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42-V battery requirements—lead–acid at its limits

B. Spier*, G. Gutmann

DaimlerChrysler Research Center, DaimlerChrysler AG, Wilhelm-Runge Street 11, 89013 Ulm, Germany

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Abstract

For future vehicles, the 42-V power system offers a variety of new applications, from the capability to sustain increased comfort loads up to mild hybridization. To meet these requirements, considerable progress is needed for the lead–acid system to achieve reasonable lifetime and reliability in service. In addition to cycle-life improvement at partial state-of-charge, both a state-of-health indication and a battery management system with sophisticated algorithms to achieve sufficient cycle-life are required. Due to the inherently lower cost of lead–acid, only a slow migration towards more advanced battery systems is anticipated. Some applications for nickel–metal-hydride and Li-ion batteries are discussed.

Keywords: Cycle-life; Hybrid car; Lead–acid batteries; Limitations; 42-V PowerNet; Reliability; State-of-health

1. Introduction

Because of the pressure on vehicle component costs, the commonly used lead–acid battery is able to maintain its strong position as the storage system of choice in the PowerNet. The chief reasons for the outstanding low costs are the heavy competition of what is today a buyer's market and an unsurpassable material and manufacturing situation. This is characterized by abundant lead ores, low energy consumption for metal production and refining, a relatively simple manufacturing technology, and a well-established recycling process which collects 95% of batteries after use. The almost complete recycling process has even appeased public concern about the toxicity of lead.

In the past, the weaknesses of lead–acid battery performance, such as in specific energy and calendar and cycle-lives, have been offset by the low costs. In addition, the lead–acid system can be adapted sufficiently to different applications, e.g. standby or cycling. The automotive (starting, lighting, ignition) battery has been optimized for cold cranking. This closed storage system with excess electrolyte usually claims a service life of 4–6 years, if the voltage regulator of the charger works correctly and the energy throughput is limited. Some enhancement in energy throughput, with additional challenges in lifetime and in service requirement (due to water loss), has been achieved by introducing advanced valve-regulated lead–acid (VRLA) batteries of the absorptive glass mat (AGM) design.

Future requirements of the PowerNet will include a steep increase in both high-power and high-energy load profiles. Furthermore, because the stored energy is limited due to weight and volume restrictions, this will be associated with frequent charging and, on the average, with a lower state-of-charge of the battery. This, in turn, squeezes the battery design into an area of conflict, which is presently met by dual or twin batteries.

Anticipating some of the PowerNet requirements, this paper questions whether the lead–acid battery will meet the desired performance criteria.

2. 42-V PowerNet applications and battery requirements

The key task for the battery is first and foremost to start the engine. Increasing quiescent currents required by the multitude of electronic equipment of high-end ('luxury') cars may drain the battery within 6 weeks, e.g. during airport parking. This reduces the reliability of cranking, which is accorded top priority not only by car manufacturers but also by operators. Reliable cranking has provided the incentive to create a twin-battery PowerNet which separates the high-power applications from high-energy, low-power consumers. This permits the use of batteries which are

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* Corresponding author. Tel.: +49-731-505-2960;
fax: +49-731-731-4211.
E-mail address: bernd.spier@daimlerchrysler.com (B. Spier).

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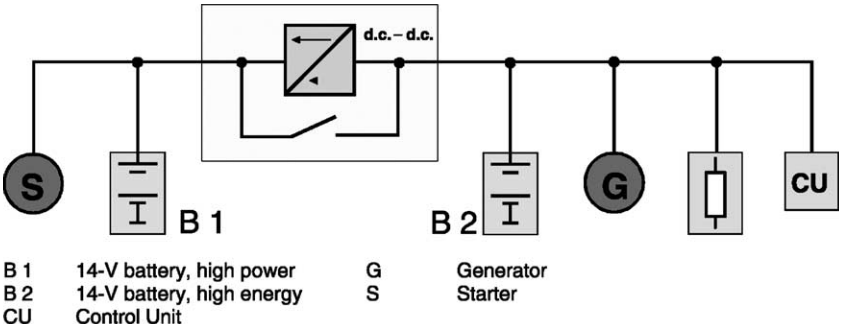

Fig. 1. Twin (dual)-battery system layout.

Table 1
Present and future PowerNet loads (charge, discharge) [3]

Feature	Peak power (W)	Commercialization status	Purpose
Lights	600	Established	Safety
Power windows	700	Established	Convenience
Rear defroster	1500	Established	Convenience
Power seats	1000	Established	Convenience
Heated seats	500	Established	Convenience
Electrically actuated ABS	2500	Established	Safety
Electric fan	500	Established	Efficiency
Coolant pump	500	1–3 years	Efficiency
Power steering	1500	1–3 years	Efficiency
Air pump	400	1–3 years	Efficiency
Instant heating	3000	1–3 years	Convenience
Heated windshield	1500	1–3 years	Convenience
Catalyst heating	2000	3–5 years	Environment
Electrical AC	3500	3–5 years	Efficiency
EM valve actuation	4000	5–10 years	Efficiency
Brake by wire	2500	8–15 years	Safety
Steer by wire	1500	8–15 years	Safety
Active suspension	12000	8–15 years	Safety

optimized for the particular application, and shifts energy to the low starter battery if required (Fig. 1).

With the higher loads already prevailing or anticipated (see Table 1), it is straightforward to increase the power branch voltage to three times the nominal 14 V, i.e. to a new nominal voltage level of 42 V (Fig. 2). This is well below the shock-hazard voltage, while the available power is significantly enhanced and electronic parts are available at low price. Taking this as the background, it is important to understand the poor acceptance of the 42-V PowerNet [1]. At present, there is a trend to keep 12-V batteries for as long as possible in order to avoid costly 42-V electrical components, which lack economy-of-scale. This includes the claw-pole generator which, by virtue of its limited power and efficiency, is the major contributor to the limited availability of energy in the PowerNet. By contrast, a multitude of high-power functions are already considered. These all rely on the 42-V PowerNet [2].

The features of conventional internal combustion engine (ICE) powered vehicles are listed in Table 1. Many of these, whether already implemented or planned for the future, target increased efficiency by shifting auxiliary functions from continuous to on-demand service.

The best prospect for increasing efficiency is, however, presented by hybridization of the vehicle drive-train. Even soft hybrids call for the 42-V PowerNet. As far as the power-train is concerned, a minimum level of control has to be imposed for both the storage system and the drive-train for reasons of safety. Such a management system is also beneficial for the energy balance of the power system.

2.1. Scope of 42-V PowerNet applications

With respect to the wide range of applications and associated power requirements that will influence selection of the battery, it is useful to provide the following detailed classification [4]:

- 12-V twin-battery system for the PowerNet (high-power, high-energy—standby), this is the predecessor of the 42-V dual-voltage PowerNet;

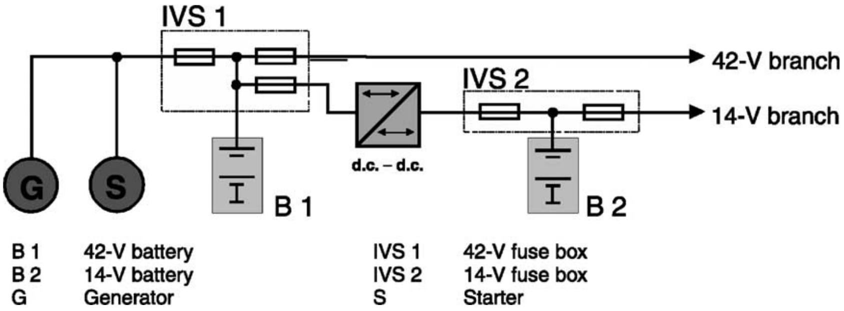

Fig. 2. Example of 42-V PowerNet design.

Table 2
Performance expectations for 42-V applications

	SLIPA	Stop–start	Soft hybrid	Mild hybrid
Example		Zero power-assist (ZPA)[a]	THS-M	Partial power-assist (PPA)[a]
Discharge pulse power (kW)	n.a.	6 (2 s/15 s)	6/12	15/18
Charge power (kW)	2.4	2.4	2.6	4.5
Regenerative pulse power (kW)	n.a.	n.a.	8	18
Cold cranking power at −25 °C (kW)	6	6	8	8
Engine-off accessory load	0.8–1.5	0.8–1.5	3	3
Cycle-life	100000	100000	150000	150000
Calendar life (years)	4–5	4–5	15	15
Life energy throughput (MW h)	1	1	4.5/5	4.5/5
Service temperature (°C)	−30 to 52	−30 to 52	−30 to 52	−30 to 52

n.a.: not applicable.

[a] FreedomCAR classification.

- 42-V scaled-up automotive battery for starting, lighting and ignition, as well as for powering ancillaries (SLIPA);
- 42-V with stop–start;
- 42-V for (super) soft hybrid;
- 42-V for power-assist hybrid (mild hybrid).

The power requirements of these 42-V functions and applications are set out in Table 2. The following systems are not 42-V compliant and are mentioned solely for reasons of completeness:

- high-voltage power-assist (with or without electric range) for ICE or fuel cell hybrid;
- plug-in hybrid (with electric range).

2.2. Battery requirements

2.2.1. The scaled-up automotive battery

Through reduction of fuel consumption and emissions via support of power ancillaries (SLIPA), i.e. replacement of continuous loads with on-demand loads, the battery suffers from a higher depth-of-discharge (DoD) than in standard applications. This results in higher water losses and increased battery stress. Here, VRLA batteries are appropriate since the pressurized stack and oxygen recombination offer increased cycle-life and low maintenance, respectively. According to one report [5], a wet 100-Ah automotive battery can be replaced by a 74-Ah AGM type of VRLA battery. While both batteries have the same power, the VRLA version yields 67% more cycle-life, 43% greater calendar life, and a life-cycle cost reduction of 16%. Nevertheless, the present authors' experiences from volume production have shown 20% more costs for the replacement of an automotive battery with a VRLA type of the same capacity.

2.2.2. Avoid engine idling: stop–start

In urban traffic, engine idling is a major contributor to pollution and energy waste. This can be minimized by adopting a stop–start driving strategy. In this case, the battery challenges are defined by the power demands during the stop phase, which burdens the battery with 800–1500 W. According to the new European driving cycle (NEDC), a medium power of 1 kW generates an energy throughput of 1 MWh within 4 years, which corresponds to 50 000 km of driving. Regardless of the PowerNet voltage, the average DoD per cycle is between 1 and 1.5%. These conditions do not allow the use of a conventional automotive battery because 100 000 cycles have to be achieved (see Table 3). To prolong battery life, frequent full recharges are mandatory—even with a VRLA battery.

2.2.3. The soft hybrid

The Toyota Crown is the first soft hybrid to appear in the market and is fitted with a 42-V VRLA battery. The power requirements are moderate and with extremely shallow

Table 3
Stop–start battery load requirements and drawbacks

Item	Property
DoD per cycle (%)	<1–1.5 (12 and 42 V)
VRLA lead–acid	100000 cycles at 1% DoD Goals for stop–start can be met Main risk: partial SoC—frequent full recharge necessary Sensitive to high ambient temperature (<65 °C)
Automotive flooded lead–acid	25000 cycles at 1% DoD Goals for stop–start cannot be met High risk: partial SoC—continuous full recharge necessary Less sensitive to high ambient temperature (<75 °C)

Table 4
Battery data of the Toyota Crown

Voltage (V)	42
Peak power (kW for 3 s)	6
Energy content (kWh)	0.72
Weight (kg)	27
Cycle-life, ±3% DoD	>50000
Calendar life (years)	>3

Table 5
Battery data for soft hybrids

Voltage (V)	42
Peak power for 18 s (kW)	12
Power at −25 °C for 15 s (kW)	6
Energy content (kWh)	1
Weight (kg)	<20
Cycle-life, ±3% DoD	>50000
Calendar life (years)	15

cycles, a battery life of more than 50 000 cycles is anticipated (Table 4). The driving strategy is, however, compromised to achieve a long battery life, i.e. by a low peak power of 3 kW for some seconds. Obviously, operator experience will show whether the battery is qualified for this application or whether frequent replacement of the storage system is a major drawback.

A battery for a more powerful soft hybrid is defined in Table 5. Under NEDC conditions, a vehicle with a curb weight of 1200 kg requires 12–15 kW of power for 18 s. Over a 15-year life, 1-kWh battery must withstand more than 500 000 cycles. This is a performance well beyond that achievable from present VRLA batteries. The solution would be either battery replacement every 2–3 years, or increase in the battery size to reduce significantly the DoD.

2.2.4. *The partial power-assist hybrid*

The battery requirements for the partial power-assist hybrid are well above the capabilities of present lead–acid batteries (Table 2). Given the high stresses during power discharge/recover and the deep-discharge levels, a VRLA battery is able to withstand only 1 year of service. To avoid deep cycling and to increase cycle-life, the battery size has to be increased by a factor of 3–5. This would introduce undesirable weight and volume burdens to the car, as well as higher costs. Thus, either lead–acid technology needs further improvement or the car manufacturers are forced to use nickel–metal-hydride (Ni–MH) or Li-ion battery systems.

From the data given in Table 2, where performance expectations are defined for the various applications, it is obvious that some of the values cited are simple target values. Properties that can be achieved today, together with the major drawbacks of lead–acid, are discussed in the next section.

3. Lead–acid limitations and development needs

Basically, the limitations of the lead–acid system are caused by its electrochemistry. The cell voltage, which is numbered among the principal advantages of lead–acid, well exceeds (by 1 V) the reversible electrolysis voltage of water; battery operation relies on the high overpotentials for hydrogen and oxygen evolution on the lead substrate. The cell reactions proceed via soluble products, and the active materials are subjected to large changes in volume during cycling. Thus, the electrochemistry is the origin of the well-known aging and failure mechanisms, namely [6]

- anodic corrosion of grids, plate-lugs, straps or posts;
- degradation of positive active material and loss of adherence of the material to the grid by shedding;
- irreversible formation of lead sulfate in the active material;
- short-circuits;
- loss of water.

The first three problems will be encountered much more often in future vehicle applications. These applications require enhanced power and cycle-life and will cause the battery to function at a lower SoC.

There is also a conflict in battery design, namely, higher power requirements call for thin grids, while cycle-life necessitates thick grids to withstand corrosion. The lowest, but still life-limiting, corrosion rates are found with pure lead grids, but these are restricted to use in small cells. To achieve low weight, high utilization of the active materials is required. This, in turn, is associated with large changes in the volume of the material that limit cycle-life.

Of course, there are measures for improvement, some of which are set out in Table 6. Nevertheless, the question behind every measure is: “What are we prepared to trade off?” For example, to gain higher specific power, are car manufacturers prepared to accept lower specific energy which, after all the empirical optimization, ends up at 35–40 W h kg^{-1}? Does the cylindrical design, selected on account of the high pressure that this design exerts on the active materials, really improve cycle-life compared with the flat-plate design, or is the extra life anticipated from the increased plate pressure then negated by corrosion of the

Table 6
Correlation of battery design, performance, and measures for improvement

Battery design property	Characteristic	Improvement
Grid thickness and materials selection	Defines calendar life on float charge; automotive, UPS applications	Optimized mechanical and corrosion-resistant alloys
Active material conductivity, adherence to grid and coherence	Defines cycle-life on cycling batteries	Additives such as C, glass fibers, semi-conductive oxides, AGM glass mat separators, pressure on active materials
Electrolyte concentration and water balance	Influences grid corrosion and active material sulfation (calendar life)	Additives such as lignosulfates to prevent sulfate grain growth
Predominant SoC	Influences grid corrosion and active material sulfation (calendar life), shorting	Battery management system which controls sufficient SoC >70%, makes use of refresh algorithms

Table 7
Estimated data for 42-V applications

	SLIPA	Stop–start	Soft hybrid	Mild hybrid
Example		Zero power-assist (ZPA)[a]	THS-M	Partial power-assist (PPA)[a]
Discharge pulse power (kW)	n.a.	6 (2 s/15 s)	6/12	15/18
Charge power (kW)	2.4	2.4	2.6	4.5
Regenerative pulse power (kW)	n.a.	n.a.	8	18
Cold cranking power at −25 °C (kW)	6	6	8	8
Engine-off accessory load (kW)	0.8–1.5	0.8–1.5	3	3
Cycle-life	100000	100000	20000–30000	20000–30000
Calendar life (years)	3–4	3–4	1	1
Life energy throughput (MW h)	1	1	4.5–5	4.5–5
Service temperature (°C)	−30 to 52	−30 to 52	−30 to 52	−30 to 52

n.a.: not applicable.

[a] FreedomCAR classification.

thinner grids required for coiling? Calendar and cycle-life are among the most desired and sensitive properties to be achieved and proof-tested. In real vehicle service, there is no guarantee for the SoC or for the ambient temperature to be in the most comfortable range for the battery. If the car is stopped and left for an indefinite time, the battery may be at a low SoC or may experience inconvenient temperatures. Despite these problems, reasonable battery life must be achieved in the vehicle.

Another challenge with the 36-V lead–acid battery is manufacturing and quality control. The technology required for manufacturing the new VRLA types is demanding with respect to reliable, closely controlled, production processes. Plate thickness, reproducible weight of active material filling, reproducible composition of materials on assembly, quantity of electrolyte filling and pressure on the electrode plates on assembly are among the parameters that require much closer tolerances and control. Moreover, the costs will exceed those of present automotive batteries.

In addition to improvements at the cell level, measures have to be taken at the system level with two main targets in mind.

(i) A reliable state-of-health (SoH) indication is required for the battery. Because of the poorly defined working conditions, rapid deterioration of the battery may occur, which requires a timely indication.

(ii) Sophisticated refresh algorithms are necessary to keep the battery in good working condition. These algorithms have to consider both the SoH and the available energy of the vehicle PowerNet. For instance, if the battery SoC is low, the opportunity to recharge should be taken as soon as possible to prevent premature failure because of the partial SoC effect.

These initiatives will not, however, eliminate all the basic weaknesses of the lead–acid battery which prevent the system from being used under high-power, multi-cycle regimes. Estimated data for 42-V applications are shown in Table 7.

4. Favored applications of Ni–MH and Li-ion storage systems

As soon as high cycle numbers, high service life, and low extra volume and weight are required, the drawbacks of lead–acid imply the use of Ni–MH or Li-ion battery systems. Such is the case for all power-trains which are sustained electrically for boost and acceleration. This includes full hybrids as well as mild or soft power-assist hybrids—whatever they are called—with a power that exceeds roughly 10 kW.

The main advantage of Ni–MH is its outstanding cycle-life (Table 8) and the relatively low investment in research and development as well as in manufacturing facilities. The first cells that were used in HEVs were adapted from power tool types. Large-volume quantities of HEV batteries justify the development of dedicated ultra-high-power traction cells. It should be noted, however, that the cold cranking performance is in urgent need of improvement.

Li-ion cells are gaining market shares in all applications. Materials costs are competitive to those for Ni–MH. On the system level, the more costly single-cell supervision that is required for Li-ion compared with module supervision for Ni–MH units is offset somewhat by the high cell voltage,

Table 8
Comparison of Ni–MH and Li-ion batteries for mild power-assist applications

Ni–MH	36-V/28-Ah battery—load per cycle 7% DoD >200 000 cycles at 7% DoD 10-s peak discharge power: 10 kW at 27 V 2-s peak charge power: 12 kW at 48 V Cold cranking power: 6 kW at −25 °C for 3 s Total cell weight: 21 kg
Li-ion	36-V/19-Ah battery—load per cycle 10% DoD >150000 cycles at 10% DoD 10-s peak discharge power: 17 kW at 27 V 2-s peak charge power: 14 kW at 44 V Cold cranking power: 6 kW at −25 °C for >15 s Total cell weight: 9 kg

which reduces the number of Li-ion cells required to one-third that of Ni–MH. Among the great advantages of Li-ion are the cold cranking and low-temperature performance (Table 8). Besides costs, safety is another concern. Nevertheless, recent developments at both the cell and the system level have opened the way for the development of safe automotive Li-ion batteries [7]. Evaluation of a mild power-assist HEV battery showed that, on the cell level, about 50% of weight could be saved by using Li-ion cells, with approximately the same performance data. In the long run, there is reasonable incentive for the development of Li-ion batteries for HEV applications.

5. Conclusions

As the data presented illustrate, the requirements of the different applications determine the usability of lead–acid battery systems in cars. Because of the low cost and the high recycling capability, lead–acid will remain the solution of choice for the standard PowerNet. With growing demand for hybridization, however, even advanced lead–acid batteries are not suitable for all cars. The limits of lead–acid have been shown in this study and the following conclusions can be drawn:

- twin-battery systems (12-V/14-V) offer flexible adaptations to vehicle demands;
- stop–start applications are most likely covered by VRLA batteries;
- limitations of lead–acid are characterized by the 42-V soft hybrid;
- efficient fuel consumption reduction calls for the 42-V mild hybrid;
- the present status of lead–acid development does not allow the introduction of mild hybrids;
- advanced hybrid vehicles call for: (i) improvement in lead–acid cycle-life by a factor of three; (ii) reduction in Ni–MH or Li-ion battery costs.

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