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Vehicle electric power systems are under change! Implications for design, monitoring and management of automotive batteries

Eberhard Meissner*, Gerolf Richter

Varta Automotive, Vehicle Electric Systems & System Development, P.O. Box D-30405, Hannover, Germany

Abstract

New technical features, the demand for fuel economy, and the potential to reduce production and operational cost are leading to additional and more powerful electrical consumers and making the overall electrical demand in vehicles increase. Vehicle electrical architecture is performing an evolutionary change to improve the efficiency of production, distribution, control and storage of electrical energy in the vehicle.

New battery designs with performance patterns designed for the new architectures are needed, and some of the new demands may even exceed the capability of lead/acid batteries. Single and dual battery systems offer a wide variety of applications when combined with intelligent means to keep the batteries in an appropriate operational window. Detection of state-of-charge (SOC) and state-of-health (SOH) is essential to help the battery to fulfil its role as a key element for vehicle functionality and safety. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Automotive battery; SLI; Vehicle electric power system; 42 V PowerNet; Battery monitoring; State-of-charge; State-of-health

1. Introduction

The overall electrical demand in vehicles is going to increase: new technical features, the demand for fuel economy without comfort losses for the customer and for higher reliability to supply safety-relevant devices (x-by-wire), and the potential to reduce production and operational cost leading to additional and more powerful electrical consumers.

To meet these demands, the vehicle electrical architecture is going to change. Dual battery, dual voltage (14 V/42 V), and high voltage systems, starter/alternator integration, recuperation and boosting, etc. (which may be realised independently or in combination with each other) are under discussion to improve the efficiency of production, distribution, control and storage of electrical energy in the vehicle.

Intelligent means to keep the batteries in an appropriate operational window, and detection of battery state-of-charge (SOC) and state-of-health (SOH) become more essential when new types of duties raise to the batteries with high specific battery power and energy. Some of these demands may even exceed the capability of lead/acid batteries [1,2].

These developments generate more consequences for the battery industry than just providing batteries of standard technology for 14 V and for future 42 V systems: the basic technical and economic motivation which dictates the electrical architecture changes the role of the battery from a passive component to a pivot unit which has to be monitored, supervised and managed to maintain the vehicle functionality and safety.

2. Analysis of technical demands on the battery

The technical demands on the battery for these innovations are manifold:

- new cranking technologies, which accelerate the combustion engine from stand still to idle speed within some hundreds of milliseconds [3], reducing both exhaust and noise emissions, need high discharge power; the situation is aggravated if simultaneously an electrically heated catalyst has to be powered;
- increased energy demands during engine-off and idle periods need high battery capacity, and if this situation occurs many times, high cycling capability;
- as energy taken from the battery during such periods has to be recharged quickly to provide repeatable function, good recharge capability is needed;

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[*] Corresponding author.

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- high reliability for cranking and providing energy to safety-relevant components may be provided by redundancy from multi-battery architectures and/or battery monitoring and management [4];
- the situation is aggravated when start/stop function or even boost/recuperation function are implemented in the car: periodically a lot of electrical energy has to be provided during stand still, to crank the engine, and even to assist during vehicle acceleration. The energy given before has to be recharged a.s.a.p., and very high recharge power has to be accepted to recover braking energy.

These various functions may be realised independently or in combination with each other. It is obvious, that there is no universal battery which can fulfil all these types of duties at the same time efficiently with respect to technical and cost constrictions [1,2]. Specialisation in battery design will be needed to follow this development.

The development of vehicle electric systems operating at a nominal voltage of about 42 V compared to the present 14 V level is proceeding rather quickly (cf. the papers collected in [5]). The voltage level of 42 V is chosen as a compromise between the demand for an increased voltage to achieve higher efficiency in electrical and electronical components, and to exclude safety hazards even under extreme operational conditions like load dump, etc. The term "42 V PowerNet" or simply "PowerNet" is now established world-wide.

The American MIT 42 V Automotive Electrical System Standards Group (MIT/Industry Consortium) and the European Vehicle Electrical System Architecture Forum 'Forum Bordnetz' bring together ideas, concepts, and technical solutions for the 42 V PowerNet. The 'Forum Bordnetz', comprising most of the European car manufacturers and their suppliers, has established a standards group as early as 1998. This group has worked out a draft standard to give basic specifications of voltage levels in the 42 V PowerNet without prescribing specific technical solutions, e.g. architectures or battery technologies. This draft standard was submitted in April 2000 to the international standards boards (cf. [6]).

To find the appropriate battery solution for a vehicle, the functional goals of the system and the motivations of the vehicle manufacturer have to be defined to quantify the technical demand (energy/power versus time profile) of the whole vehicle electric system in the expected operational scenarios. From the real overall electrical demand, the electrical demands on the battery can to be deduced. However, this will depend not only on the power demands of the various electrical consumers in the vehicle, but also on the overall design of the electrical harness, the characteristics of power generation (alternator including its electronic control; possibly dc/dc converters, etc.) and especially on the expected characteristic operating profiles.

This analysis brings up the performance profile of the battery needed. For possible approaches, which may be of single or multi-battery type, having more or less effort on battery monitoring and management, etc. weight, volume, packaging, cost, durability, reliability, etc. have to be quantified. These data are fed back to the designers of the electrical system, which optimise alternator, battery, power converters, etc. iteratively and may even modify the layout of the electrical system completely until a technical and cost effective solution has been created.

This iterative process among vehicle manufacturer, system designer and battery manufacturer is essential to improve mutual understanding which is a precondition for finding good overall solutions. To provide this, a questionnaire has been developed to support this process of iterative optimisation. It allows for analysis if the profile of demands can be covered by a single battery, or a combination of two batteries specially designed for different performance can be a better solution. Furthermore, the operational range in terms of battery temperature and SOC allows for estimation of the limitations in functionality, also when the battery is going to wear out, i.e. the implications of battery SOH.

This questionnaire saves a lot of time at the side of both carmaker and battery manufacturer to work out what battery properties are really needed, and for quantification of those needs. As the introduction of new electric architectures are driven by functions which cannot be realised with the standard approach, the relative importance of various battery properties is usually different from those of standard SLI batteries.

In Fig. 1, a spider diagram is given, which shows schematically the relative values of various battery properties like available energy at low and high rate, available discharge power at low and ambient temperature, recharge capability, and possible overall energy throughput, i.e. cycling capability.

Every battery can be characterised by such a spider diagram, which of course can be further extended to include electrical properties like self discharge, mechanical properties like weight and volume, or even commercial data like cost. And every application can be characterised by a similar spider diagram, describing the smallest (hypothetical) battery optimised for exactly the very application. The (real) battery fitting best for a very application has a spider diagram which envelops the spider diagram of the application without too much variation.

When only the battery size is changed, i.e. capacity or voltage (or both) are varied without design change, the *absolute value* of these properties are scaling accordingly (cf. Types 1a and 1b in Fig. 1). But the *relationship* between the values of the properties, i.e. the pattern of the diagram, remains unchanged, if there is no change in cell design.

When the spider diagram of demands for a special application has been developed, the battery type fitting best can be selected. It is obvious from Fig. 1 that using just a larger type of battery (either higher capacity or higher voltage) will be the right choice only if the ratio between the values of the various properties, i.e. the pattern in the

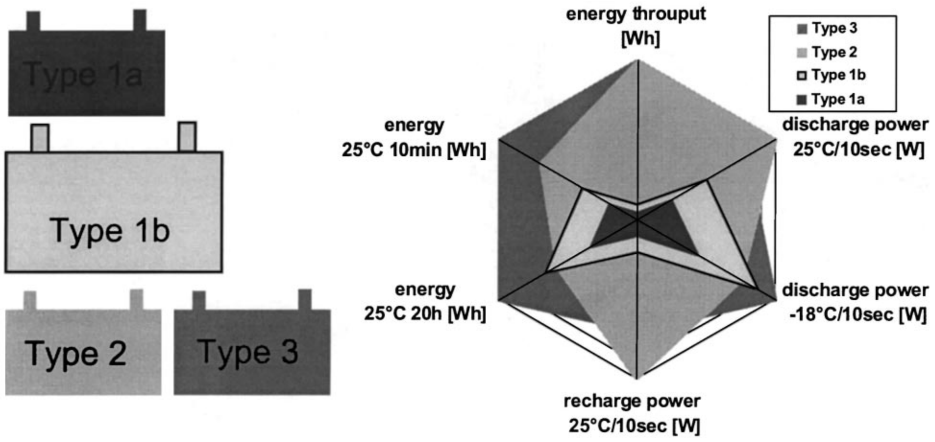

Fig. 1. Spider diagram for for different batteries: Type 1b is of same design like Type 1a but of larger size; i.e. the values all properties are higher by the same factor, their relative ratio is the same; Types 2 and 3 are of different design.

spider diagram, is the same. Otherwise, if the pattern of the application and the battery differ too much, preferably another type of battery should be selected.

Today, there is a much larger variety of battery designs available for selection than some years ago. Besides standard SLI batteries, there are prismatic lead/acid derivatives like the power optimised battery (POB) and AGM designs [7,8] (v.i.), and spiral designs like Inspira® [9,10].

Furthermore, nickel metal hydride batteries of both prismatic and cylindrical cell design are now available for automotive use, and lithium ion and lithium ion polymer batteries are in an advanced state of development. Also super capacitors and fuel cells are under consideration for road vehicles. To retain its position also in the market of advanced vehicle electric systems, the lead/acid battery of standard design will have to compete.

The dissolution/precipitation process as the main reaction of the lead/acid system is a fundamental handicap for both cycle life and recharge performance, especially at low temperatures: structural information is lost upon cycling, as the electrode morphology of both electrodes is changing during operation (which may induce failure modes like softening, shedding, mossing, dendrite growth, and reversible capacity decay [12]), and the dissolution rate of lead sulphate limits recharge at high rates especially at low temperatures. As the sulphuric acid electrolyte is involved in the main reactions, depletion processes show up at high discharge and recharge rates.

On the other side, electrodes involving only solid state reactions like nickel oxide, hydrogen storing alloys, Li(C_6), etc. do not show shape changes with their main reactions (however, there due a lot of secondary reactions, too, acting on a longer time scale!), which makes these appropriate for applications with very high cycling duty. As the solid state diffusion of hydrogen and lithium in their electrode matrix is less rate limiting at low temperatures than the dissolution of lead sulphate, the recharge behaviour of lead/acid batteries is outperformed by far by Ni/MH and LiIon batteries especially at low temperatures [15,16].

The strengths of the lead/acid system are its excellent high-rate discharge capability, good specific energy, high reliability and robustness, and low cost in both manufacturing and recycling, as they are manufactured mainly from a single low-cost raw material.

3. Batteries designed for special purposes

Analysis of the demands of the automotive manufacturers shows that two types of battery different from the standard SLI types are needed already short-term

1. a high-power battery providing high voltage also under cold cranking conditions for applications like SLI in diesel engines and for cranking of vehicles with dual battery systems;
2. a battery for extended cycling duty, i.e. higher integral energy throughput for applications like taxi cabs and for power supply of vehicles with dual battery systems.

The application field (a) is covered with the POB, which provides a much higher ratio of cc amperes per ampere-hour of capacity than standard SLI lead/acid batteries. This is achieved by using special plates with reduced height, which reduce the internal resistance of the battery significantly. The container height is only 140 mm compared to 175 and 190 mm of the standard DIN series, while the footprint of the battery is kept the same. Fig. 2 sketches the low plate height compared to standard plates and sketches the beneficial effect on the equipotential curves on the grid (cf. [11]), providing higher voltages at high discharge rates. Fig. 3 shows the improved voltage curve: the initial cold cranking voltage of POB is about 0.5 V higher at about 20% higher specific current (A/kg).

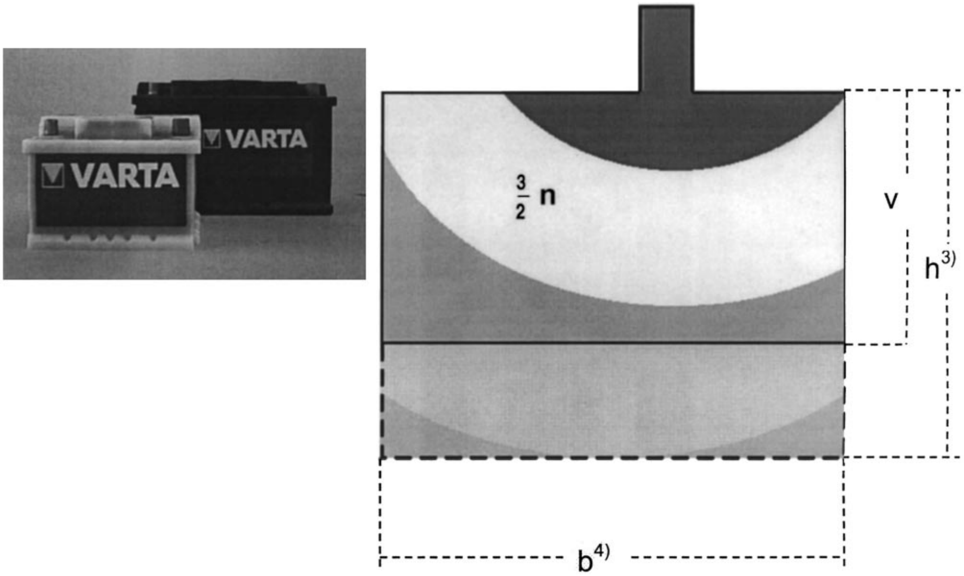

Fig. 2. Power optimised battery (POB): low plate height reduces internal resistance and provides higher voltages at high discharge rates; container height is only 140 mm instead of 175 and 190 mm of the standard DIN series.

The application field (b) is covered by the AGM design. Mechanical compression on the active materials, provided by the absorptive glass mat which immobilises the electrolyte, improves cycle life significantly as shown in both extended taxi field tests and laboratory tests (e.g. [7,8]). Battery life was extended in taxis by a factor of 2.5–3 compared to a robust design with free electrolyte. Furthermore, AGM design is vibration proof, free of spillage, maintenance free, gives higher cold cranking power per volume, and shows better charge acceptance and recovery from deep discharge than standard designs.

Despite significant improvements in cycle life, the integral energy throughput of AGM batteries of standard size (i.e. ~500–1000 W h) is limited to some hundreds of kilowatt hour. This is high compared to SLI designs with liquid electrolyte, but may not be sufficient for start/stop systems when the start/stop function is used extensively. If the vehicles would need only about 500 W at stand still (a number which may be much higher under harsh conditions), the battery may last 1000 h of stop mode at maximum — if there were no further cycling duties at all. This may be sufficient for customers with limited downtown driving (but for them start/stop concepts are of little benefits), but not for courier and delivery services (where start/stop may save a lot of money). In those cases, nickel metal hydride systems, which can be cycled about 5000 times their nominal capacity (at 80% depth of discharge, and much more with shallow cycling [1,2,13]), may be the appropriate choice.

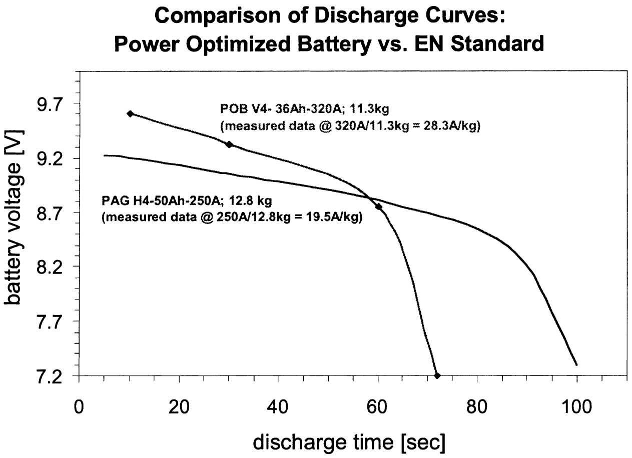

Fig. 3. Discharge curve of power optimised battery (POB) vs. reference.

This course estimation shows the open border of the use of AGM batteries versus other electrochemical storage systems in future vehicle electric systems with high cycling duty.

The ultimate high-power design with thin-film electrodes is realised with the Inspira® [9], which can provide very high power for short periods of time — exactly what is needed for quick starting concepts, e.g. crankshaft starter/alternators [3].

4. Approaches for new vehicle electric power systems

The changes of the vehicle electric power architecture are expected to proceed in an evolutionary rather than a revolutionary way. The automotive industry and their suppliers are aiming at solutions comprising the 42 V PowerNet [5,6] to be open for technical solutions with very high power demand. However, due to cost considerations as well as uncertainties with respect to availability and reliability of newly designed components, modifications will be introduced stepwise only when really needed. This process is expected to last many years. Therefore, besides considerations about the long-term solutions of vehicle electric power architecture and its implications on battery design and manufacturing, the possible intermediate steps have to be considered carefully by the battery industry.

Several of the new functions, especially those aiming at improved reliability and comfort, can be realised already on the basis of the existing 14 V electrical system.

A dual battery system, e.g. may guarantee the capability to crank the combustion engine and to keep the mobility of the vehicle even in extreme operating scenarios and in case of failure or misuse of the power supply system. Two different batteries, specialised for high discharge power (cranking) and high energy storage and cycling (energy), respectively, are combined with a control unit to keep the SOC of the starting battery high. Furthermore, the control unit handles irregular situations to make maximum use of the redundancy provided by the dual battery concept.

4.1. Example: vehicle with dual battery 14 V/14 V electrical system

Vehicle electric systems comprising the dual battery approach have been developed by Robert Bosch GmbH and VB Autobatterie GmbH to be on the market in 2001. Long-term tests with experimental cars having implemented this electric architecture show that this concept can fulfil the expectations under both usual and unusual conditions.

Fig. 4 shows an example for the electrical system layout. While a cycle-poof AGM battery, directly connected to the consumer harness and to the alternator, is buffering electric energy just as in conventional vehicles, a high-power battery (POB-type) is provided for the cranking operation only. The POB is recharged via the control unit from the alternator (or the AGM battery) via a dc/dc converter, which gives recharge priority to the POB. As the dc/dc converter is used only to recharge the POB, its voltage can be controlled according to the battery's needs only. So elevated recharge voltages can be applied without compromising other electrical components like headlights, etc. and recharge can be terminated when the POB has reached sufficient SOC to avoid overcharge. This intelligent recharge strategy considers both battery temperature and duration of recharge.

Fig. 5 compares the recharge current, measured 10 min after start or recharge, achieved by the temperature-controlled recharge voltage, with a recharge at constant 14.4 V independent of temperature (N.B.: 14.4 V is already more than most of the batteries see at their terminals today!), at SOC values of 10, 25, 50, 75, and 100%. To make this number independent of battery size, it is normalised to the 20 h nominal current I_{20}. The figure shows the significant improvement at lower states of charge in the critical temperature range between +10 and −10°C. At even lower temperatures, further elevation of the recharge voltage would be of little effect. At higher SOC and higher temperatures, the intelligent recharge avoids overcharge, i.e. the current is lower than the reference.

This dual battery approach provides a fully charged cranking battery to guarantee mobility, even when the energy battery is down due to over-discharge or failure. Furthermore, the control unit is by-passed, supplying energy to the electrical harness from the POB when necessary to keep the vehicle operable also after cranking.

This is one example for a dual battery design. However, high mobility, i.e. high reliability for cranking, is not the only goal which can be approached with a dual battery design.

Table 1 comprises various designs with two batteries, aiming at different goals like cranking reliability, extreme needs for cranking power, the operation of an electrically heated catalyst, or the supply of systems needing very high reliability like electrical power braking and steering. Of course, more than one individual goal can be achieved by a dual battery system of appropriate design simultaneously.

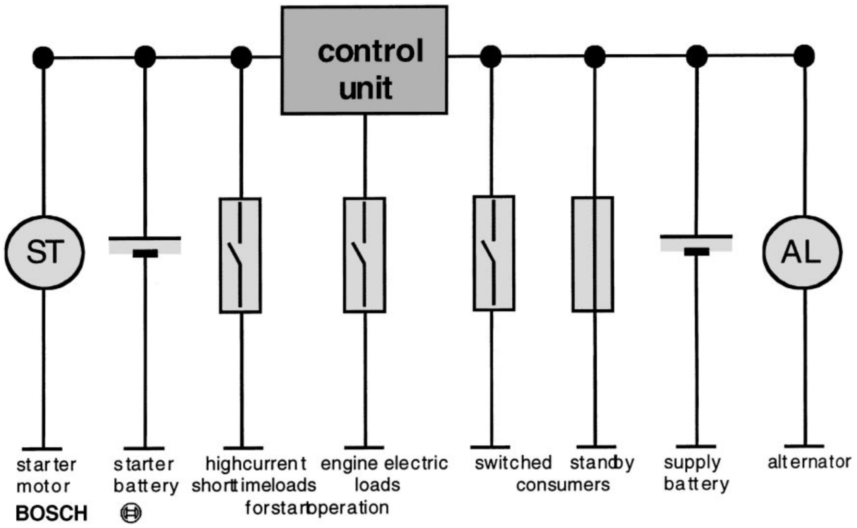

Fig. 4. Layout of an 14 V/14 V dual battery vehicle electric system.

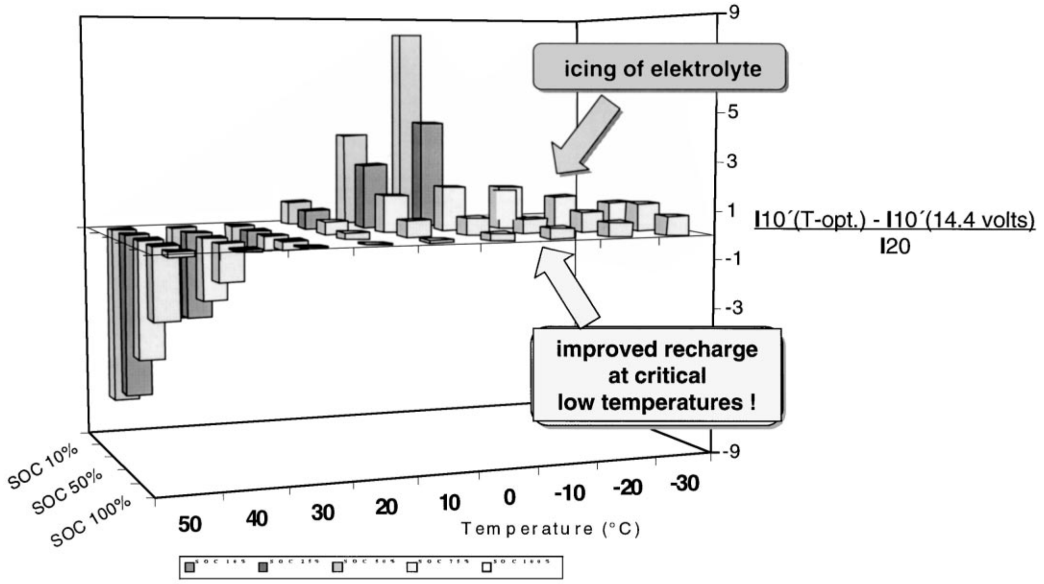

Fig. 5. Improvement of recharge current $I_{10'}$ (10 min after start of recharge) at temperature-optimised voltage vs. standard 14.4 V recharge (in units of 20 h rate current I_{20}).

To make full advantage of the two independent batteries, the control unit should comprise individual recharge and a sophisticated switching strategy to conduct energy flow also in extreme situations (e.g. high quiescent loads due to defects, battery defects, extended traffic jam in cold or hot climate, etc.). Table 1 shows features which can be realised with a dual battery approach, still on the present standard 14 V level. Other new features, e.g. high-effective starter/alternator concepts [3], electromagnetic valve actuators, electrical power steering, electromagnetic brakes, or simply windshield heating, are meaningful or even feasible only in new electrical systems with elevated voltage [5], including batteries of new design and technologies, and/or advanced battery monitoring and management [1,2,8,13].

Due to the "activation hill" of increased cost upon introduction of any new system, the time scale for volume production of vehicles comprising 42 V systems is still vague. However, manufacturers have already announced to start production in 2004 [14]. But once the 42 V PowerNet is realised in a vehicle, the manufacturers will convert many functions to the new voltage level when the meaningful and relevant components are available at low cost. Dual voltage approaches 14 V/42 V, partially comprising two batteries at the two voltage levels, are under discussion for the interim period [4].

Whatever the final design of the vehicle electrical system may look like: there will be more electrical power needed on board than today, and as this will be the case also when the vehicle is on standstill, and as the alternators are chosen for the average rather than the maximum power demand, the battery will have to bridge even more than today. In addition, for systems needing a high-reliable power supply, the battery has to serve as a fall-back in case the alternator does not provide power (enough or at all). Therefore, battery monitoring and management will be of higher importance than today to keep the battery in a good operational range, to check its actual state, and to predict its capability in the near future. Again, this is true already for advanced vehicle electric systems on the 14 V level.

5. Battery monitoring and battery management

As battery performance depends on temperature, SOC and SOH, it is essential to measure or estimate these properties to guarantee full functionality of electrically powered components, for triggering means to keep the battery in its best operational window, and for early detection of limited battery functionality. Battery monitoring allows for best use of the capability of a battery of given size, to guarantee

Table 1

	Type of battery 1	Type of battery 2	Features (optional)	Goal
1	High power	High cycle and energy	Recharge preference to battery 1	High cranking reliability
2	Standard (high power)	Standard (high cycle)	Recharge preference to battery 1	Very high cranking power
3	Standard	Standard (high cycle)	Recharge preference to battery 2	Electrical heated catalyst
4	Standard (high power)	Standard (high cycle)	Recharge preference to battery 1	Redundancy for systems needing high reliability
5	Ultra high power	High cycle	Recharge preference to battery 1	Weight saving

power supply for high-reliability devices, and for replacement strategies.

Strategies for SOC and SOH have to be chosen according to the goals which are aimed at, including expected operating scenarios and acceptable error tolerances. Various approaches are under development, including those with and without sensing of battery current.

5.1. Definition of state-of-charge (SOC)

Surprisingly from the first glance, a lot of misunderstanding usually comes up when discussions on SOC and SOH enter into detail. Obviously, the meaning of these terms is not commonly understood. As finding values of SOC and SOH is not a goal itself, the attitude towards these terms strongly depends on the ultimate goal of the individual. And as these may differ very much, a common sense definition of SOC and SOC is essential.

This seems to be easy in case of state-of-charge, which from the view of battery people is simply the percentage of electrical charge actually stored with respect to the total storage capacity: SOC = actual stored capacity/total storage capability.

However, is this the total storage capability, the nominal or the actual capacity, and what discharge rate is meant? Nominal rate (e.g. the 20 h rate for SLI batteries) is much lower than typical discharge loads, and the actual temperature is rarely the nominal one. And what about reduced residual discharge capability after previous discharge, at low temperature, or when already ageing has taken place?

Automotive people are interested in the amount of charge they can get right now from the battery, including the actual status of the battery.

Fig. 6 may help for visualisation of a definition of SOC as a monotonous state function, which does not change with temperature changes or with time (expect of self discharge) without an electrical current flowing. Therefore, algorithms and mathematical treatments can be easily applied to such SOC values. This SOC can be compared with the filling state of a barrel, independent from the properties of the inlet or outlet, which may charge in the case of a battery showing a distinct dependency on temperature and SOC itself.

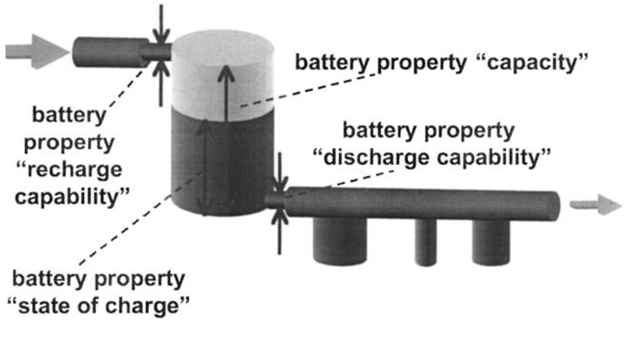

Fig. 6. Visualisation of term ‘‘state-of-charge’’ using a barrel with inlet and outlet.

Many approaches have been made to implement SOC sensors within the lead/acid battery, making use of property changes of the electrolyte like specific gravity (SG), conductivity, refraction, vapour pressure, etc. However, as most of them can do only a local measurement in a single cell, the relevance of such data for the behaviour of the overall SLI battery of today six and possibly in future even more cells is limited. In addition, cost considerations give a harsh limit to such sensors in the automotive industry.

The equilibrium open circuit voltage (OCV) after extended periods of relaxation time is a good way to measure SOC from the outside of a lead/acid battery. Due to the simple, nearly linear relationship between SG of electrolyte, OCV and SOC, the state-of-charge can be calculated as

$$\mathrm{SOC} = \left(\frac{\mathrm{OCV}_{\mathrm{actual}} - \mathrm{OCV}_{\mathrm{min}}}{\mathrm{OCV}_{\mathrm{max}} - \mathrm{OCV}_{\mathrm{min}}}\right) \qquad (1)$$

where $\mathrm{OCV}_{\mathrm{max}}$ and $\mathrm{OCV}_{\mathrm{min}}$ are equilibrium open circuit voltages at two different SOC values, e.g. 100 and 30%, marking the linear, and for SLI application, relevant range of values.

Unfortunately, this definition of SOC alone is of little use with a car battery, which scarcely ever shows an equilibrium open circuit voltage (OCV) after an extended relaxation time. Fig. 7 shows the curve of voltage versus current during a driving period of a car. This series of hysteresis-like patterns, sketched in Fig. 8, which is limited at high voltages by the regulator voltage, depends much on temperature, initial state-of-charge, and especially the actual load profile. With low loads, the battery current is scarcely negative, while discharge currents exceeding −40 A can be seen in the example presented in Fig. 7 for a driving period comprising high loads. It is obvious that simply taking the actual battery voltage is an inappropriate way to estimate SOC.

But even when the car is parked, it is unknown if there was a recharge period just before, and the OCV needs many hours or at low temperature even some days to achieve its equilibrium. In addition, the rather high quiescent loads of today’s cars reduce the measured voltage always below the ‘‘true’’ OCV. This has to be considered with state detection as described in Section 5.3.

5.2. Definition of state-of-health (SOH)

For state-of-health, the individual understanding of different people diverges even more. What characterises a healthy battery, and when is it called old? A battery may be not able to fulfil a special specification, but is still ready to do another.

Therefore, a definition is chosen which defines SOH using the power profile which describes the duty the battery really has to do in reality. Under the load of this power profile $P(t)$ or current profile $I(t)$ of duration t_0, which may depend on time t, the voltage of the battery will show a minimum (U_{min}). In the simple case of a load independent of time, this

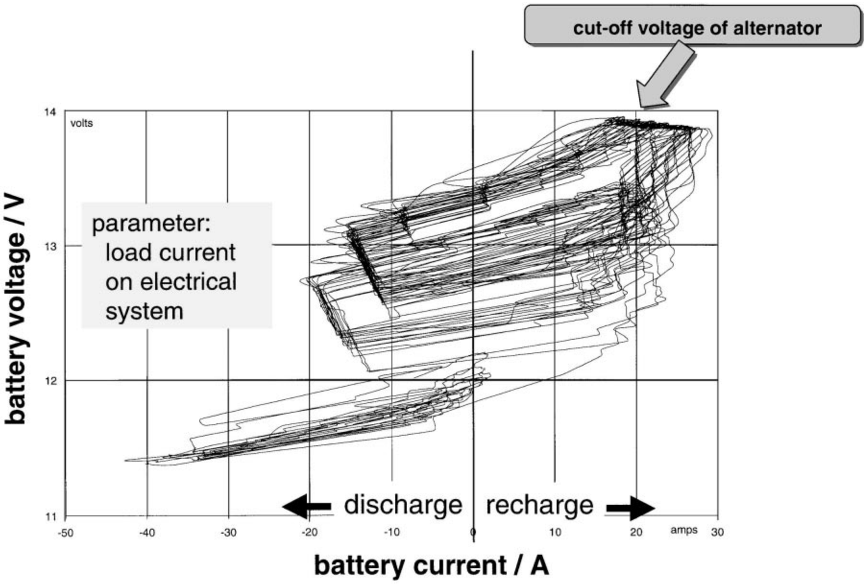

Fig. 7. Example for battery voltage vs. battery current curve under high load.

will happen at t_0. The lowest acceptable voltage under load (U_1) for the application in question, and the lowest voltage (U_{fresh}) of a typical fresh battery are used to define SOH according to

$$\text{SOH} = \left(\frac{U_{\min} - U_1}{U_{\text{fresh}} - U_1}\right) \tag{2}$$

with this definition, also SOH is a monotonous state function with distinct values, which can be used for mathematical treatments, instead of fuzzy states like ‘‘fresh’’, ‘‘aged’’, ‘‘old’’, and ‘‘worn out’’. A fresh battery is given the nomination $\text{SOH} = 1$, a battery just meeting the threshold is named $\text{SOH} = 0$, and negative SOH values are given to batteries which fail the specified duty. SOH has a characteristic dependency on temperature and SOC, which can be used to deduce to SOH values at other temperature/SOC combinations.

5.3. Battery state monitoring

Upon driving, the current flow to and from the battery can be measured, and from balancing of these charges, the actual SOC can be calculated. However, current integration will give the more deviation the longer it is done. Therefore, regular standstill phases are needed which are long enough for an algorithm to estimate the ‘‘true’’ OCV from the OCV(t) curve. As described in Section 5.1, the algorithm has to consider both temperature and (if necessary) quiescent loads. The SOC value calculated from that estimated OCV may serve as a reset.

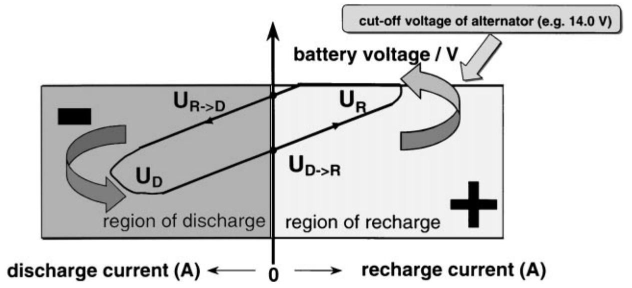

Fig. 8. Sketch of hysteresis-like patterns of battery voltage vs. battery current curves.

Besides SOC, a valuation of its capability to provide power is needed. The best probe to estimate the actual battery resistance is its voltage response on a high-current load. Cranking gives excellent opportunity for such a procedure. In Fig. 9, battery voltage and current during the cold cranking of a 1.8 l diesel engine at −18°C are presented. Clearly the sinusoidal shapes from compression and decompression can be seen. Fig. 10 shows the same data as a voltage versus current plot. The linear relationship indicates the Ohmic behaviour of the battery at very high rates during the short period of cranking, which allows for calculation of an internal resistance which is typically in the range of some milli-Ohms. Of course, the value achieved in this was has to be corrected again for battery temperature and SOC.

From the actual SOC (taken from the a reset calculated from voltage readings, and tracked by current integration) and the battery resistance (taken from the last cranking and corrected for changes of battery SOC and temperature in the meantime), a prediction can be made how the battery is expected to behave under a certain load profile. Comparison of the expected minimum voltage ($U_{\min}$) with the threshold value (U_1) and the voltage of a fresh battery according to Eq. (2) allows for a valuation of actual battery state-of-health.

For this prediction of future battery behaviour under load, more or less sophisticated models of battery behaviour can be used. On the other side, a high-sophisticated model of the

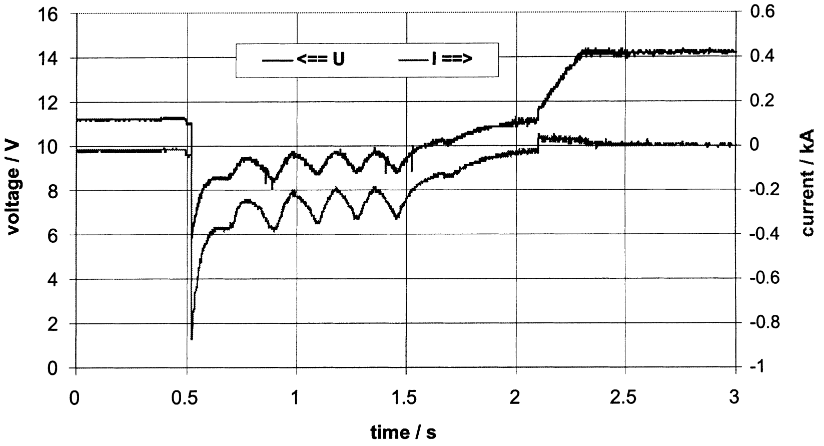

Fig. 9. Battery voltage and battery current profiles during cold cranking of a 1.8 l Diesel engine at −18°C.

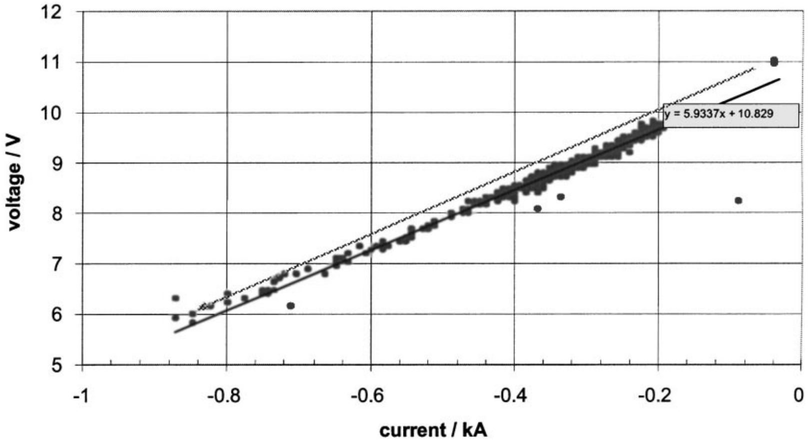

Fig. 10. Battery voltage vs. battery current (data from Fig. 9) during cold cranking of a 1.8 l diesel engine at −18°C.

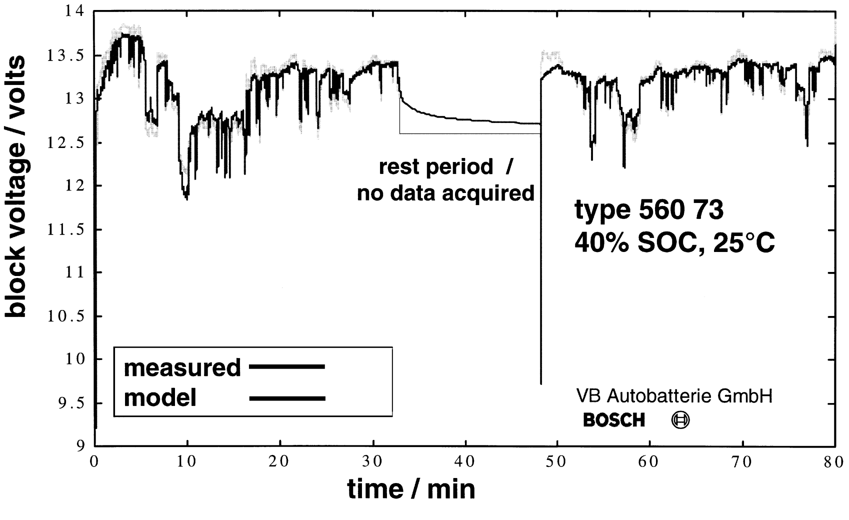

Fig. 11. Comparison of modelled (on-line) and real battery voltage using an intelligent equivalent circuit. State parameters and model parameters are concluded from the comparison using the Kalman filter technique.

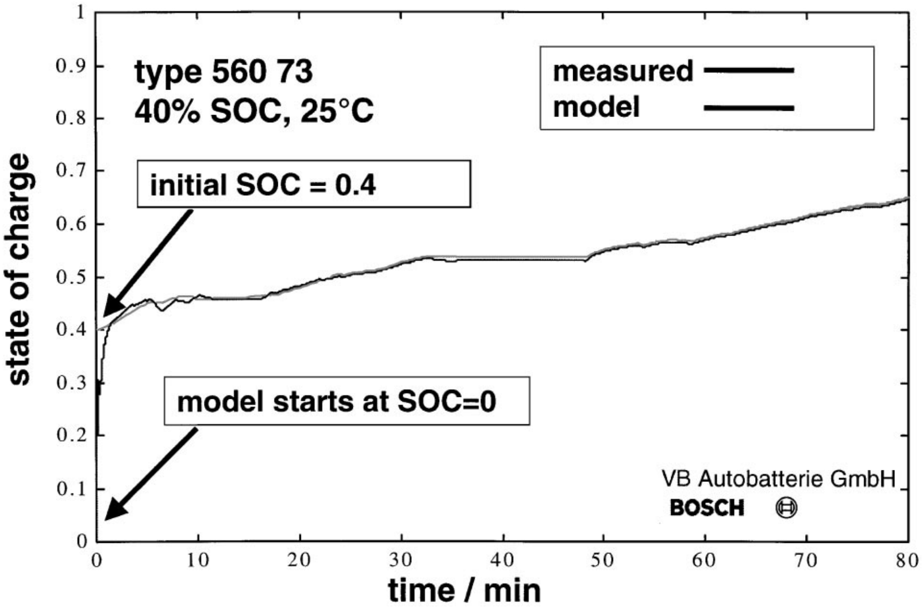

Fig. 12. Catching the real state-of-charge by the algorithm, which has been initially set to zero by default, using the intelligent equivalent circuit model and the Kalman filter to find state parameters (model parameters kept constant here).

battery can be used also for analysis of actual battery state. If such a model is fed with the actual battery current and temperature, it may calculate the voltage response. This calculated voltage is compared with the real measured voltage at the battery. From this comparison, which is done on-line while the vehicle is being operated, the model parameters (describing the characteristics of the battery) and the state parameters (describing the actual state of the battery) can be deduced. This is done using the Kalman filter approach known from control theory.

Fig. 11 shows a comparison of the modelled and the real voltages. During the rest period, no data were recorded (straight line), while the model provided the calculated relaxation curve. However, after a short period of time, the model catches voltage reality again after the rest period.

Fig. 12 demonstrates, how quickly the algorithm catches the real SOC of the battery, even though the model was intentionally set to start with SOC = 0. Battery ageing can be estimated from long-term changes of the model parameters, which allows for a prediction of expected residual life time, if appropriate threshold values are known.

None of the described procedures alone is sufficient to provide all the information about the state of the battery which is needed to measure battery SOC or to predict short-term or even long-term battery performance. In any case, a combination of these and/or other methods is needed to assure sufficient plausibility and reliability.

6. Summary

The changes of vehicle electric system architecture have immediate consequences for the performance profile expected from the battery: more specialised battery designs will be needed, multiple batteries will be combined to meet the demands, and battery state detection to will help to keep the battery in its best operational window and to assure sufficient power supply also for critical components in all operation conditions of the vehicle.

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