Available online at www.sciencedirect.com

SCIENCE DIRECT®

Journal of Power Sources 144 (2005) 505–512

JOURNAL OF POWER SOURCES

www.elsevier.com/locate/jpowsour

Requirements for future automotive batteries – a snapshot

Eckhard Karden[a,*], Paul Shinn[b], Paul Bostock[c], James Cunningham[c],
Evan Schoultz[d], Daniel Kok[a]

[a] Ford Research Centre Aachen, Süsterfeldstraße 200, D-52066 Aachen, Germany
[b] Ford of Europe, Technical Centre, Laindon, Basildon SS156EE, UK
[c] Jaguar/Land Rover, Coventry Engineering Centre, Whitley, Coventry CV34LF, UK
[d] Volvo Cars, PV, S-40531 Gothenburg, Sweden

Abstract

Introduction of new fuel economy, performance, safety, and comfort features in future automobiles will bring up many new, power-hungry electrical systems. As a consequence, demands on automotive batteries will grow substantially, e.g. regarding reliability, energy throughput (shallow-cycle life), charge acceptance, and high-rate partial state-of-charge (HRPSOC) operation. As higher voltage levels are mostly not an economically feasible alternative for the short term, the existing 14 V electrical system will have to fulfil these new demands, utilizing advanced 12 V energy storage devices. The well-established lead–acid battery technology is expected to keep playing a key role in this application. Compared to traditional starting–lighting–ignition (SLI) batteries, significant technological progress has been achieved or can be expected, which improve both performance and service life. System integration of the storage device into the vehicle will become increasingly important. Battery monitoring systems (BMS) are expected to become a commodity, penetrating the automotive volume market from both highly equipped premium cars and dedicated fuel-economy vehicles (e.g. stop/start). Battery monitoring systems will allow for more aggressive battery operating strategies, at the same time improving the reliability of the power supply system. Where a single lead–acid battery cannot fulfil the increasing demands, dual-storage systems may form a cost-efficient extension. They consist either of two lead–acid batteries or of a lead–acid battery plus another storage device.

Keywords: Automotive battery; Lead–acid battery; AGM battery; Battery monitoring system

1. Introduction

The demand for electric power in automobiles is growing. New electric functions are entering the vehicles, increasing safety or comfort and partly replacing mechanical or hydraulic systems. Furthermore, electrification of the vehicle's main function, propulsion, is an option to reduce the fuel consumption and CO_2 emissions in hybrid-electric vehicles. All these trends are imposing new requirements on the electrochemical energy storage devices used in automobiles [1].

This paper aims at summarizing these trends from a European car manufacturer's perspective. The integration between Jaguar/Land Rover, Volvo Car, and Ford of Europe, all of which are European subsidiaries of Ford Motor Company, is progressing and will yield, among many other harmonization efforts, a common battery specification soon. In a next step, Ford Motor Company is open to further harmonize battery specifications with other car manufacturers, which would allow further increasing the production volumes per battery type. Similarly, a cross-brand approach is taken when introducing 12 V battery monitoring systems (BMS), using a common specification regarding both hardware and software.

The paper will show some "specifically European" trends. So far, full hybrid-electric vehicles are of minor importance in Europe, compared with the Japanese and US markets. On the other hand, fuel economy and hence reduction of CO_2 emissions across the vehicle fleet has high priority. At the same time, customers expect technologically advanced solutions to enhance comfort, safety, and driveability of the vehicles. In

---

[*] Corresponding author. Tel.: +49 241 9421 337
E-mail address: ekarden@ford.com (E. Karden).

0378-7753/$ – see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.jpowsour.2004.11.007

the first instance, these conflicting targets have to be resolved within the framework of the existing 14 V vehicle electric system. Future vehicles require intelligent energy management systems and, last but not least, for improved 12 V energy storage systems. The introduction of a 42 V powernet would help many of the challenges, but is not affordable as a short-term solution for price-sensitive mainstream passenger cars [2].

This paper is organized as follows: Section 2 will summarize the trends in vehicle-level requirements, both related to “classic” electric functions and to powertrain hybridization. Derived from these, Section 3 will highlight foreseeable changes in the battery requirements. Section 4 will discuss the different storage technologies that can contribute to meeting these requirements. The new challenges cannot be met, however, by just changing the electrochemical system. Instead, it will be necessary to develop a system view (Section 5), involving battery monitoring and battery management as well as, in some cases, dual storage devices. A concluding discussion is provided in Section 6.

2. Vehicle-level requirements

2.1. Power supply system

Ford Motor Company is an automotive manufacturer that develops, produces and markets vehicles that comply with customer, legal and corporate requirements. Modern customer demands drive the introduction of new vehicle technologies that offer increasing levels of performance, comfort and safety. This trend is expected to push forward the introduction of more electrified subsystems and components. Typical examples are the introduction of heated and climate-controlled seats, electrically driven charge air compressors (EDC) for improved transient response of the internal combustion engine (ICE) and corresponding vehicle agility, as well as electro and electro-hydraulic power assist steering (EPAS, EHPAS) systems for enhanced vehicle dynamics features. In North America, appliances such as refrigerators, microwaves, and 110 VAC power points are also becoming marketing items.

Typical values for the total vehicle electric content over generator power ratio are in the range of 2–3 today. Future electrical systems must provide energy to advanced electrical features as well. For mid-class vehicles, the high-end vehicle electric content over generator power ratio is expected to double within one or two vehicle generations. This trend will extend the need for the energy storage system to support the electrical system more frequently, under normal driving conditions.

Additionally, the trend for lower engine idle speeds for improved emissions and fuel economy has placed further pressure on the vehicle power supply. This is because the generator available power output is speed-dependent and therefore less power is available at reduced speeds. Thus automotive manufacturers deploy low idle speeds and then take actions to increase above the base idle speed under certain drive or load conditions. These actions can include the use of a fixed idle speed increase when specific vehicle features such as air conditioning are operational, or when the vehicle experiences certain operational conditions, for example when the system voltage falls below a preset value. A more complex approach is to have an adaptive idle strategy where idle speed increases can be made on a reactive or proactive basis, based upon the vehicle electrical loading and the generator operating conditions. Each individual idle speed increase is typically smaller than the fixed increase value but repeatable and additive. This therefore allows the system to continually vary the idle speed in an attempt to balance the electrical system.

Dynamic peak current levels from individual high power features pose a threat to voltage stability and thereby vehicle operation reliability. The generator’s inability to react quickly enough to the sudden demands of transient electrical loads such as electric power steering places further burden on the energy storage system.

2.2. Fuel economy, hybridization

Several European Union member states are expected to introduce CO_2 based tax incentives in the oncoming years, of which the UK company car taxation is an apparent example. Ford Motor Company voluntarily agreed to reduce carbon dioxide (CO_2) fleet average emission levels to 140 g $CO_2\,km^{-1}$ in the year 2008, as established in the ACEA commitment [3]. This corporate requirement is regarded as a strong statement, expressing Ford’s commitment to introduce ecologically friendly transportation solutions.

In Europe, low CO_2 emission transportation is traditionally found in the application of diesel engine technology. Across Europe, the diesel market share within passenger cars has grown from 22% in the mid-1990s to 46.1% in the first quarter 2004, and strong further growth is expected [4]. Additionally, the hybridization of powertrains will play an important role. Per definition, a vehicle with electric propulsion assist is a (mild) hybrid electric vehicle (HEV), even when the customer perceived assist is limited.

- Stop/start function (micro-hybrid, electric power 1–2 kW, up to 5 kW for 42 V systems): as soon as the vehicle has come to a stop during normal operation, e.g. at city traffic lights, the engine is shut down to save the amount of fuel which normally is burned during engine idle. The engine-restart can be achieved by an enhanced conventional starter motor, another dedicated electrical machine that replaces the starter, or an integrated starter-generator (ISG) that replaces the alternator. The mechanical link between an ISG and the powertrain can be via the belt-drive (B-ISG) or the crankshaft (C-ISG). Each mechanical realization has its own pros and cons. For a given target vehicle, the selection will be based primarily on the speed and reliability of the restart, the noise and vibration perceivable by the driver, and cost. Battery usage profiles will be very similar in all cases because they are largely determined by the power consumption of the loads when the engine has been shut down during standstill.

- Mild/medium hybrid powertrains (electric power 10–20 kW): in the traditional voltage range around 14 V, significant electric vehicle propulsion would require unrealistic currents. At higher voltage levels (ca. 42–150 V), a limited form of electric propulsion assist becomes possible, and here larger B-ISG and C-ISG systems with limited HEV functionality are offered. These systems allow for optimization of fuel consumption by shifting the engine operating point with both positive and negative ISG torques.
- Full hybrid powertrains (electric power 30–50 kW): a more revolutionary approach to powertrain electrification is found in high voltage (>200 V) HEVs, of which the Ford Hybrid Escape is an excellent example. This vehicle combines the benefits of series and parallel hybrid concept through the use of a planetary gear set. Yielding V6-like performance with a 4-cylinder engine, while meeting AT-PZEV emission standards, it is marked as the first no-compromise hybrid SUV [5].

The higher the voltage and the installed electrical propulsion power, the higher the absolute CO_2 (or fuel) savings that can be achieved [6]. However, the relative cost per gram CO_2 km^{-1} reduction increases with the degree of hybridization, too. Hence, at least in Europe an evolutionary path towards powertrain hybridization, starting with micro- and mild-hybrids, which offer the best cost/benefit ratio. In contrast to Europe, both in Japan and the US, legislation is explicitly in favour of high-voltage hybrids, which are therefore being introduced in these markets.

2.3. *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 14 V/42 V system, had been considered as a viable solution. However, the high cost associated with the generation and distribution of a second voltage level in the vehicle turned out to be prohibitive for many applications. Furthermore, the electric propulsion that can be generated on this voltage level is generally considered still too low to make mild-hybrid electric vehicles attractive. At the same time, some hardware components for the conventional 14 V system experienced significant technological progress. For example, enhanced 14 V clawpole alternators were developed that can continuously generate an electric power output of 3 kW and more. AGM batteries offer at least three-fold longer shallow-cycle life, compared to conventional SLI batteries (cf. Section 4.2). Finally, the introduction of high-level energy management control strategies can ensure powernet robustness and optimal energy efficiency and thus help stretching the boundaries of the 14 V system. Energy management will be discussed here in some more detail because it has significant consequences for battery operation. More detailed descriptions can be found in the literature [7,8].

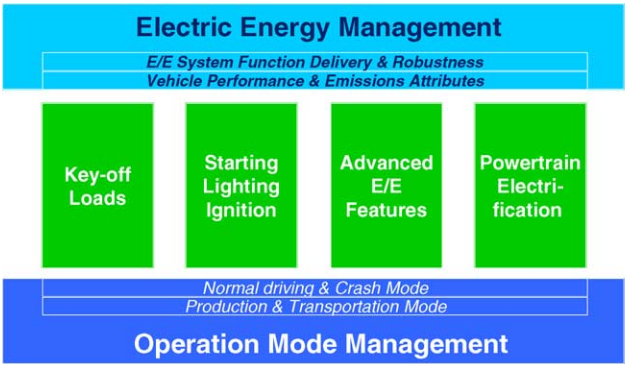

Fig. 1. Electric/electronic system functions controlled by electric energy management.

Fig. 1 shows the structure of an electric energy management system. Operation mode management forms the basis of energy management by identifying individual vehicle states, and the subsequent allocation of electrical system attribute specifications for each state. For example, a group of electrical features can be assigned a maximum of energy consumption in a key-on, engine-off situation, or the electrical system is set to a battery refresh mode with individual settings for generator setpoints and load prioritization. Apart from a normal driving mode, special modes may be assigned for crash detection, as well as production and transportation modes. In the normal driving mode, the energy management functionalities can be separated into two groups:

- Power supply management (PSM): control of the on-board electric generation, i.e. in conventional electrical systems of the alternator setpoint, aiming at an optimization of availability of electrical functions, battery life, vehicle performance (e.g. reduce 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 called growing attention recently. Electric generation contributes significantly to fuel consumption, at least under real-world conditions. An average alternator output of 1 kW causes as much as 1–1.4 l per 100 km gasoline fuel consumption, depending on vehicle parameters and driving conditions. Decoupling the electric generation from the loads' demands can significantly reduce this specific fuel consumption by optimizing the system efficiency of engine and alternator at any point of time. This will introduce rail voltage fluctuations into the electrical system and systematically exploit the battery as short-term energy buffer. 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 case of peak loads. Depending on the definition of electric feature priorities, a PSM strategy can decide to allow a temporary functional degradation. Here, a careful balancing of priorities is required, especially for functions that are directly perceivable by the customer. Advanced PDM algorithms will schedule priorities 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 has to deliver these essential inputs to the energy management, see Section 5.1.

3. Battery requirements

3.1. “SLI” requirements

The “classic” requirements for automotive battery selection follow the basic electrical performance fundamentals of cold cranking amperes, capacity (Ah) and reserve capacity whilst considering physical package.

3.1.1. Cranking

It is the ability for the battery/starter motor/cable combination to rotate the engine at sufficient speed and duration to achieve the correct conditions for engine start. Different design criteria exist dependent on engine and transmission type. The automotive designer has to consider, for example, the number of cylinders, cylinder configuration, fuel type, manual and automatic transmissions when engineering the starter motor and battery combination.

Additionally, automotive manufacturers consider the countries into which they will market their products and may categorise these countries into temperature regions for starting. This would allow the manufacturer to engineer a different battery and starter motor combination by region. For example, a smaller CCA rated battery could be specified for Spain compared to Finland.

3.1.2. Capacity

One of the main areas of consideration when determining the battery capacity performance is the need to support the vehicle quiescent loads, i.e. loads that require power when the ignition is switched off. The automotive manufacturers have their own corporate design standards that consider these key-off loads and their battery requirements are based on predicted duration of vehicle stand and allowable reduction in capacity. Regardless of corporate standard, the designer must consider conventional low current loads for example, alarm, radio memory; and also those loads that operate post ignition off such as run on cooling fans and puddle lighting.

A secondary consideration for the battery capacity is the ability of the battery to support the power supply system when the vehicle is operating under certain heavy electrical load conditions. There is no single design standard for power supply sizing, with each manufacturer applying its own design criteria. This can range from a net charge condition were no battery contribution is allowed, to the opposite condition were complete battery discharge could be allowed to occur over a predetermined load profile, vehicle drive profile and time duration.

3.1.3. Reserve capacity

This parameter is regarded as the least critical of the electrical performance values. Automotive designers take account of the RC rating when considering the ability of the battery to support the vehicle should the generator fail, thus allowing the vehicle to continue to be driven for a period of time.

Additionally, the battery’s ability to support electrical features with the engine not running is also considered. For example, consider the ability of the battery to support the vehicle’s lighting system for a predetermined period of time.

3.1.4. Package

The automotive designer has to consider a number of requirements when packaging the battery. The physical dimensions demand significant cubic capacity whether placed in the engine compartment, under seat or in the rear of the vehicle. This package dimensions are continually being challenged by other component designers as available space becomes further restricted. With increased requirements of pedestrian impact protection, the battery height in particular has become a major issue.

The need for designers to find solutions to the packaging constraints continues, whilst the demand for similar performance from reduced physical case size is increasing.

If packaged in the engine compartment, the battery has to withstand high temperatures, typically around 70 °C and above. So far, it is a major drawback of AGM batteries that they tolerate less heat than today’s flooded batteries do. The changes in the vehicle associated with moving the battery towards a colder place would cause significant extra cost.

3.2. Energy throughput/shallow-cycle life

Cyclic wear has been known for long as the dominating battery failure mode in “heavy-duty” applications like taxis. Recently, two factors tend to increase cyclic wear of SLI batteries in “normal” passenger cars, particularly in the premium segment:

- An increasing number of electronic control units (ECU), typically more than 60 in recent luxury cars, draw currents during key-off, which may be increased as a consequence of part defects, insufficient software testing, or unexpected interactions. As a consequence, battery depletion during key-off can become excessive.
- The power consumption of the comfort loads is not continuously matched by the alternator output. For example during idle, the battery may have to supply the total load current to a significant fraction.

In both cases, the discharge/charge cycles are typically very shallow ($\ll$10% depth-of-discharge (DOD)), but the accumulated Ah turnover over years 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 that equals 100 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 that of flooded batteries.

Energy management or (micro-)hybridization may add significantly more cyclic battery use. For a stop/start vehicle a typical cycle may consist in supplying 40 A loads for 20 s, re-cranking the engine within 0.4 s with an average current of 250 A, and being recharged during subsequent driving. The turnover per stop/start cycle would then equal 0.25 Ah. Assuming two stops per kilometre, the abovementioned 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 $4 \times 50 \times 150/2 = 15{,}000$ km. This example illustrates that cyclic wear tends to become the dominating battery failure mode in such applications.

3.3. 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 enough. As a consequence, charge acceptance will be paid more attention 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. A simple example of a heuristic PSM is regenerative braking [9].

Regenerative braking (REGEN) is nearly standard for battery-electric and hybrid-electric vehicles. The electric drive is operated in its generator mode during vehicle deceleration, charging the battery. Batteries in hybrid-electric vehicles are for this reason operated at partial-state-of-charge (PSOC), providing significant boost-charge acceptance during REGEN (charge acceptance is best and batteries easiest to control between 20% and 70% SOC). Contrastingly, classical 12 V automotive batteries are continuously charged at alternator output voltage and thus operated at high SOC where their boost-charge acceptance is only marginal. A starter-generator or an alternator could provide limited REGEN power in 14 V systems if the voltage setpoint is modified as a function of the acceleration/deceleration situation and the battery is operated at PSOC. Fuel consumption and CO_2 emissions can be reduced by 1.5–4%, depending on vehicle, drivetrain, and driving conditions. This requires batteries that can withstand prolonged PSOC operation and additional energy throughput, requirements that are similar to those towards batteries for mild-hybrid electric vehicles. Given typical alternator and battery sizing as well as driving patterns, the battery will typically limit the power that can be captured during a REGEN phase [9]. Taking cost into account, an enhanced flooded battery would best serve the broad application of regenerative braking in 14 V systems. This enhanced flooded automotive battery would be characterized by superior dynamic charge acceptance, stable PSOC operation and ca. two-fold extended shallow-cycle-life, compared to classic SLI batteries.

3.4. 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, to satisfy customer expectations it has become necessary for a component to provide six-sigma (<12 ppm failures) reliability over its operational life, now assumed to be ten years or 240,000 km. Current production SLI batteries do not perform to this standard, but are seen as a wear component that needs replacement several times during vehicle life. This should not, however, coincide with the same number of unexpected car breakdowns, each causing serious inconvenience for the driver or safety risks if critical components like the brakes are electrified. Hence, a dependable indication method of required battery replacement (as in the case of fuel, oil, or brake pads) is essential. The introduction of battery monitoring systems in 14 V vehicle electric systems (see Section 5.1) is expected to increase the reliability of the energy storage system significantly: Not only can the average service life of the battery be extended by avoiding abusive conditions, but also should early and unexpected battery failures be largely eliminated.

Another aspect of battery reliability should not be overlooked [10]: 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 higher-voltage batteries (36 V or more) have to meet much more stringent reliability targets on cell level in order to just maintain battery reliability on the level it had for a 12 V battery. As a consequence, battery-manufacturing processes will need improved process controls in order to meet the higher Cpk (process capability index) necessary for higher reliability.

4. Battery technology

The well-established lead–acid battery technology is expected to maintain a key role in automotive applications. Compared to traditional starting–lighting–ignition (SLI) batteries, significant technological progress has been achieved or can be expected, which improve both performance and service life. The stretched technological limitations of both flooded and valve-regulated lead–acid systems will be discussed.

4.1. Flooded lead–acid batteries

The liquid-electrolyte lead–acid battery for classical starting lighting and ignition (SLI) is a commodity based on a mature technology at low part cost around 35$ kWh^{-1} (C/3) or 4$ kW^{-1}. SLI batteries have to be replaced typically after 3–7 years in service, which is far from meeting the reliability definition for automotive parts of 12 ppm failures per 10 years or 240,000 km service life. However, 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. Battery manufacturers will continue to be faced with strong pressure from carmakers, demanding both improved quality and reduced part cost. The only chance to resolve these conflicting targets is the introduction of highly automated, continuous, and defect-free battery manufacturing processes.

As future powertrain concepts will require significantly higher battery charge throughput, the lead–acid battery should be regarded and sized as a serviceable system with wear characteristics. The charge turnover acts as battery wear, but since the SLI battery is normally sized for cold cranking specifications, it has some reserve to deliver higher charge turnover without compromising service life. Further optimizing the shallow-cycle life of flooded automotive batteries – beyond the typical 150 capacity turnovers – appears possible at lower cost than those of AGM batteries.

4.2. Valve-regulated lead–acid batteries

Valve-regulated lead–acid (VRLA) batteries can withstand higher Ah turnover than the classical SLI battery. The absorptive glass mat (AGM) versions use a glass fibre mat that is drenched in electrolyte. Both prismatic and spiral-wound plate geometries are considered for automotive applications. These batteries allow for an at least three-fold increase of cycle life compared to SLI, at equal or even higher power density [11]. Further improvement can be expected from ongoing R&D work optimizing AGM technology for high-rate partial-state-of-charge (HRPSOC) operation. This technology development has 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 [12]. On the other hand, ongoing research work aims at enabling AGM technology to replace NiMH batteries in full-hybrid electric vehicles [13].

Currently, low volume AGM battery part cost amounts to almost twice the cost of SLI technology, with a potential of long term and high volume part cost lowering to ca. 1.2–1.3 times. Since the cost per charge throughput during battery life outperforms the SLI battery technology, AGM batteries have a good potential to become the de facto standard for automotive applications where medium to high cycle life is required. However, the development of high-temperature resistant AGM batteries would be a key to their broad introduction because they should replace their flooded counterparts at the same position, frequently in the engine bay.

4.3. Advanced batteries and supercapacitors

Cyclic energy throughput is the most important constraint that excludes lead–acid batteries, despite their low cost, from some applications, particularly HEVs [11]. 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 watt-hour to the level of NiMH batteries. Serious technological issues are related to their safety under abuse conditions or accident, and their service life.
- Electrolytic double-layer capacitors (supercapacitors) have extremely long shallow-cycle life because no electrochemical reaction is associated with their discharge/charge cycle. Their energy density, however, is inferior to batteries, and their voltage sags proportional to SOC. Technological concerns are related to exposure to high voltage and temperature. The choice of the electrolyte is still an open question because acetonitrile is considered toxic in some markets, and possible replacements would compromise cost and/or performance.

NiMH batteries are currently used in all commercially available full-HEVs. Li-ion batteries are likely to become serious competition in this application. 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 cost of either of these technologies can be further brought down significantly, it may, though, complement the lead–acid battery in a dual-storage system, covering the shallow-cycle power throughput requirement (see Section 5.2). Supercapacitors are currently seen as the most feasible candidates for research programmes aiming at such systems.

5. Energy storage system technology

With the requirements to the vehicle-electric storage device growing, it is more and more looked at as a storage system rather than only a single low-cost commodity. On the one hand, this means intelligence will be necessary in the form of an electronic monitoring system and a dedicated battery management strategy to maintain safety, battery charge, and life costs. On the other hand, it may also lead to splitting up the energy storage function between two (or more) storage devices. In both cases, failure risks are shifted from the electrochemical cells to the control electronics.

5.1. Battery monitoring systems

Classically, the alternator output voltage in vehicle-electric systems was chosen such that sufficient recharge of the battery after lighting and engine cranking was guaranteed. Presently, the alternator voltage setpoint is typically modified depending on estimated battery temperature, vehicle acceleration demand, etc. With growing vehicle electrification and the introduction of fuel-saving power supply management strategies, more sophisticated management of the battery operation becomes eminent [14,15]. As a prerequisite, precise knowledge of the battery state is needed, which the battery monitoring system (BMS) has to deliver. The BMS can thus fulfil a two-fold function: improving the reliability and robustness of the power-supply system, and allow for fuel-/CO_2-saving measures that put higher demands on the battery.

Battery monitoring systems (BMS) are expected to become a commodity, penetrating the automotive volume market from both highly equipped premium cars and dedicated fuel-economy vehicles (e.g. stop/start). A BMS consists of a sensor that 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). Several suppliers offer novel integrated sensor units that determine the battery current to a remarkable precision over a huge span ranging from milliamps to cranking currents, together with voltage and temperature [16]. Given the difficulty of precisely determining a lead–acid battery's SOC and capacity without measuring the current, it is likely that such sensors will be used in all advanced BMS.

The BMS outputs are traditionally defined in terms of state-of-charge (SOC) and state-of-health (SOH). For deep-cycle battery applications like uninterruptible power supplies, forklifts, or battery-electric vehicles, this type of information is highly relevant for system-level energy management. In recent automotive applications, however, dynamic power delivery and charge acceptance are at least as important. They are only loosely linked to SOC and capacity-based SOH. For example, the cold-cranking capability of a battery may be drastically reduced, whereas the capacity and SOC are still acceptable. As a consequence, it has been proposed to define the outputs of an automotive BMS using the "state-of-function" (SOF) concept [14,15]. Each SOF directly informs the vehicle-level energy management to which degree the battery could currently perform an intended function, be it cold or warm cranking, supporting specific loads, delivering propulsion power, or accepting REGEN charge. This concept can thus form a generalized BMS interface for different applications ranging from highly electrified 14 V systems over stop/start microhybrids up to full-HEVs.

5.2. Dual-storage systems

Sometimes a single lead–acid battery can no longer meet the storage requirements, e.g. in terms of providing reliable cranking power in the presence of uncontrollable battery drain during key off. In such cases, splitting the battery into two complementary units can help to meet the requirements. Typically, one battery would keep the task of engine cranking, whereas the second battery would take over most of the cyclic loads support. The former will be optimized for power output (for example a small-capacity high-CCA flooded battery), whereas the latter will be optimized for cycling capability (for example an AGM battery with low or moderate power ratings). As a low-cost variant, using two identical starter-type batteries may be considered, e.g. in order to provide standby power for power tools, etc. in commercial vehicles without compromising cranking capability. Whether the two batteries are equal or different, both batteries have a nominal voltage of 12 V and are connected in parallel during normal driving (charging). Vehicles with flooded/AGM dual-battery systems of this type are already on the market, primarily European premium cars. In the US, such systems are used in trucks and some recreational vehicles.

As an option, the two batteries could be connected in series to meet special requirements. This is an established topology in agricultural machinery, where 24 V tuck starter motors are used but the electrical system voltage is 12 V. Relays are used as switching devices here. Recently, similar topologies with semiconductor switches have been proposed to achieve a fast and comfortable engine-start in diesel stop/start vehicles with belt-driven starter/generators, which provide higher cranking torque when supplied with 16–20 V.

Dual-storage systems may involve advanced storage features, too. This is of particular interest if a cycle-optimized AGM battery cannot meet the ampere-hour turnover requirement, e.g. in the case of mild hybrids. These vehicles typically carry their conventional loads in a conventional 14 V system with an SLI battery, whereas an advanced (e.g. NiMH) battery supplies the propulsion and REGEN functions. Typically the second battery operates on a higher voltage (e.g. 42 V) in order to improve its power capability at reasonable currents. If this second voltage is not distributed through the car but only used in the mild-hybrid electrical drive system, on-cost associated with the electrical architecture can be restricted.

Another example of lead–acid plus advanced battery dual storage systems currently under investigation is a supercapacitor module (nominal voltage ca. 20 V) that accompanies the 12 V SLI battery in a stop/start system [17]. Particularly for large diesel engines, comfortable and fast cranking after an idle-off period is difficult with belt-driven starter generators and can be significantly improved by temporarily overloading the electric machine with applying a higher voltage. Besides, the supercapacitor can increase the system's REGEN charge acceptance. It turns out that the SLI/supercapacitor dual-storage system can be an economically attractive option if the price of supercapacitors declines to ca. 0.3 Euro-cent per Farad and cell [18] or less.

It should be noticed that additional components are needed to realize dual-storage systems, which add cost and complexity. In the simplest case, this is a single switch that allows for disconnecting the starter-type battery from the key-off loads. Switch arrays may allow for connecting the two devices either in parallel or in series, depending on the vehicle's operating mode. Many topologies require a dc/dc converter that shifts energy between the two storage devices (and voltage levels).

6. Conclusions

Automotive batteries will be required to meet growing demands, emerging from the needs both for a reliable power supply supporting the increasing electric content of modern vehicles and for reduced fuel consumption and CO_2 emissions. The low-cost concepts of a 14 V single-voltage electrical system and the lead–acid battery technology will, however, remain the standard solutions at least for short-term vehicle programmes. Important measures to stretch the scope of the 14 V system will be: vehicle-level energy management, battery monitoring systems using low-cost battery sensors, and dual-storage systems. The flooded automotive battery will be challenged to deliver extended shallow-cycle life, robust PSOC operation, and good dynamic charge acceptance. The AGM battery technology can replace or amend the flooded starter battery, improving battery life and reliability, but its applicability is currently limited by on-cost and heat sensitivity.

The most relevant driver for introducing a second voltage and advanced battery chemistries will be high (mild, medium or full) hybridization of the vehicle propulsion, where needed. The NiMH battery technology has been chosen for all full hybrids commercially available up to now. The lithium-ion battery technology is catching up and still promises cost savings. Supercapacitors, which provide very little energy density, might find specific applications, complementing a lead–acid battery or fuel cell, if the predicted further fall in their prices becomes reality.

Acknowledgements

The authors thank their colleagues Karl Keckan, Ted Miller, Ron Brost, and Don Kees for valuable discussions and reviewing the manuscript.

References

[1] M. Anderman, The challenge to fulfill electrical power requirements of advanced vehicles, J. Power Sources 127 (2004) 2–7.
[2] H.-G. Burghoff, Opportunities and challenges of advanced automotive powernets, in: Proceedings of the Third International Advanced Automotive Battery Conference, June 10–13, Nice, France, no. 1–2, 2003.
[3] Monitoring of ACEA's, Commitment on CO_2 Emission Reductions from Passenger Cars (2002), Association des Constructeurs Européens d'Automobiles, Brussels, 5 September 2003, http://www.acea.be/ACEA/20040317PublicationEmissions.pdf.
[4] AID, Schmidt's Diesel Car Prospects to 2009, www.eagleaid.com/dsltxt.htm, accessed 01.09.2004.
[5] http://www.fordvehicles.com/escapehybrid/, accessed 01.09.2004.
[6] J.M. Miller, K. Hampton, R. Eriksson, Identification of the optimum vehicle class for the application of 42V integrated starter generator, Convergence 2000 International Congress on Transportation, Detroit, MI, USA, October 16–18, 2000, SAE Paper 2000-01-C073.
[7] T. Miller, D. Kok, S. Ploumen, E. Karden, Energy management in future drivetrain concepts, in: Proceedings of the Fourth Advanced Automotive Battery Conference, June 1–4, San Fransisco, 2004.
[8] H.-M. Graf, Open software solution for the energy management, Automobiltechnische Zeitschrift (ATZ) 106 (1) (2004) 46–50.
[9] E. Karden, S. Ploumen, E. Spijker, D. Kok, D. Kees, P. Phlips, Rekuperatives Bremsen in Fahrzeugen mit 14 Volt-Bordnetz, in: Energiemanagement und Bordnetze, Haus der Technik, Essen, Germany, 2004.
[10] R. Brost, Valve-regulated lead-acid batteries in automotive applications – a vehicle manufacturer's perspective, in: D.A.J. Rand, P.T. Moseley, J. Garche, C.D. Parker (Eds.), Valve-Regulated Lead-Acid Batteries, Elsevier, Amsterdam, 2004, pp. 327–396.
[11] B. Spier, G. Gutmann, 42 V battery requirements – lead-acid at its limits, J. Power Sources 116 (2003) 99–104.
[12] E. Karden, D. Kok, E. Spijker, A European view of batteries for future automobiles, in: Proceedings of the Advanced Lead/Acid Battery Consortium Meeting, Nice, 2003.
[13] A. Cooper, Development of a lead-acid battery for a hybrid electric vehicle, J. Power Sources 133 (2004) 116–125.
[14] E. Meissner, G. Richter, Battery monitoring and electrical energy management – precondition for future vehicle electric power systems, Proceedings of the Eighth European Lead battery Conference (8ELBC), Rome, 2002; J. Power Sources 116 (2003) 79–98.
[15] E. Karden, E. Spijker, D. Kok, Batteriemanagement im Kraftfahrzeug für Großserienanwendungen, VDI-Tagung Elektronik im Kraftfahrzeug, Baden-Baden, 2003.
[16] A. Heim, Intelligent Battery Sensor: Key Component of Active Energy Flow Control in Motor Vehicles over the Whole Product Line, VDI-Tagung Elektronik im Kraftfahrzeug, Baden-Baden, 2003.
[17] Valeo, Electrical Energy Management 42 V Perspective, in: MIT Consortium Program Review Meeting, 5–6 March, Dearborn, MI, 2003.
[18] M. Eifert, L. Gaedt, E. Karden, D. Kok, M. Leyten, S. Ploumen, M. Rienks, Comparing lead-acid nattery and supercapacitor technology in a 42 V mild hybrid vehicle, in: Proceedings of the Boostcap Conference, November 18, 2002.