42) V	YES	Minimal	Minimal	NO
Mild-HEV: ~42 V ISG *GM Silverado*	YES	Modest	Modest	NO
Medium-HEV: ~144 V *Honda Insight, Civic*	YES	YES	YES	Modest
Full HEV: >200 V *Toyota Prius, Ford Hybrid Escape*	YES	YES	YES	YES

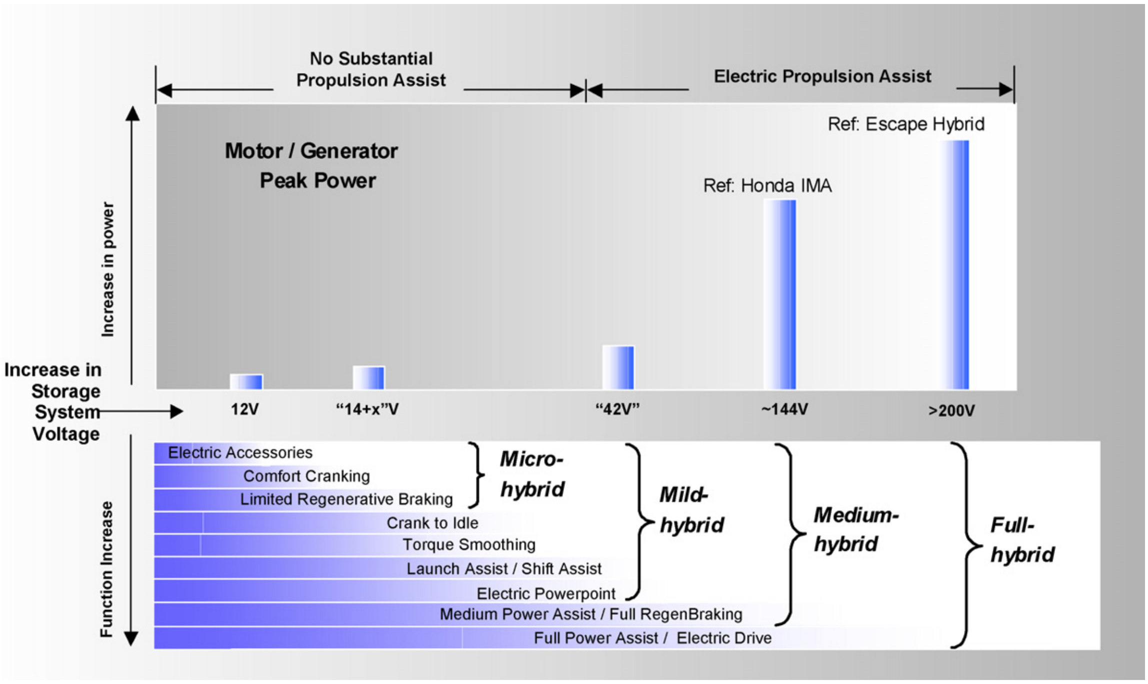


Fig. 1. Hybrid classification based on incremental powertrain functionality.

a consequence, the energy storage device of mild- and medium-HEVs will see a strong increase in energy throughput, necessitating implementation of more advanced technologies than conventional flooded lead/acid battery technology. Additional mild/medium HEV features can include engine torque smoothing or shift assist. As the generator is more powerful than with the Micro-HEVs, 110 V or 220 V ac power outlets are feasible.

Full or *Power-assist HEVs* offer strong electric propulsion assistance and also limited electric-only range. Electric drive and battery typically operate at high voltages above 200 V. For example, the Ford Escape hybrid combines an efficient 2.3 l 16 V I4 Atkinson cycle engine with a 70 kW permanent magnet traction motor and 45 kW generator to operate as an electric continuously variable transmission. Reaching SULEV and AT-PZEV emission levels, this Full-HEV offers world-class versatility to the customer and is an important product in the growing HEV market in North America. Yielding V6-like performance with a four-cylinder engine, it is marketed as the first no-compromise Full-Hybrid SUV.

Plug-In HEVs are attracting increasing interest in North America. From the powertrain perspective of Table 1, they form a subset of the full hybrids that is characterized by the feature that their batteries can theoretically be recharged from the typical residential high voltage ac power grid. This imposes large energy storage demands on the battery, which are not met by typical state-of-the-art HEV batteries. Additionally, significant enhancements beyond typical full HEV powertrain configurations would be required in order to properly handle the increased thermal management system loading and other factors associated with Plug-In HEV usage.

2.3. Market drivers for HEVs

There is a clear market pull for HEVs in the United States. The early adopters are environmentally aware and/or tech-savvy customers who are prepared to pay a premium for this evolving technology. Over the next decade, this market is expected to grow, and relative vehicle costs to fall.

The Ford Escape hybrid is in the third year of US production, with the Mercury Mariner hybrid following closely behind in its second year of production. The Mazda tribute hybrid is to be launched in 2007, with the Ford Fusion hybrid and Mercury Milan hybrid to follow in 2008. A third-generation hybrid system has been under development and will be used in a vari-

Fig. 2. Ford Escape hybrid electric vehicle, 2005 North American truck of the year (left), Ford Fiesta micro-hybrid technology demonstrator (right).

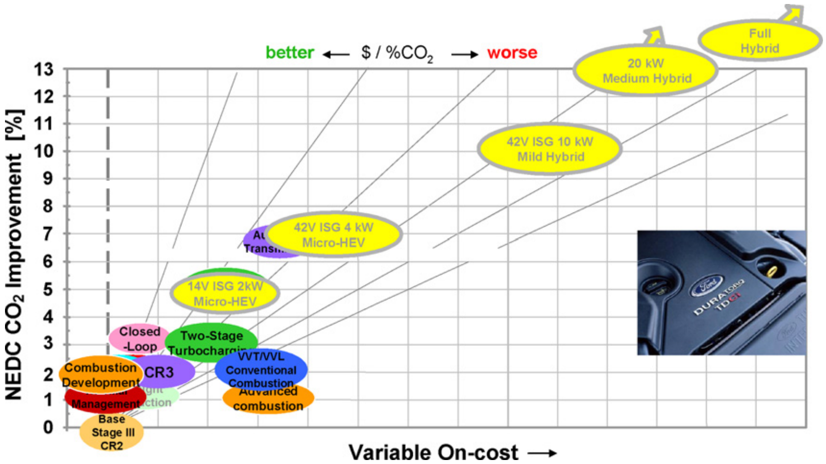


Fig. 3. Cost/benefit trade-off for various CO_2 reducing technologies for use in automobiles (schematic representation for the example of a compact car with diesel engine as baseline).

ety of Ford global vehicles going forward. Ongoing research projects include the development of lithium-ion battery-powered hybrids.

For Europe, the HEV market is also forecasted to grow. However, the drivers as well as the initial situation are different from those in either North America or Asia, and so too will be the European hybrids.

- Compromise of high-speed "Autobahn" performance is generally not accepted in European core markets, but an HEV's high-speed performance is determined almost exclusively by the internal combustion engine. This limits the ratio of installed electric to mechanical propulsion power. If the engine is going to be downsized in a European hybrid, this should be compensated for by measures like advanced turbocharging.
- The wide market penetration with diesels as well as the generally low fuel consumption of modern European vehicles call for careful justification of every HEV business case. Full hybrids with diesel engines would certainly achieve world-leading fuel economy, but at an even higher total powertrain cost than gasoline hybrids.
- Hybridization competes with other technology options that can reduce vehicle CO_2 emissions, as illustrated in Fig. 3.
- Legislative and voluntary political actions in Europe call for a reduction of CO_2 emissions of a manufacturer's vehicle fleet, rather than for iconic niche products. Micro-hybrids offer, at lowest absolute fuel or CO_2 savings, still the best cost/benefit ratio among all hybrid concepts (Fig. 3). If applied in large volumes, they may offer the best leverage for fleet CO_2 emissions reduction within the European market.

3. Energy storage systems requirements

3.1. Robustness and reliability

Within the last few decades the automobile industry has undergone a revolution in overall vehicle reliability. With the large number of components and the number of potential failure modes, it has become necessary for a component to provide six-sigma (<12 ppm failures) reliability over its operational life (now typically assumed to be 10 years or 240,000 km), in order to satisfy customer expectations. Current production SLI batteries do not perform to this standard, but are seen as a wear-out component that requires replacement several times during vehicle life. New electric functions like stop/start or electrified brakes will create more serious consequences of an unexpected battery failure, though. Hence, a dependable indicator for required battery replacement (as exists in the case of fuel, oil, or brake pads) is essential in such applications, cf. Section 3.5. Not only can the average service life of the battery be extended by avoiding abusive conditions, but early and unexpected battery failures also should be largely eliminated.

Another aspect of battery reliability should not be overlooked [3]: the reliability of a battery is basically the product of its cells' reliabilities. Assuming constant cell reliability, the battery reliability depends with a power law on the cell number. That means that traction batteries with higher voltage have to meet much more stringent reliability targets at the cell level in order to just maintain battery reliability at levels similar to those observed for typical 12 V automotive batteries. As a consequence, battery-manufacturing processes require improved process controls in order to meet the higher process capability index (Cpk) necessary for these higher reliability levels.

3.2. Shallow-cycle life

Cyclic SOC usage has historically been a dominating battery failure mode for SLI batteries in heavy-duty applications like taxis. Recently, two factors have tended to increase the cyclic wear rate of SLI batteries in normal passenger cars, particularly in the premium segment:

- An increasing number of on-board electronic control units (ECU), typically more than 60 in recent luxury cars, draw current during key-off, which may be increased as a consequence of part defects, software faults, or unexpected interactions. As a consequence, battery depletion rates during key-off can be excessive.

- The power consumption of the comfort-related loads is not continuously matched by the alternator output. For example, during idle, the battery may have to supply a significant fraction of the total load current.

In both cases, the discharge/charge cycles are typically very shallow ($\ll$10% Depth-of-Discharge, DOD), but the accumulated Ah turnover with time may be significant. As a consequence, some carmakers have adopted requirements towards shallow-cycle life into their specifications for normal automotive batteries. Flooded SLI batteries are then typically required to withstand shallow cycles with an accumulated Ah turnover equivalent to 150 times the nominal capacity before the end of their service life. The shallow-cycle life requirement for AGM batteries replacing SLI batteries is typically three times higher.

Energy management or (micro-) hybridization may add significantly to cyclic battery use. For a stop/start vehicle, a typical cycle may consist of supplying 45 A loads for 20 s, re-cranking the engine within 0.4 s with an average current of 450 A, followed by the application of significant sustained recharge rates during subsequent driving. The turnover per stop/start cycle would then equate to 0.3 Ah. Assuming 2 stops km^{-1}, the above-mentioned shallow-cycle life of 150 capacity turnovers, and a battery capacity of 50 Ah, we should expect a flooded SLI battery to fail after only $50 \times 150/0.3/2 = 12{,}500$ km. This example illustrates that cyclic wear tends to become the dominating battery failure mode in such applications.

For mild to full hybrid batteries, throughput demands on the battery are of course higher. The traction battery is a separate device in addition to the 12 V SLI battery, which – depending on the hybrid concept – may or may not have to crank the cold and/or warm engine. As a preliminary standard for battery performance parameters, service life requirements, and test methods, the proposals made by the USCAR/US Department of Energy initiative FreedomCar tend to be generally adopted in Europe as well. Table 2 shows the FreedomCar goals defined for two size classes of high-voltage power-assist hybrids, including target costs, which have to be understood in conjunction with the corresponding test manual [6]. Table 3 shows FreedomCar performance, life, and cost targets for three classes of 42 V hybrid batteries, ranging from a pure stop/start system to a medium hybrid (here called P-HEV). The corresponding test methods are defined in [7].

It is useful to compare the battery energy throughput requirements for the above battery classes. Throughput will always be counted in the discharge direction only. It turns out that the battery throughput per kilometer for a full hybrid can be 20–30 times larger than that for the stop/start function alone.

- 12 V micro-hybrid: 2 cycles km^{-1}, 0.3 Ah cycle^{-1}, 11 V average voltage: 6.6 Wh km^{-1}.
- 42 V “Start–Stop”: The ZPA profile [6] assumes 2 kW electric loads during engine-off rather than $40\text{ A} \times 11\text{ V} = 440$ W in the 12 V case, and in addition 2 s 6 kW launch-assist at every warm-start. Accumulated throughput over ZPA profile: 45 Wh mile^{-1} = 28 Wh km^{-1}.
- 42 V “M-HEV”: The PPA profile [6], in comparison to ZPA, assumes 13 kW launch-assist power rather than 6 kW, still for 2 s per start. Accumulated throughput over PPA profile: 57 Wh mile^{-1} = 35 Wh km^{-1}.
- 42 V “P-HEV”: The FPA profile [6], in comparison to PPA, assumes 14.4 kW launch-assist power for 5 s per start. Accumulated throughput over FPA profile: 95 Wh mile^{-1} = 59 Wh km^{-1}.
- High-Voltage “Minimum Power-assist” (25 kW): The cycle life test profile in [7] represents one stop/start/drive cycle with 25 Wh throughput. Assuming 3 cycles mile^{-1}, we get 75 Wh mile^{-1} = 47 Wh km^{-1}. Urban driving data from real vehicles, however, indicate that the true electrical energy consumption may be a factor of two higher.
- High-Voltage “Maximum Power-assist” (40 kW): Assuming 3 cycles mile^{-1} with 50 Wh throughput each [7], we get 150 Wh mile^{-1} = 93 Wh km^{-1}. Actual vehicle data indicate again that two times larger throughput may best represent reality as well.

Table 2
FreedomCAR energy storage system performance goals for power-assist hybrid electric vehicles (November 2002) [6]

Characteristics	Power-assist (minimum)	Power-assist (maximum)
Pulse discharge power (10 s) (kW)	25	40
Peak regenerative pulse power (10 s) (kW)	20 (55 Wh pulse)	35 (97 Wh pulse)
Total available energy (over DOD range where power goals are met) (kWh)	0.3 (at C1/1rate)	0.5 (at C1/1rate)
Minimum round-trip energy efficiency (%)	90 (25 Wh cycle)	90 (50 Wh cycle)
Cold cranking power at −30 °C (three 2 s pulses, 10 s rests between) (kW)	5	7
Cycle life for specified SOC increments (cycles)	300,000 à 25 Wh (7.5 MWh)	300,000 à 50 Wh (15 MWh)
Calendar life (years)	15	15
Maximum weight (kg)	40	60
Maximum volume (l)	32	45
Operating voltage limits (V_{dc})	max $\leq$ 400, min $\geq$ ($0.55V_{max}$)	max $\leq$ 400, min $\geq$ ($0.55V_{max}$)
Maximum allowable self-discharge rate (Wh day^{-1})	50	50
Temperature range (°C)		
Equipment operation	−30 to +52	−30 to +52
Equipment survival	−46 to +66	−46 to +66
Production price at 100,000 units year^{-1} (US$)	500	800

Table 3
FreedomCAR 42 V energy storage system end of life performance goals (August 2002), selected items [7]

Characteristics	Start–stop	M-HEV	P-HEV
Discharge pulse power (kW)	6 (for 2 s)	13 (for 2 s)	18 (for 10 s)
Regenerative pulse power (kW)	N/A	8 (for 2 s)	18 (for 2 s)
Engine-off accessory load (kW)	3 (for 5 min)	3 (for 5 min)	3 (for 5 min)
Available energy (at 3 kW) (Wh)	250	300	700
Energy efficiency on load profile (%)	90	90	90
Cycle life, miles and profiles (engine starts)	150,000 (450,000)	150,000 (450,000)	150,000 (450,000)
Cycle life and efficiency load profile	Zero power-assist (ZPA)	Partial power-assist (PPA)	Full power-assist (FPA)
Cold cranking power at −30 °C on cold-start profile (kW)	8 (21 V min)	8 (21 V min)	8 (21 V min)
Calendar life (years)	15	15	15
Maximum system weight (kg)	10	25	35
Maximum system volume (l)	9	20	28
Maximum operating voltage (V_{dc})	To be specified by battery supplier	To be specified by battery supplier	To be specified by battery supplier
Maximum open circuit voltage (V_{dc})	48 (after 1 s)	48 (after 1 s)	48 (after 1 s)
Minimum operating voltage (V_{dc})	27	27	27
Self-discharge (Wh day^{-1})	<20	<20	<20
Temperature range (°C)			
Operating	−30 to +52	−30 to +52	−30 to +52
Survival	−46 to +66	−46 to +66	−46 to +66
Selling price (at 100,000 year^{-1}) (US$ system^{-1})	150	260	360

3.3. Service life in partial-state-of-charge (PSOC) operation

Regenerative braking is standard for battery-electric and hybrid-electric vehicles. The electric drive is operated in its generator mode during vehicle deceleration, charging the battery. For this reason, batteries in hybrid-electric vehicles are operated at partial-state-of-charge, in order to provide significant pulse-charge acceptance. In contrast, classical 12 V automotive batteries are generally continuously charged at alternator output voltage (to high SOC's) and thus operated at high SOC where their pulse-charge acceptance is negligible. Various kinds of active power-supply management configurations in 14 V systems will require the battery to be routinely operated at PSOC like hybrid traction batteries. Typical automotive lead/acid battery designs are not optimized for this condition. A significant fraction of the battery capacity might then be lost early during service life due to sulphation [4], particularly in the lower part of the negative plates. At higher discharge and charge rates, as they would be typically applied to traction batteries in Mild-HEVs, lead/acid (AGM) batteries tend to show equally detrimental sulphation in the form of other patterns of unequal distribution across the negative plates [5]. Ensuring robust PSOC operation is, hence, a key challenge for the application of lead/acid batteries in advanced applications, and requires careful joint optimization of battery design and operating strategy of the battery system and vehicle.

With impacts somewhat similar to those of sulphation in lead–acid battery systems, memory effects in NiMH systems can significantly reduce usable power in HEV applications where the SOC window of operation is necessarily significantly smaller than the full 100% charge/discharge SOC window capability of the battery. In the case of NiMH systems, however, these effects are to a large degree much more easily and significantly reversible during actual vehicle operation in HEV applications in relative comparison with lead–acid battery sulphation effects. Still, the optimal usage of NiMH battery systems in HEV applications again requires careful joint optimization of battery design and operating strategies, in consideration of memory effect impacts.

3.4. Dynamic charge acceptance

Charge acceptance, particularly at low temperatures, is a battery requirement that determines the charge balance of the power supply system. The more the battery has to contribute to supplying electrical loads, the more essential it becomes that it can be recharged quickly. As a consequence, more attention has been paid to charge acceptance in vehicles with an increasing content of power-hungry electric loads and/or with a PSM that makes extended use of the battery as a buffer. As opposed to recovery from deep discharge in traditional non-HEV applications, advanced HEV applications will require good charge acceptance in a dynamic discharge/charge micro-cycling operation. We call this feature dynamic charge acceptance (DCA). In the particular case of lead/acid batteries, DCA capability is extremely sensitive to the short-term previous charge/discharge exposure of the battery. Following a preceding high-rate discharge, DCA may be several times higher than that following a charging period. DCA test procedures are defined in common HEV battery specifications [6–8], but these procedures involve high-rate charge and/or discharge steps that would significantly bias the results for lead/acid batteries.

The following case study demonstrates the effect of DCA on the fuel economy or CO_2 benefits of a hybridized vehicle. We simulated a hybrid electric vehicle based on a compact car. Its powertrain consists of a diesel engine and an automated manual transmission, in which the electric machine is mounted on the input shaft of the gearbox. The traction battery is located in the vehicle's trunk. With this E-motor arrangement, it is possible to realise engine stop/starts at vehicle standstill and during driving, high power brake energy recuperation with decoupled engine, electric motor assist during accelerations as well as low speed electric driving.

As reference simulation, the vehicle was set up as full hybrid, employing a NiMH or Li-ion battery with a maximum discharge power around 20 kW. The fuel economy benefit was used as the reference, i.e. normalised as 100%. The baseline battery was then replaced in simulations with an advanced AGM battery that would be available at significantly lower cost. We chose a 6 V 24 Ah (C_{20}) spiral-wound AGM module that had been developed in the framework of the Advanced Lead/Acid Battery Consortium [9]. A 60 V battery would be built up from 10 of these modules, weighing 4.7 kg each. It was assumed that due to lead/acid specific throughput and DCA limitations the vehicle should then be operated as a medium hybrid only, effectively limiting the battery discharge power to about 10 kW. The operating strategy was optimized for fuel economy under the boundary condition that non-CO_2 emissions like NO_x were not penalized.

Fig. 4 shows the results for simulated fuel economy benefits in the European homologation drive cycle NEDC. In the first column the DCA is assumed as it was measured according to the (slightly modified) EUCAR test procedure [8] that involves high-rate discharge steps for SOC conditioning prior to the power test pulses: 6 A Ah^{-1} over the first 5 s of each deceleration event. By absence of maximum power data for >5 charge pulses, we assumed a more conservative value of 1 A Ah^{-1} from the 5th second onwards for longer decelerations. Note that 6 A Ah^{-1} for this 24 Ah battery, when charged with 72 V, corresponds to ca. 10 kW. The fuel economy benefit for this medium hybrid car amounts to 77% of that determined for the baseline full hybrid, which might be a very attractive proposal, given the projected large cost difference. However, under more realistic operating conditions with only shallow cycling within a narrow SOC window, the same AGM battery will show significantly lower DCA. We performed simulations for three lower DCA levels, no longer differentiating between the first 5 s and the rest of the charge pulse. The fuel economy benefit varies almost linearly with DCA in a range up to 2 A Ah^{-1}, with an offset essentially defined by the stop/start benefit alone.

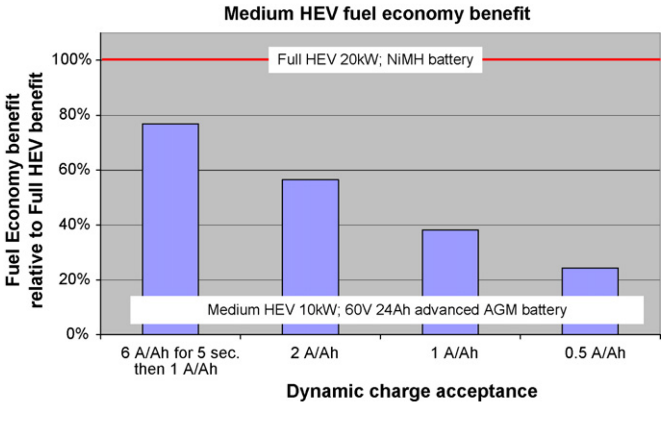


Fig. 4. Fuel economy benefit of a simulated medium HEV as a function of the dynamic charge acceptance of the traction battery. Assumptions see Section 3.4.

Strongly simplifying, one could state that using the available high discharge power of an advanced AGM battery is energy efficient only if a comparable level of DCA is available. To avoid large amounts of battery energy to be charged and stored in normal generating mode, i.e. at the expense of fuel, it is necessary to limit the amount of discharge energy, i.e. power and duration of propulsion boost, to a level comparable with the total regenerative energy. Since the cumulative duration of all regenerative braking events is constant for a given drive cycle, the maximum charge power, i.e. dynamic charge acceptance, is one of the important factors for the overall fuel economy benefit, if not the most important one.

3.5. *Battery management*

Traditionally, automotive batteries have been looked at as passive standalone components. Energy management and powertrain hybridization require precise monitoring and active control of the battery. Battery monitoring means continuously calculating application-relevant battery state quantities based on sensed physical quantities, typically current, voltage, and temperature. Configurations of this type have been common for traction batteries for some time, but have more recently been introduced for demanding 12 V SLI battery applications as well. Examples for active control measures are state-of-charge (SOC) control by discharge/charge management and thermal management that maintains upper and lower temperature thresholds and limits temperature gradients within the battery. Together with subsystems involving elements such as sensors, monitoring algorithms, and cooling fans, the battery then forms an energy storage system that interacts with the vehicle in a complex manner.

4. Technologies

4.1. *Electrochemical storage systems*

Improved flooded SLI batteries: Due to their unrivalled low cost, they will continue serving as the primary energy storage system for automotive applications where the charge (Ah) turnover is not critical. In order to meet the above micro-hybrid requirements, the battery would need significant improvements in shallow-cycle life and dynamic charge acceptance. Furthermore, the inherent tendency to build up acid stratification needs to be addressed because it aggravates sulphation during PSOC operation as well as cyclic wear. In addition, battery manufacturers will continue to be faced with strong pressure from carmakers, demanding both improved quality and reduced part cost. The only potential way to resolve these conflicting targets is through the introduction of highly automated, continuous, and defect-free battery manufacturing processes.

Valve-regulated lead/acid (VRLA) batteries have been shown to withstand an Ah turnover at least three times higher than conventional SLI batteries. The AGM versions use a glass-fibre mat that is drenched in electrolyte, using either prismatic or spiral-wound plate geometries. Further improvement can be expected from ongoing R&D work optimizing AGM technology for high-rate partial state-of-charge (HRPSOC) operation [10]. Many of these technology developments have been originally devoted to 42 V mild-hybrid vehicles, but can also yield significantly improved 12 V batteries, e.g. for engine stop/start applications and regenerative braking [11]. On the other hand, the availability of high-performance AGM batteries might lead to re-opening the discussion about the use of lead/acid storage systems in mild-hybrid electric vehicles [12].

Advanced batteries and supercapacitors: Life dependence on cyclic energy throughput and relatively isolated success within industry in addressing PSOC life issues are the most important constraints that exclude lead/acid batteries, despite their low cost, from some applications, particularly full HEVs. Among the electrochemical alternatives, the following are most promising:

- Nickel/metal-hydride (NiMH) batteries offer significantly higher shallow-cycle life and energy density, compared to AGM batteries. Technological issues are primarily their limitations at extreme temperatures (cold cranking, hot charge acceptance). The potential for further cost reduction is limited.
- High-power lithium-ion (Li-ion) batteries are currently experiencing rapid technological progress, which has already brought down their specific cost per Wh into the range of NiMH batteries. Some areas which may require further work include greater industry-wide demonstration of HEV cycle and calendar life capability, as well as abuse tolerance and related pack system control strategies and configurations.
- Electrolytic double-layer capacitors (supercapacitors) have extremely long shallow-cycle life. Their power density is high and declines only slowly at low temperature. Their energy density is inferior to batteries, and their voltage sags proportional to SOC. The potential for significant cost reduction is controversial [13]. Technological concerns are related to exposure to high voltage and temperature. The choice of the electrolyte is an open question because acetonitrile decomposition products in the event of device venting are considered toxic in some markets.

NiMH batteries are currently used in all commercially available Full-HEVs. Li-ion batteries are likely to become serious competition for NiMH in these applications. The use of supercapacitors is currently under investigation in several research and demonstration projects. For a 14 V vehicle-electric system, their cost as well as the technological drawbacks will prohibit each of the above systems from completely replacing the lead/acid battery. Only if the relative cost of either of these technologies can be further reduced significantly, might they then potentially complement the lead/acid battery in more widespread implementations of dual-storage systems.

4.2. Battery monitoring and management for 12 V SLI batteries

Traditionally, the operation of automotive lead/acid batteries does not involve feed-back control, but only feed-forward setting the charging voltage setpoint. The recent introduction of low-cost 12 V battery monitoring systems offers the opportunity to fundamentally improve this situation by providing precise information about the battery condition [14–16]. These BMS consist of a sensor that precisely measures current, voltage and temperature of the battery, and an algorithm that determines characteristic information about the battery state and recommended operation (charging voltages and actions like refresh cycles). The BMS outputs should be defined in a way that can be directly evaluated by vehicle-level controllers, utilizing interface concepts like state-of-function (SOF) [17,18] rather than only the traditional state-of-charge and state-of-health (SOH) indicators.

4.3. Battery monitoring and management for HEV traction batteries

HEV traction batteries naturally require a more active management system. Components like fuse, contactors, fan control, and a monitoring system are seen as integral components of the HEV battery system, as well as mounting and other package components. For example, the cooling concept (liquid or air, cabin air or separate isolated thermal system) is important for the performance/cost trade-off of the HEV as a whole, and it is strongly linked with vehicle design, package, and safety. The hybrid powertrain operating strategy needs to take battery condition into account in order to guarantee reliable vehicle operation and battery life.

4.4. Opportunities and challenges for the HEV battery system supplier/integrator

So far, the system integration of traction batteries in commercially available full-hybrid vehicles has been to a large extent within the responsibility of the vehicle manufacturer. This responsibility could in the future be outsourced to a tier-one battery system supplier. For potential HEV battery cell/module suppliers and respective system integrators and suppliers of HEV battery systems, operating as external partners, or as internal partners within the same organization, numerous opportunities and rewards, as well as significant business and engineering challenges exist in entering the production HEV system market. These opportunities and challenges can be outlined as follows:

Opportunities

- HEV applications represent a significant growth segment of the automotive market.
- The cell/module supplier can partially define/limit cell usage and control parameters (in the case of internal partners within the same organization).
- Critical system design trade-offs (mechanical interface, thermal interface, etc.) with respect to the cell/modules can be optimally determined or negotiated.

- HEV system supply may in some cases provide inherent access to opportunities for supply of other electronic component content in a given vehicle OEM's vehicle base.

Challenges

- The absence of significant pre-existing tier 1 OEM experience and related supplier infrastructure can be a significant issue.
- The collective resolution of IP issues between cell supplier, system integrator, vehicle OEM's, and related third-parties may involve significant complications.
- OBDII and/or other system service/emissions diagnostics requirements can represent a significant knowledge prerequisite, even for well-established automotive tier-one suppliers who do not otherwise have experience with emissions-related components.
- Implementation of a high voltage safety infrastructure in the development, engineering, and production environments can involve significant consideration and planning.
- High voltage engineering expertise and design personnel are necessities for HEV battery system design above 42 V.
- Battery system to vehicle system software integration/negotiation can be challenging, even for well-established automotive tier-one suppliers who have experience otherwise with other non-propulsion related component software integration into the vehicle.
- Modelling requirements at the system and cell/module level can be significant and can require the acquisition of sparse available talent within the HEV industry.
- Testing and validation requirements such as EMI/EMC, large component environmental, vibration, and shock testing can represent non-trivial challenges for larger components like full hybrid battery systems.
- Automotive OEM nomenclature can represent a significant initial hurdle for suppliers new to the automotive industry.
- Support of vehicle OEM vehicle development/validation activities can require significant resources beyond the actual battery system development phase.

5. Discussion

Hybrid electric vehicle markets are growing worldwide. As for conventional cars, different market conditions in Europe, America, and Asia will lead to differentiated products. For example, diesel full hybrids can be attractive for Europe. Similarly, lower degrees of hybridization (from micro to medium) offer advantages under European conditions, e.g. uncompromised high-speed performance and better CO_2 fleet reduction leverage.

For the foreseeable future, NiMH and Li-ion are the dominating current and potential battery technologies for higher-functionality HEVs. It is expected that Li-ion battery technology can offer a 40–50% battery weight reduction, a 20–30% battery volume reduction, and some margin of efficiency improvement in comparison with NiMH batteries [19]. Additionally, in the longer term, Li-ion batteries are expected to offer greater opportunities for cost-reduction, and ultimately, a lower relative cost than NiMH battery systems in HEV applications, as illustrated in Fig. 5. Supercapacitors may be considered for applications with low energy, but high power demand, particularly at low temperatures, but cost reduction remains pivotal.

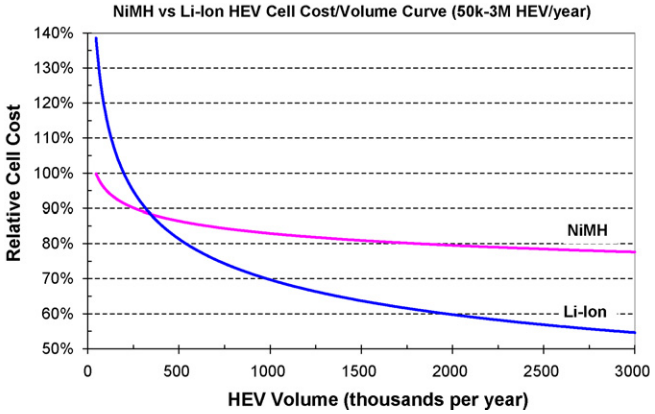


Fig. 5. NiMH and Li-ion HEV cell cost as a function of vehicle production volume [19].

Lead/acid technology, though offering potentially lower total energy storage system cost, suffers from some inherent disadvantages, including higher battery mass for a given application, limited cycle life, vulnerability due to PSOC operation, and limited pulse charge power capability. As far as the energy turnover (cycle life) is concerned, the requirements compiled in this paper for the various levels of HEVs differ by one and a half orders of magnitude. Pulse charge power is inherently limited by lead/acid batteries' DCA, which deserves further research aiming at optimizing both battery designs and operating strategies. High dynamic charge acceptance under real world driving conditions would provide an opportunity to realise fuel economy benefits comparable with NiMH and Li-ion technology in mild to medium hybrid applications. In summary, lead/acid batteries will continue to enter the HEV market in micro-hybrids. The most advanced AGM batteries developed recently exceed the demands of this application already and might be considered for more significant application in mild hybrids, or potentially even in medium hybrids in the longer term.

Aside from new cell technologies, there is a growing awareness of the necessity for a holistic approach to the integration of the energy storage device with the electrical and powertrain controls systems. This requires complex but cost-optimized battery monitoring systems, even for 12 V lead/acid batteries. For dedicated hybrid traction batteries, system integration is naturally more complex and includes, for example, thermal management of the battery pack. This can become the interesting but challenging task for tier-one suppliers.

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