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Performance requirements of automotive batteries for future car electrical systems

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Abstract

The further increase in the number of power-consuming functions which has been announced for future vehicle electrical systems, and in particular the effects of new starting systems on battery performance, requires a further optimization of the lead acid system coupled with effective energy management, and enhanced battery operating conditions. In the face of these increased requirements, there are proven benefits to splitting the functions of a single SLI battery between two separate, special-purpose batteries, each of which are optimized, for high power output and for high energy throughput, respectively. This will bring about a marked improvement in weight, reliability, and state of charge (SOC). The development of special design starter and service batteries is almost completed and will lead to new products with a high standard of reliability. The design of the power-optimized lead acid accumulator is particularly suitable for further development as the battery for a 42/36 V electrical system. This is intended to improve the efficiency of the generator and the various power-consuming functions and to improve start/stop operation thereby bringing about a marked reduction in the fuel consumption of passenger cars. This improvement can also be assisted by a charge management system used in conjunction with battery status monitoring. © 1999 Elsevier Science S.A. All rights reserved.

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1. Introduction

The demands on future automotive batteries will be influenced by the trends and key developments of the automotive industry as shown in Table 1.

2. Vehicle electrical systems

As an interesting example two different initiatives to reduce fuel consumption of passenger cars should be mentioned. The initial approach, to simply reduce the weight of components, does not necessarily lead to an optimum. Therefore, other possibilities such as the vehicle electrical system with improved electrical generation, optimized energy consumption and efficient energy storage became important. The argument: an average mid-size car with a fuel consumption of 10 l/100 km needs an additional 0.17 l/100 km for every 100 W of electric power. This corresponds to a weight increase of approx. 50 kg. In other words, we have to address the vehicle's overall efficiency.

Tables 2–4 show the development goals of the automotive industry in greater detail, as far as they have an impact on the electrical system [1–5]. These are arranged on the basis of the key focal areas already cited above.

Most of the above development goals must not be viewed in isolation, but in the context of networked projects which have a powerful impact on each other. For example, the electromagnetic valve actuation and the anticipated improvement in efficiency by reduction of the throttle valve losses need a far higher performance power supply. This in turn makes new alternator concepts necessary, involving a higher voltage level (42 V).

Fig. 1 shows an overview of the effects of the listed development goals on the electrical systems of future passenger cars in terms of the electrical power generated and consumed and the throughput of electrical energy (particularly with the vehicle battery) compared to a current-day passenger car of the upper mid-class.

Whereas

- alternator powers between 1 and 2 kW,
- cold-cranking power levels of approx. 4 kW, and
- an energy throughput of approx. 100 kW h within a

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Table 1
General development trends of the world's automobile industry

Reduction in fuel consumption and emissions
Increased comfort, safety and reliability
Reduction in manufacturing and maintenance costs
Improvement in the ratio between payload volume and total vehicle volume
New drive concepts

Each of these key aspects affects the vehicle's electrical system to a very considerable extent and therefore has a major influence on the development of the vehicle battery.

Table 2
Development goals for the electrical systems of passenger cars

Focal point 1: Reduction in fuel consumption and emissions
–Drive-related aspects
· Electromagnetic or electrohydraulic valve actuation (EVA)
· Electrical drive of the ancillary systems (beltless engines)
–Generation and distribution of the electrical energy
· Larger alternators with enhanced efficiency
· Additional 42/36 V vehicle electrical system
· Energy management
–Electrical consumers
· High-performance starter (e.g., in combination with alternator)
· Converting mechanical and/or hydraulic assemblies to electrical operation (including safety-relevant functions such as brakes and steering)
· Introduction of electrically preheated catalysts (environmental aspect)
–Weight reduction

Table 3

Focal point 2: Increased comfort, safety and reliability
–Electrical consumers
· More comfort-related functions (heaters, air-conditioning system, servomotors)
· Growth in safety-related electronic systems (directional control, dynamic behaviour of suspension)
–Systems and components to reduce the consequences of accidents
–Indicators for specific exchange strategies of wear parts

Table 4

Focal point 3: Reduction in manufacturing and maintenance costs
–Standardization of components through the use of global specifications
–Purchase from a small number of large suppliers (single suppliers, single sources)
–Increasing of maintenance intervals for systems and components
Focal point 4: Optimization of useable vehicle volume
–Miniaturization and combination of components and systems
–Increase in energy and power densities
Focal point 5: New drive concepts
–Automatic start/stop function for reducing idle running consumption
–Different forms of parallel hybrid with the options which exist for
· Boosting (support during acceleration)
· 'Sailing' (overcoming rolling friction and air resistance)
· Energy recovery

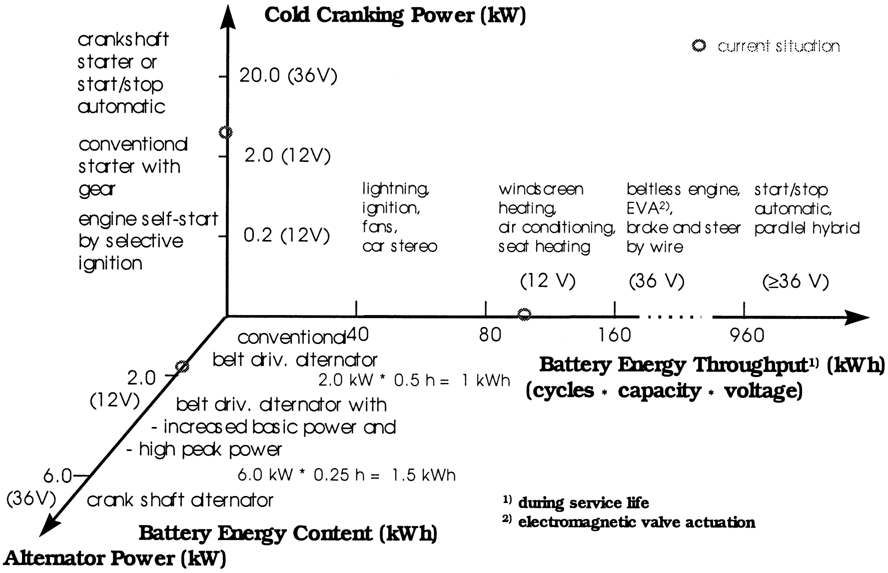

Fig. 1. Development steps of electrical systems in passenger cars.

period of approx. 4 years are common today, far higher values can be anticipated in the future.

The cold cranking performance for the crankshaft starter/alternator—which for the first time will provide a highly convenient and comfortable automatic start/stop feature—will need up to 20 kW very likely in conjunction with a 42/36 V vehicle electrical system. The alternator side of this electrical machine is likely to have an output of approx. 6 kW and to satisfy the necessary requirements for the fuel consumption reduction referred to as focal point 1.

The expected substantial increase in battery energy throughput is due to the additional power-consuming functions listed in Table 2 and/or the conventional functions converted to electrical drive in the 42/36 V electrical system. From experience gathered to date for the lead/acid system, this is likely to result in application problems if strict weight limits are to be obeyed.

The only exception to this general trend will be the changes in the nominal capacity of vehicle batteries where a rise in the range of 1–1.5 kW h will be relatively moderate. The reason for this is the increase of the alternator output. It is highly probable, however, that the nominal battery voltage of 12 V will be increased to 36 V.

The energy throughput required for introducing a vehicle drive system based on the parallel hybrid principle lies well outside the range of lead/acid batteries with the above capacities. Battery voltages will need to be dramatically increased for this particular application segment to a figure in excess of 36 V. Table 5 shows the relationships between the battery characteristics which are required and future electrical systems and their requirements.

The question is how the demands on future vehicle batteries, as set out in Fig. 1 and Table 5, can be satisfied by the lead/acid system. In principle, there are three possible solutions which can be implemented, either individually or separately:

- Use of a single vehicle battery with modified/adapted characteristics.
- Combination of special batteries with very different characteristics in a dual-battery system or multi-voltage system.
- Use of intelligent control systems, e.g. energy management, which can be used to improve the efficiency of batteries and adapt their characteristics.

In Table 6, the above considerations have been taken to define the development goals for lead/acid accumulators.

Fig. 2 shows the battery developments mentioned in Table 6 in a form which corresponds more or less to that used in Fig. 1. It provides a means of illustrating the possibilities for using lead/acid batteries in future vehicle

Table 5
Requirements by new electrical systems on the battery

	Voltage (V)	Energy content (kW h)	Energy throughput (kW h)	Starting power (kW)
Current electrical systems	12	0.4–1.2	40–120	. . . 4
Future electrical systems, conventional design	12 (36)	. . . 1.5	. . . 450	. . . 6
Crankshaft starter alternator	≥ 36 V	. . . 1.5	. . . 450 (1500)	. . . 20
Parallel hybrid (start/stop, booster, etc.)	≥ 36 V	1 . . . 2	. . . 5000	20

Table 6
Development goals for lead/acid automotive batteries

- –Maintenance-free SLI batteries of a particularly reliable construction
    - Weight-optimized and/or
    - Volume-optimized
- –Cycle-stable energy throughput batteries (AGM or Gel), suitable for use as
    - Universal batteries (SLI) or as
    - Supply batteries in the dual-battery system
- –POB for use as
    - Universal batteries (SLI) or as
    - Pure starter batteries in the dual-battery system
- –Batteries with a nominal voltage of 36 V in the versions
    - POB for general use or
    - HPB for use solely in the starter circuit
- –Battery modeling and monitoring for
    - Mathematical simulation of vehicle electrical systems during vehicle development,
    - Calculating the battery's SOC in the vehicle as a basis for energy management and
    - Display of the battery's SOH to improve the reliability of the electrical system and for optimizing service aspects

electrical systems. This shows that the current SLI battery is an extremely balanced compromise in terms of cold-crank performance, energy content and energy throughput and can be incorporated harmoniously into the vehicle electrical system of today.

Manufacturing costs have been minimized in the past with particular regard to the battery attributes characterized with the three axes. However, it is also clear that far better cold cranking characteristics must be achieved or that considerably higher energy throughputs may be needed. These technical solutions, particularly combined with the dual-battery systems, will inevitably result in higher production costs, however, and will therefore need to provide a far greater advantage in terms of the vehicle development goals under discussion. The following sections will therefore examine in detail the specific characteristics of the design variants together with the opportunities offered by intelligent monitoring and control units and the status of development work for the latter.

The following sections look at this development for vehicle batteries and examine promising solutions and the results achieved to date.

3. Current SLI batteries

Up until a few years ago, the main factor preventing a general move towards the maintenance-free automotive battery was the need to improve the lead alloys and the process for manufacturing the grids used in the positive electrodes.

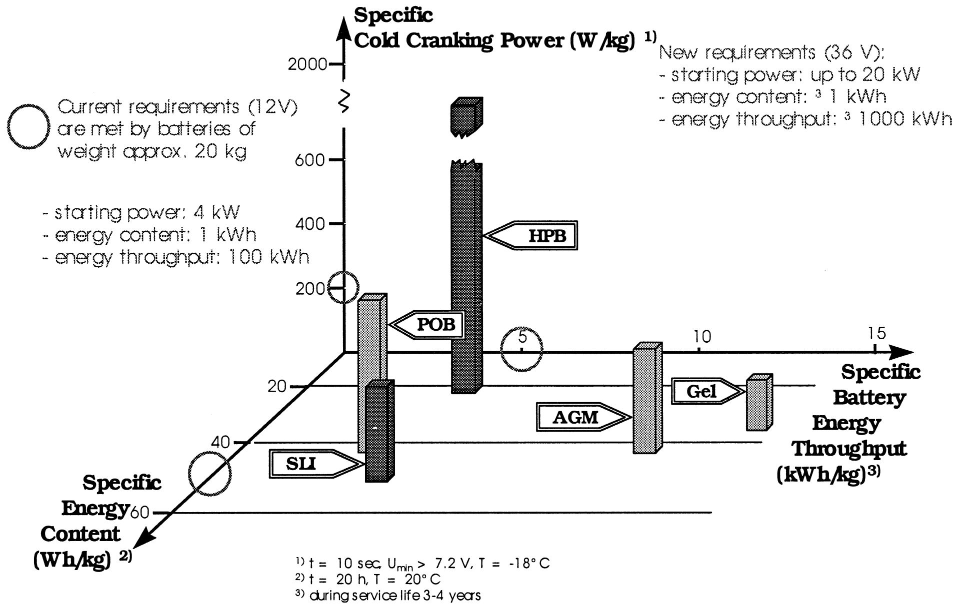

Fig. 2. Specific characteristics of lead acid starter batteries.

The problems in detail were:

- grid growth,
- grid corrosion,
- low charge acceptance following complete discharge (flat stand recovery), and
- capacity decay during cycling.

The relatively high tin levels in the positive grid alloys and a reduction in the calcium content resulted in the minimization of grid corrosion and poor rechargeability in the case of antimony-free starter batteries. Measures designed to enhance strength, such as cold rolling of the lead strip material used for expanded-metal grids and the addition of silver in conjunction with optimized grid structures in the case of cast grids, greatly reduce grid growth at normal electrolyte temperatures. When used at high temperatures, as is increasingly the case in modern vehicles where the battery is accommodated in the engine compartment, cast grids with new Ca/Ag alloys have proven particularly successful in preventing grid growth. Capacity decay under cycling and the effects of acid stratification in laboratory tests have been discussed for many years. This has been successfully overcome by:

- specifically modifying the battery design,
- special positive mass morphology, and
- ensuring a good grid connection to the positive mass in the case of Ca/Ca starter batteries within the typical specifications applicable in the vehicle industry.

Regarding safety aspects, sophisticated lid designs with the following features have become popular for wet, maintenance-free automotive batteries:

- protection against leakage while tipping by providing covers with a labyrinth structure,
- prevention of an external ignition by flame arrestors,
- providing comfortable fold-out handles for transport and handling.

The manufacturing costs of maintenance-free automotive batteries, with liquid electrolyte, which are now becoming industry-standard worldwide have been reduced considerably over recent years. Major reasons are:

- continuous plate production,
- highly automated battery assembly,
- water cooled fast formation, and
- grouping of the production sites into units of at least two million batteries per year.

As already mentioned, automobile engineers are directing their efforts towards reducing fuel consumption and, consequently, to raising overall vehicle efficiency. Since this can be achieved by providing the appropriate electrical energy, a particular development potential exists for maintenance-free SLI batteries by improving the average SOC. This can be achieved by energy management and by improving charge acceptance.

4. VRLA batteries of type AGM and gel

Many of the demands which would be made of future vehicle electrical systems can be met by using SLI batteries separated by microporous glass mat or with gelled electrolyte. In addition to the known characteristics of modern Ca/Ca batteries with liquid electrolyte, these batteries also feature

- absolute freedom of maintenance and, consequently,
- the avoidance of acid leaks with the charge gas,
- excellent charge acceptance,
- an improved energy throughput and
- either a high cold-start power density (AGM) or
- an additional advantage in energy throughput (Gel).

A further feature of the VRLA battery which is becoming increasingly important for future vehicle concepts is the possibility of fitting the battery in the passenger compartment, since there is no danger of acid leakage in the event of a crash.

Table 7 shows the typical areas of application for AGM batteries.

The above comparison shows the advantages of AGM batteries (Tables 8 and 9), particularly

- if a high energy throughput is required and/or
- the space available in the vehicle is limited.

The potential for cutting manufacturing costs is small due to the very demanding needs of an AGM battery employing oxygen recombination, a process which requires the use of expensive materials and very precise production operations. The production of mat-separated

Table 7
Typical areas of application for AGM batteries

–As a universal SLI battery
- Special-purpose vehicles with high energy throughput, e.g., passenger cars with electric catalyst preheating
- Top-of-the-range vehicles with large displacement engines (battery in trunk)
- Sports cars with very little space for assemblies
- Fitting in the passenger compartment

and naturally as a
–Compact service battery in all kinds of two-battery electrical systems with
- 12 V and
- 36 V nominal battery voltage

In order to emphasize the suitability of modern AGM automotive batteries for the above applications, the following table provides a comparison with a maintenance-free starter battery using liquid electrolyte.

Table 8
Comparison of AGM battery with maintenance-free battery, liquid electrolyte

(1) Electrical features	
–Spec. cold-start power (W/kg)	110–120%
–Spec. energy content (W h/kg)	80–85%
–Cold-start power density (W/l)	120–130%
–Energy density (W h/l)	85–90%
–Spec. charge acceptance (A h/kg)	110%
–Charge acceptance density (A h/l)	130%

starter batteries with excess acid (quasi-AGM) does not represent a feasible alternative given the attributes which are required.

Compared to AGM, Gel-type batteries are used in more specific areas of higher energy throughput and lower power applications.

5. Power-optimized (POB) and high-power batteries (HPB)

POB are interesting for high power cranking applications, e.g., for dual-battery-electrical systems with one battery for starting and one for energy throughput.

Many of the examples of development projects in the automobile industry with the goal of reducing fuel consumption are based on the concept of changing mechanic or hydraulic actuations to electric drives. The improvement in the vehicle's overall efficiency can nevertheless only be achieved if the following technical changes are made to the electrical system:

- increase in the alternator voltage to 42 V,
- increase in the large-power-consumer voltage to 42 V,
- covering short-term peak loads by means of a battery with 36 V nominal voltage and, in individual cases,
- splitting of the electrical store into a HPB and an energy throughput battery.

This gives battery manufacturers a development goal to produce a POB or HPB with a nominal voltage of 36 V (Fig. 3). The short-term peak loads in this context include, in particular, a new generation of starter motors which can start even large engines very quickly and with particularly low noise without the need for reduction gearing.

Table 9

(2) Service life	
–In cycles	
• In compliance with DIN	300%
–In calendar time, with constant ambient temperature	
• Grid corrosion	comparable
• Corrosion of neg. connector	comparable
• Grid growth	comparable
• Mass shedding	much lower
–In exceptional situations	
• High temperature	higher risk
• Recharge after deep discharge	comparable
• Separator fault, in particular with expanded metal grids	more frequently
(3) Manufacturing costs	much higher

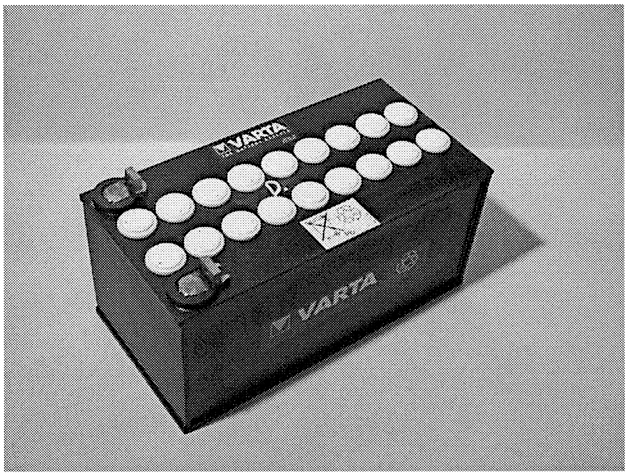

Fig. 3. 36 Volt Starter battery with 0.9 kWh.

The above application needs batteries with high power and equal or less capacity. Solutions are an optimized prismatic battery (POB) or a battery in spiral wound technology (HPB).

Type POB is a power-optimized battery in both 12 and 36 V versions which supplies high cranking power and peak currents without requiring excessive volume and weight for 'excess' capacity. K factors (CCA/C20) up to 10 are possible.

Type HPB is a high-power battery which is meant for vehicle use in conjunction with a cycle-stable service battery. These cells—under development by JCI using very thin electrodes—have a very high cranking current at a low capacity and low weight. HPB batteries could be, e.g., well suited for starting large combustion engines with starters that are mounted directly on the crankshaft without gear reduction.

6. Battery modeling and battery monitoring

A mathematical description of the lead/acid battery is generally extremely difficult. Changes in mass and energy transfer which are due to heat and aging, coupled with various phase conversions and the effect of geometry and mass morphology mean that models can become extremely complex.

Calculations to simulate starter batteries under the conditions found in the vehicle are particularly complex due to the frequently changing charge and discharge processes, whose duration and intensity are statistically distributed (Fig. 4). Nevertheless, it has proven possible to develop battery simulation models which can be used along with mathematical models for the remaining components of the

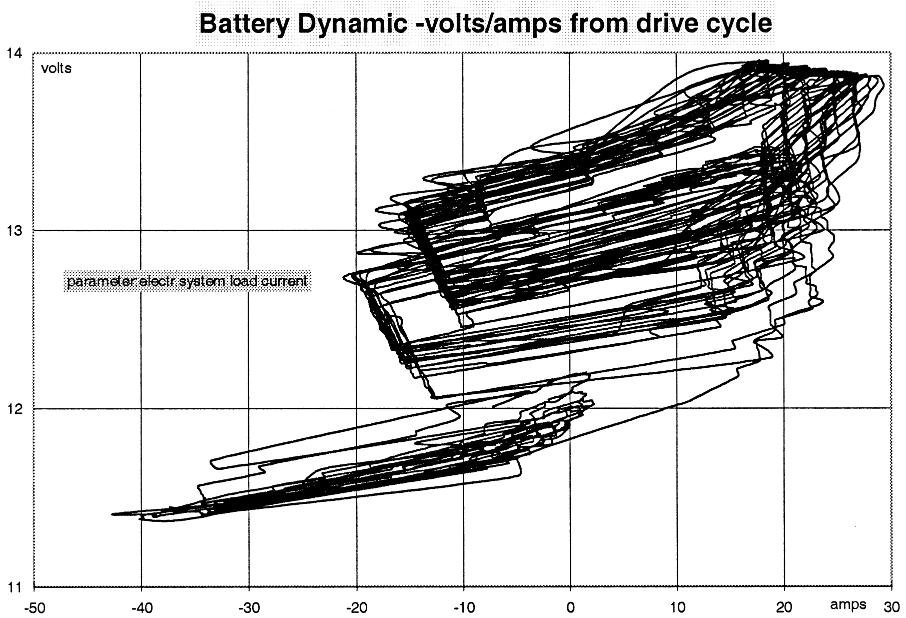

Fig. 4. Current/voltage behaviour of a typical drive cycle.

vehicle electrical system in order to design and optimize the entire vehicle electrical system.

Fig. 5 shows the high degree of agreement between the battery terminal voltage and the calculated voltage response of the model for a specified current profile. Other development operations involve the improvement of the dynamic response of the model across a broad temperature range as a function of different aging profiles.

Things are not much easier as regards continuous recording of the SOC referred to a defined discharge for an SLI battery in the vehicle. The only practicable solution is a simplified model which takes the form of a battery equivalent circuit diagram coupled with a dynamic adaptive system which, for a given current profile, uses the difference between the battery voltage and the voltage response of the equivalent circuit diagram to continuously calculate the battery parameters which are of interest, with elimination of measuring and sequencing errors [6].

The purpose of endeavours to calculate the SOC is to establish an energy management system in the vehicle and to use the possibilities which this gives to improve the efficiency of the vehicle electrical system and to optimize

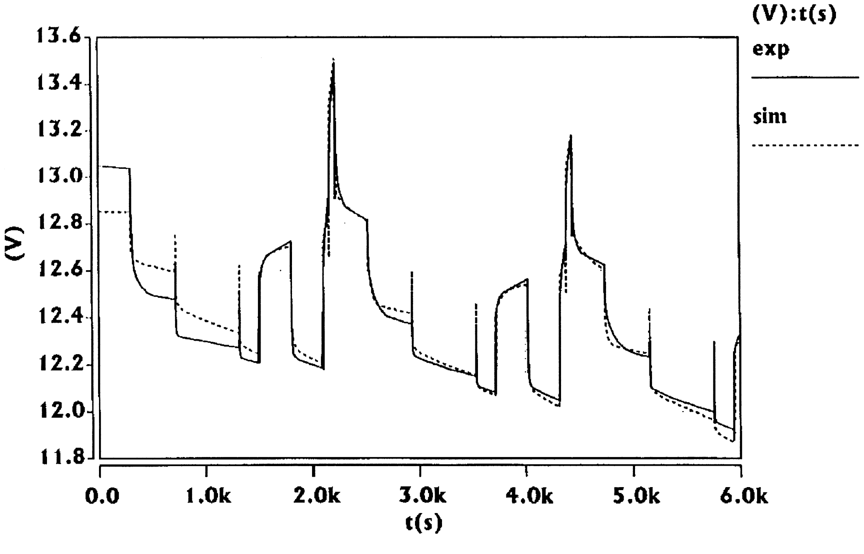

Fig. 5. Comparison of battery to model voltage responses.

the components of this system. The following temporary measures to improve the charge balance in the vehicle are being discussed:

- increasing the charging voltage
- increasing the engine's idle speed
- shutting down power-consumers based on a list of priorities.

The ability to record the battery's state of health (SOH) is also of particular interest for the vehicle manufacturer. This would allow a defined battery exchange strategy by the driver or service personnel in order to enhance the overall reliability of the vehicle. One side effect would be the use of SOH to calculate the SOC. In this case too, a combination of battery parameter measurement and calculation through modeling which takes into account battery parameters will achieve the desired result.

7. Summary

The future development of the vehicle electrical system will make it necessary to have batteries with 36 V, with higher cranking performance and higher energy throughput.

Most of these targets can be achieved by lead acid batteries, based on the Ca/Ca maintenance-free system, improved in cold cranking power (POB and HPB) and/or improved in energy throughput (AGM and Gel) in 12 and 36 V versions. Battery monitoring will be essential for achieving further improvements in battery characteristics.

The possible introduction of new drive concepts consisting of different types of parallel hybrid can be expected to give rise to energy throughputs which can not be achieved with lead acid battery designs that are known today. In these cases, batteries of nickel/metal hybrid or Li-ion will have their future application.

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