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Battery Monitoring and Electrical Energy Management Precondition for future vehicle electric power systems

Eberhard Meissner*, Gerolf Richter

VARTA Automotive, Vehicle Electric Systems & System Development, P.O. Box 210 520, D-30405 Hannover, Germany

Abstract

New vehicle electric systems are promoted by the needs of fuel economy and ecology as well as by new functions for the improvement of safety and comfort, reliability, and the availability of the vehicle. Electrically controlled and powered systems for braking, steering and stabilisation need a reliable supply of electrical energy.

The planned generation of electrical energy (only when it is economically beneficial meaningful), an adequate storage, and thrifty energy housekeeping with an intelligent integration of the battery as the storage medium into the overall concept of the vehicle Energy Management, and early detection of possible restrictions of reliability by Battery Monitoring allows for actions by the Energy Management well in advance, while the driver need not be involved at all.

To meet today's requirements for Battery Monitoring and Energy Management, solutions have been developed for series vehicles launched in years 2001–2003, operating at the 14 V level.

Keywords: Automotive battery; SLI; Vehicle electric power system; Battery Monitoring; State-of-charge (SOC); State-of-health (SOH); Battery Management; Energy Management

1. Introduction

The term "Battery Monitoring" is used in a wide range of meanings, from occasional manual readings of voltages, of electrolyte gravity SG and level, and visual cell inspection, through periodical tests of capacity or manual measurement of battery resistance, to fully automated on-line supervision in critical applications with means for real-time estimation of residue bridging time, or of battery wear and tear.

In this paper, the term Battery Monitoring is used for supervision without manual engagement, which is state-of-the-art with many cycling batteries in automatically guided vehicles (AGVs), forklift trucks, submarines, electrically driven cars and trucks, as well as with standby batteries in telecom and UPS applications. With consumer applications, any mobile phone, laptop or pocket computer, or even a wristwatch is equipped with a device providing some information with respect to energy being left.

Classical industrial cycling applications and many consumer devices are characterised by

- periodical complete recharge, providing a well-defined reset to full state-of-charge (SOC),
- discharge starting from full SOC, until either the battery is exhausted or duty is completed,
- scarcely any recharge without reaching full SOC level ("opportunity charge"), and
- single type of discharge duty only to provide power for an application characterised by limited range of discharge and recharge current rates, and operation temperatures.

Periodical reset to full SOC allows for regularly re-calibration, and in the rare cases when recharge was untimely interrupted, some loss of precision may be acceptable. Discharge starting from a well-defined battery status with a limited variety of current rates and profiles facilitates tracking of battery status.

More difficult is the situation with stationary batteries operated together with solar or wind energy plants. While some of the characteristics mentioned above facilitate Battery Monitoring, as with traction batteries, full SOC is scarcely reached, because sizing of components and operational strategy aim at never reaching the extremes of the operating window in order to make optimum use of the solar and wind power potentially offered. Therefore, tracking of operational history to evaluate the actual battery condition is difficult due to the accumulation of measuring inaccuracies.

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[*] Corresponding author. Tel.: +49-511-975-2410.

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When compared with these two types of operation, the specific different situation of automotive batteries becomes obvious, technically impeding Battery Monitoring in the automotive fields:

- They are scarcely ever been completely charged, i.e. "opportunity charge" is standard.
- Recharge is performed with a wide range of different current rates.
- Discharge virtually never starts from a full SOC.
- Discharge is performed with a wide range of different current rates.
- Sometimes full discharge or (unfortunately) even over-discharge occurs.
- A large variety of electric duties must provide power for may different applications.
- Operational temperature may even exceed the window from −30 to 70 °C.

In addition, the automotive cost level excludes many solutions which may be acceptable in other fields.

While the term "Battery Monitoring" comprises

- taking and/or receiving data from and/or about the battery,
- processing of this information, including predictions of performance, and
- indicating raw data or processed information to a human being or a unit, i.e. only *passive surveillance and evaluation*,

the term "Battery Management" means *active feedback* to the battery. This may comprise control of current or voltage levels, control of recharge conditions, limiting of the operational windows with respect to SOC and/or temperature, battery temperature management, etc.

"Energy Management (Electrical)" means housekeeping with the electrical energy, i.e. control of energy generation, flow, storage, and consumption. Without the essential information from Battery Monitoring, Energy Management may scarcely work. An appropriate Battery Management may significantly enhance and improve, but is not a precondition for, a successful Energy Management. Fig. 1 sketches the layer structure of Battery Monitoring generating Battery Status Information, Battery Management, and Energy Management.

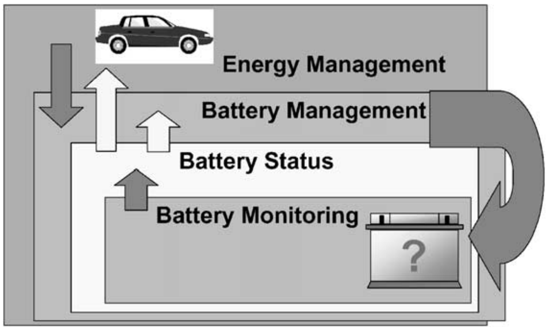

Fig. 1. Layer structure of Battery Monitoring generating Battery Status Information, Battery Management, and Energy Management, and mutual data flow.

It is Energy Management, preferably including Battery Management, which, based on the information from Battery Monitoring, allows for a self-standing operation of a system without manual input—the comfort and the technical necessity requested for a vehicle at the beginning of the 21st century.

2. Changes in electric systems and the drivers for these changes

Vehicle electric power systems are driven more and more by the needs of fuel economy and ecology as well as by new functions for the improvement of safety and comfort. New components may improve comfort and reliability, and the availability of the vehicle. In many cases, there is potential to reduce production and operational cost. Electrically controlled and powered systems for braking, steering and stabilisation need a reliable supply of electrical energy. Possible restrictions of reliability have to be prevented by the Energy Management and evaluated in advance, while the driver need not be involved at all.

Reduction of fuel consumption is expected to be achieved by replacement of mechanically driven auxiliary components by electrical components, which are been activated only when they are needed, and higher energy efficiency with generation, distribution, and use of electrical energy. While these goals are aiming at improvements of electrical engines, energy transfer and design of the electrical consumers, an important contribution can also be given by the planned generation of electrical energy, an adequate storage, and a thrifty energy housekeeping. Electric energy has to be generated when it is economically beneficial, and stored until it is needed in periods when generation is either inefficient or not possible at all.

This means an intelligent integration of the battery as the storage medium into the overall concept of the vehicle Energy Management. Careful monitoring and control of energy flows allows for minimum investment with respect to cost, weight and volume.

The overall requisite electrical performance is increasing—with much higher fluctuations of the load demand than today. This cannot be covered by simple scaling up of today's components. Procedures are needed for optimal use of the battery resource: knowledge of actual state-of-charge, power capability, and degradation of the battery as an input for Energy Management.

2.1. The automotive battery in the past

In the beginning of the development of road vehicles driven by an internal combustion engine (ICE), there was no electrical equipment at all on board of the vehicle besides the ICE ignition, realised by magneto ignition or—more reliably—by primary dry cells. Lighting of luxury cars was soon provided electrically by storage batteries. But it was as late as 1912 that the first electrical starter motor was used in a series production car. This displacement of the cranking lever by a battery-driven electrical starter motor helped the combustion engine make the final breakthrough as the source of power for road vehicles.

In view of the fact that the start routine is a very short one, both components, battery and starter motor, have, over the years, undergone a complete optimisation to obtain the best possible torque for the lowest possible manufacturing costs.

The further development of the vehicle electrical system was favoured by the fact that increasingly powerful (claw-pole type) alternators became available at ever-decreasing manufacturing costs, and the vehicle battery, which was repeatedly called upon to provide cold starting power, was able to deliver some energy at all times to cover electrical requirements even during periods when the power supply to consumers was inadequate.

The dc alternators suffered from low or even no power output at low revs, so the battery had to provide electric power not only when the engine was at rest, but also when it was on idle. This was not an issue for decades, as electrical ignition, lighting and windscreen-wipers were the only consumers, and features like radio and electrically driven fans were limited to upper-class vehicles. In the 1960s, the automotive industry countered a major electrical energy bottleneck, caused by the rapid rise in the number of electrical consumers installed, esp. the introduction of the electrical window defroster, by doubling the battery voltage to 12 V and introducing an adapted 14 V three-phase ac alternator.

2.2. *The automotive battery in present vehicles*

This technical concept is unchanged to the present day. Fig. 2 shows voltage and current measured during cranking of a high-end engine at ambient temperature. The engine is running within about 100 ms. Even at low temperature, a modern car ICE is running within some seconds—or will not crank at all.

In classical vehicles, the battery is a completely passive energy and power storage device:

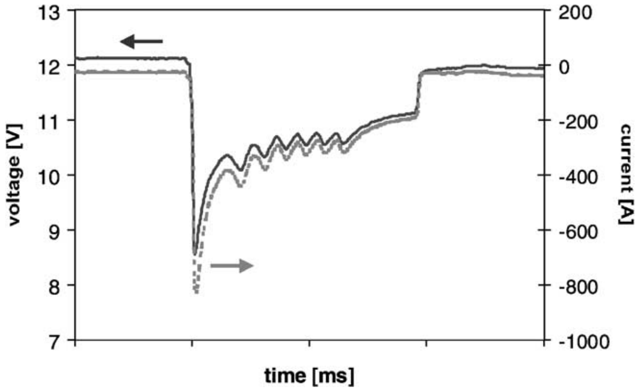

Fig. 2. Voltage and current measured during cranking of a high-end gasoline engine at ambient temperature.

- it is discharged if more energy is consumed than generated—without any check if the battery is able to give this energy (in a meaningful way), and
- energy for recharge is offered to the battery if more energy is available than is actually needed – without any check if the battery is able to take the energy.

This so-called partial state-of-charge (PSOC) operating mode is standard for SLI batteries since decades. Typical SOC levels are about 90% after an extended highway drive in summertime, down to less than 50% in a traffic jam condition in wintertime—or even much less, which may generate cranking problems when the engine is switched off in this state.

The actual recharge voltage at the battery terminals depends on the actual alternator voltage and on the Ohmic losses at their connection, according to the current flowing to or from the battery or to other components. This may reduce the battery recharge voltage by several 100 mV compared to the alternator output voltage as can be measured with upper-class vehicles with the battery mounted in the trunk. Even if a temperature-dependent voltage regulator is used, this is mounted near to the alternator, and does not care about the battery temperature which may still be low for hours when the alternator is already at operational temperature.

There is no control of recharge current, and the state-of-charge of the battery is a scarcely predictable function of electrical loads, driving conditions, alternator, and regulator properties, and battery properties including size, design, temperature, and battery ageing.

The measured voltage versus current profile (the situation is given in Figs. 7 and 8 in [1]) shows a hysteresis-like behaviour, as the SLI battery is alternately discharged and recharged. The voltage level and the duration of the periods of discharge and charge, depend on the operating conditions as well as on the layout of the system and the battery properties, cf. [1,2].

The electrical system, comprising the alternator as the source of current, the battery as current storage device, and the consumers, is designed in such a way that the combination of driving conditions (which determine the possible generation of current by the alternator according to the rpm-profile) and the expected mix of operation of various consumers (which determines the current consumption) provides the current not only in the long-term time average, but also over short periods of time.

Thanks to significant improvements of power supply even at low and idle speed of the ICE by improved characteristics and higher efficiency of the alternator, current generation by the alternator is sufficient to provide the needs of the consumers in many states of operation, and the battery's complete energy storage capability is scarcely ever used.

The battery has to jump in only if

1. The internal combustion engine (ICE) is off (quiescent loads, parking light, ICE cranking).

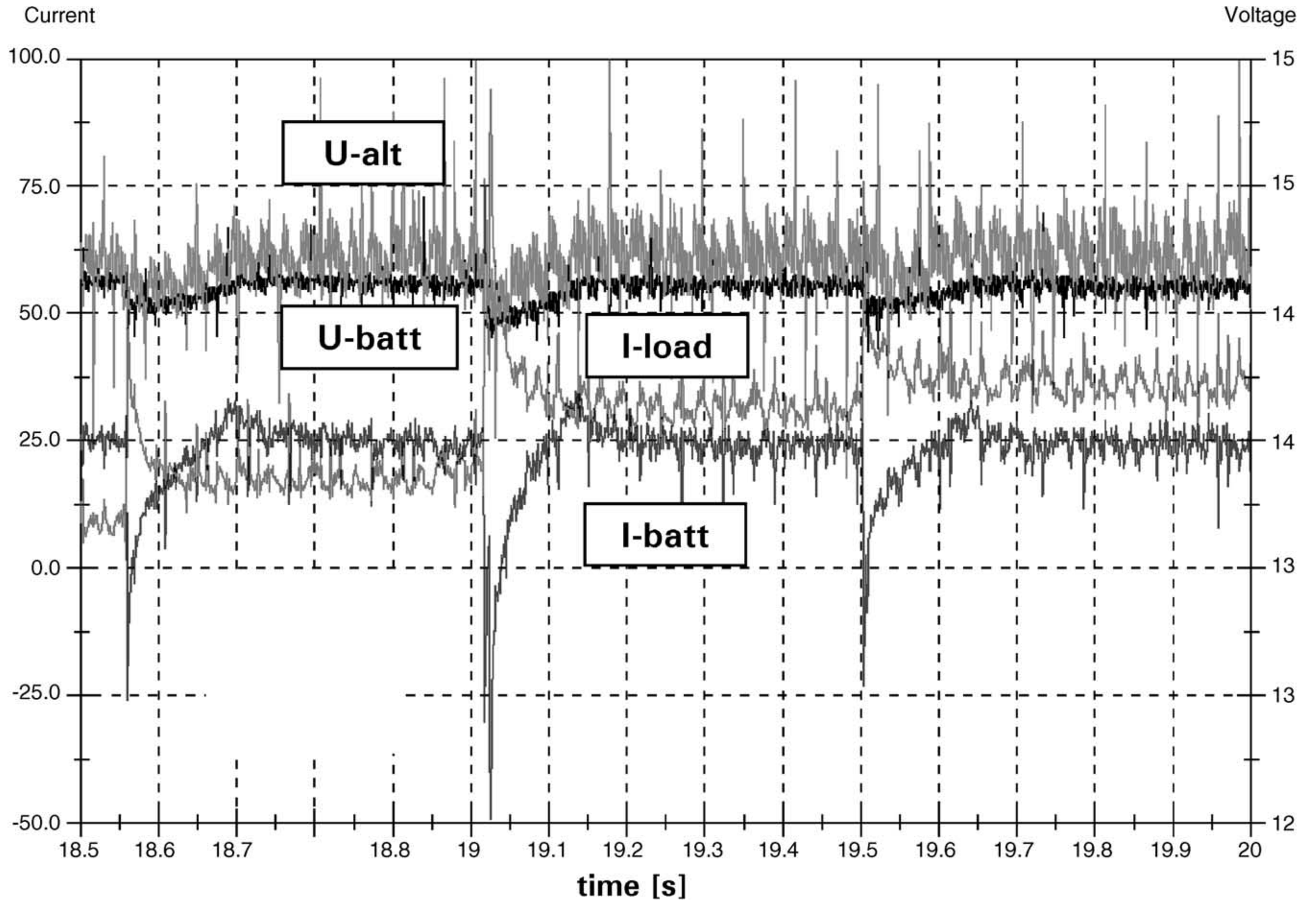

Fig. 3. Load response behaviour of alternator and battery upon onset of the battery which stabilises the electrical voltage level.

2. The energy generation cannot cover the demand, i.e. if the ICE is on idle with many electric consumers being switched on, e.g. in wintertime or night traffic jam situations.
3. The alternator cannot follow sudden load changes of the consumers, i.e. the battery stabilises the electrical voltage level. Fig. 3 shows a typical load response behaviour.
4. The alternator is defective (emergency duty).

However, with high-end class vehicles that feature a multitude of electrical consumers, discharged batteries are being found with increasing frequency in broken-down vehicles, particularly if only short daily distances are travelled at low temperatures, e.g. in stop/start traffic. More and more electrical loads have to be supplied also when the engine is off or on idle. Quiescent loads comprise not only the clock as 20 years ago, but also anti theft equipment, tele de-lock, and not to forget the electronic engine controller which is kept in ‘‘wake’’ mode for some period of time after stand-still of the engine to provide a quick and environmentally friendly re-start. And if the vehicle is opened via tele de lock, the vehicle lights blink friendly and lights its interior, consuming up to 1 Wh from the battery each time.

2.3. The automotive battery in future vehicles

Various technological directions for future road vehicles may come up independently or in combinations, depending on the different goals of safety, comfort and economy:

1. Even more components which need electrical power with high-reliability.
2. The demand for ‘‘ensured mobility’’, i.e. cranking and energy supply to essential functions under all (standard or misuse) conditions.
3. Further extension of electrical demand, including new types of electrically driven components with new profiles, including higher (peak) power demand and higher current transients.
4. Start/stop operation mode of the ICE.
5. Electrical brake energy recovery (recuperation).
6. Torque assist/acceleration assist (boost) mode.

The power demand of upper-class vehicles, starting from less than 500 W in the nineteen sixties, had increased to more than 2 kW by the year 2000, and will further increase, and will be followed by middle class and compact class vehicles. For the next decade, automotive engineers predict an explosive increase to about 10 kW (e.g. [3]).

Precise numbers for the expected power to be provided differ from various sources (e.g. [3,4]).

Today, a significant portion of fuel (about 1 l/100 km, and even more with high-end cars) is burned in an ICE vehicle to generate electric energy for the various electric components on board the vehicle [5]. Due to the poor efficiency chain of energy conversion from fuel via combustion engine and alternator to the component (sometimes stored in the battery for some time before), for generation of 100 W of electrical power the fuel consumption is increased by about 0.15 l/100 km [6,7], i.e. saving of 100 W of electrical power losses reduces fuel consumption as much as a weight reduction of 50 kg, demonstrating the high potential of optimisation the electrical power system for reduction of fuel consumption and emissions.

A completely new situation for the vehicle electrical system, and therefore for the battery, occurs if the predictions of the energy suppliers and environmental scientists are taken seriously [8,9], with consumption levels for new vehicles set to fall by the year 2015 to half of the value of approximately 9 l/100 km today. The situation is particularly critical, since this is expected to be possible only through challenging technical measures which bring up further electrical demands, many with significant current transients like automatic variable transmission control (VTC) or automatic switch gear (ASG), and the more frequent use of turbo chargers, automatic idling stop, recovery of braking energy as electrical energy, electrical support for the combustion engine by an electrical machine in the low-torque and emission-critical starting range at low revs, and avoidance of throttle valve losses and optimum mixing in gasoline engines by electromagnetic valve actuation (EMVA).

This will require more powerful batteries with greater cycle stability [8] and storage capacity [10], and possibly the introduction of a higher vehicle electrical system voltage (e.g. 42 V) [7,9,11].

These actions will provide average power demands the system is designed for. However, redundancy and reliability of energy supply can only be provided by the installation of Battery Monitoring, the appropriate Management of the energy flow (and of the battery), and/or by systems with more than one battery (or another storage system).

2.4. Dual battery systems

Long-term, the automotive industry and its suppliers are aiming at solutions comprising the 42 V PowerNet [12,13]. However, due to cost considerations and uncertainties with respect to availability and reliability of newly designed components [10], modifications will be introduced stepwise only when really needed. Dual voltage approaches 14 V/42 V, partially comprising two batteries at the two voltage levels, are under discussion for the interim period [14,15]. But 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.

Dual battery systems [1,16] 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. Generally, motivations approached with dual battery designs are as follows [1]:

- *Cranking reliability*: One battery (best a small high power type) is kept at high SOC. The other battery may be a high cycle or/and a high energy type, depending on the other demands.
- *Reliable operation of an electrically heated catalyst*: A cycle-proof battery should be kept in high state-of-charge (NB: Electrical heating of catalysts may be required due to improved engine designs and operation strategies).
- *Extreme cranking power needs of large* (*diesel*) *engines*: Two batteries may be paralleled. The types chosen may be according to other demands, but should not be too different.
- *Weight saving*: Two extreme specialist battery designs, which, however, have to be managed properly.
- *Supply of systems with very high-reliability* (*e.g. electrical power braking and steering*): The second (fall-back) battery may bridge in case of failure. The specialist battery depending on the demands of bridging.

More than one of these goals can be simultaneously achieved by a dual battery system of appropriate design. To take 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 component defects, battery defects, extended traffic jam in cold or hot climate, etc.).

A dual battery electrical system layout combined with a control unit is already used in a European upper-class sports car launched in 2001 [1], comprising Battery Monitoring, Battery Management, and Energy Management features.

While a cycle-proof AGM battery, directly connected to the consumer harness and to the alternator, is buffering electric energy similar to conventional vehicles, a power-optimised battery (POB) is provided for the cranking operation only. The control unit may handle all situations providing redundancy for the electrical supply, e.g. for cranking and the Electro-hydraulic Power Braking (EHB) system [17].

To improve reliability and performance of cranking, two batteries are connected via a control unit in another top class limousine [18]. For a mass production limousine comprising EHB technology launched in early 2002, the SLI battery is permanently monitored to activate Energy Management actions if appropriate.

These vehicles comprise Battery Monitoring and Energy Management for reliability, and a second battery to provide redundancy for cranking and/or an important component, and show two alternative operation strategies: permanent use of both batteries versus stand-by operation of a backup battery.

3. Battery Monitoring

Battery Monitoring allows for best use of the capability of a battery of given size, to guarantee power supply for high-reliability devices, and for replacement strategies. Furthermore, monitoring of the actual state-of-charge allows for an electrical power management which may include both reducing consumption of electrical power by limiting of operable luxury applications as well as increase of power generation by appropriate control of alternator or even idle speed and automatic gearbox control [19].

Battery Monitoring may be needed if

1. energy has to be provided for a component which is essential for operation, e.g. an Electromechanical Power Steering (EPS) or an Electro-hydraulic Power Braking (EHB) system, an electrically powered suspension stabilisation system, or an automatic gear shift;
2. an Electrical Energy Management (EEM) has to guarantee, e.g. for future cranking capability;
3. the cranking capability has to be supervised to operate a stop/start-system;
4. an indication of battery fatigue is needed for garage service to replace the battery.

Battery Monitoring consists of data acquisition, data processing, and some prediction of the future. For different technical goals, different information with respect to the future is needed.

Any approach for Battery Monitoring may be classified according to the following criteria, which may be combined, too, e.g. data acquisition from both long-term and the nearest past, and prediction of both battery status and behaviour:

(A) *Data acquisition*
  - ○ *Type of data*: Battery status/battery behaviour/operational conditions.
  - ○ *Time scale of data acquisition*: From long-term history/near past.
  - ○ *Source of data*: External battery parameters (e.g. U, i, T)/internal battery parameters (e.g. electrolyte properties)/vehicle data (e.g. engine rpm, speed, environmental temperature).
  - ○ *Data achieved from*: Undisturbed battery behaviour/after electrical stimulation.

(B) *Data analysis*
  - ○ Analysis of operational history (i.e. conditions the battery had to suffer so far).
  - ○ Analysis of previous performance (i.e. behaviour the battery has shown so far).
  - ○ Analysis of actual performance (i.e. recent and actual battery behaviour and status).

(C) *Prediction of battery performance* under a hypothetical future electrical load
  - ○ *Point in time for prediction*: Near future (just now, with the present battery status)/medium future (in several hours or days, when the battery charge and temperature may have been changed).
  - ○ *Type of predicted battery data*: Status (temperature, state-of-charge)/load behaviour.

(D) *determination of available electrical energy*: This is a special case of C, with the standard capacity test scheme as the hypothetical (future) electrical load.

(E) *Determination of battery degradation* (state-of-health (SOH) figure of merit).

Fig. 4 sketches the interdependence of some of these aspects.

While Battery Monitoring may provide information about the status of the battery, this knowledge is not a goal by itself. The final technical benefit has to be made clear, and a strategy and means to achieve this goal have to be worked out, to find out the relevant properties of the battery which have to be considered and evaluated.

3.1. Definitions of figures of merit

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

Surprisingly from the first glance, a lot of misunderstanding usually comes up when discussions on SOC and SOH are going more into detail.

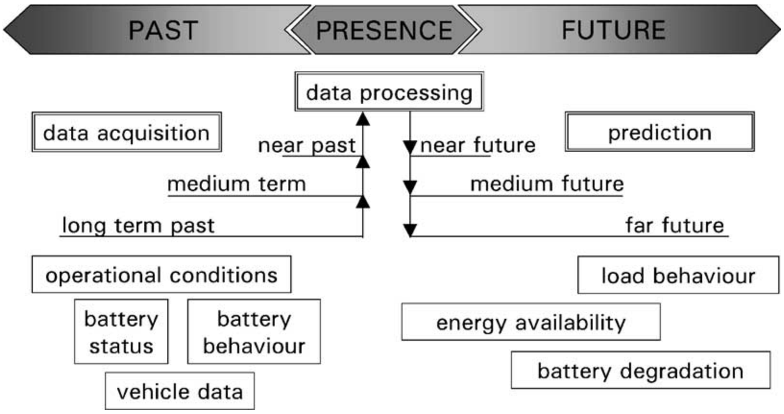

Fig. 4. Sketch of interdependence of data acquisition from battery and vehicle, data processing, and prediction with respect to time scale.

Obviously, the meaning of these terms is not straight forward, although the definition of at least state-of-charge (SOC) and depth-of-discharge $(\text{DOD}) = (1 - \text{SOC})$ seems to be an easy task: the percentage of actually stored amount of charge compared with full charge.

$$\text{SOC} = \frac{\text{actual amount ofcharge}}{\text{total amount of charge}} \tag{1}$$

The difficulties become obvious, when the terms ‘‘actual amount of charge’’ and ‘‘total amount of charge’’ are discussed. The nominal (nameplate) capacity of the battery is measured at *nominal* temperature T_0 (usually, e.g. 25 °C) with a *nominal* current (with automotive batteries usually the 20 h rate I_{20}), following a *nominal* recharge scheme. But a vehicle battery is seldom at nominal temperature and never recharged according to a nominal scheme. And nominal capacity is of little use, when an old battery shall be discharged with $10 \times I_{20}$ at -20 °C.

Several definitions for SOC have been proposed (e.g. [20,21]). Practical use is limited, as definitions of any figure of value for a battery like ‘‘state-of-charge’’ have to be made according to the technical goal of the further use of this figure, i.e. according to the intention *why* the battery is monitored. A figure of merit needs to be an observable one, preferably a monotonic and unequivocal state function, with a procedure available to calculate it from measured data.

A definition of SOC of a lead-acid battery which fulfils both these criteria uses the well-known dependence of the equilibrium voltage U_{00} (equilibrated OCV) or of the equilibrium electrolyte acid gravity ρ_{00} as a measure for SOC [1]. Due to the simple, nearly linear, relationship between ρ_{00} of electrolyte, U_{00} and SOC (Fig. 5), the state-of-charge can be calculated as

$$\text{SOC} = \frac{U_{00}^{\text{actual}} - U_{00}^{\text{min}}}{U_{00}^{\text{max}} - U_{00}^{\text{min}}} \tag{1a}$$

where U_{00}^{max} and U_{00}^{min} are the 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. This generates a monotonic and unequivocal state function to describe an intrinsic battery property, and transfers the lesson to the determination of an observable figure, the battery equilibrium voltage U_{00}. Preferably, U_{00}^{max} and U_{00}^{min} are equilibrium open circuit voltages related to nominal (nameplate) capacity.

Knowing that SOC value, the contribution of electrolyte resistance to cell impedance, the freezing temperature of the electrolyte, and the active material properties can be estimated (like residual available material, charge transfer resistance, etc. if these dependencies are been considered). However, the figure $\text{SOC} = 1 - \text{DOD}$ calculated according to this definition (1a) does not involve

- over-dimensioning, i.e. if a fresh battery shows >100% of nominal capacity,
- individual capacity scattering due to variations of manufacturing parameters, and
- loss of storage capability due to degradation over lifetime

and should not be confused with the battery's charge storage capability (CSC; cf. Section 3.4.1), the amount of charge which can be drawn from the fully charged battery (whatever SOC this may be) with nominal current until the cut-off voltage U_{EOD} is reached (whatever SOC this may be).

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

With state-of-health (SOH), a figure of merit that shall describe the degree of degradation of a battery, the individual understanding of different people diverges even more, and often fuzzy statements like ‘‘fresh’’, ‘‘aged’’, ‘‘old’’, and ‘‘worn out’’ are used.

For a UPS battery, discharged at a certain power P at 25 °C, starting at full SOC after weeks of float charging, SOH can be defined as the possible bridging time to cut-off

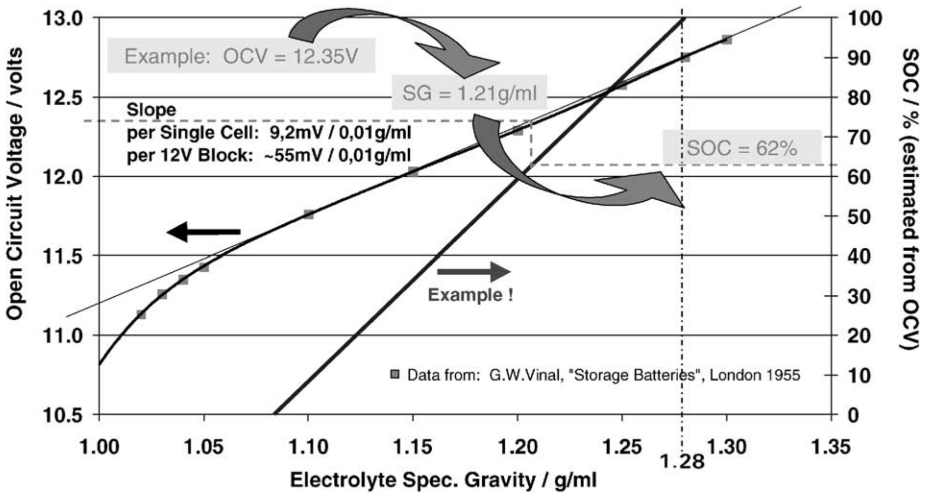

Fig. 5. The nearly linear relationship between specific gravity ρ_{00} of electrolyte and equilibrated open circuit voltage U_{00}. For fixed battery design, SOC is strictly correlated to equilibrated OCV (example shown).

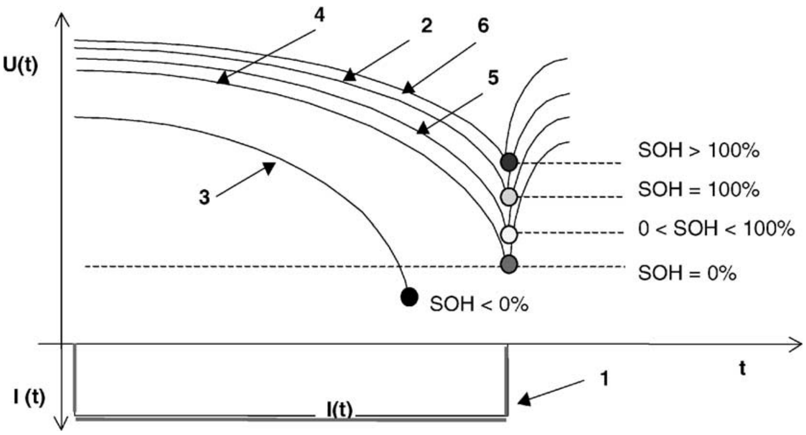

Fig. 6. Illustration of definition of SOH according to Eq. (2) for a constant current profile $i(t)$ of duration t_0, lowest acceptable voltage under load U_1, and lowest voltage of a typical fresh battery U_{fresh} at reference (SOC, T).

voltage U_{EOD} compared to the design value. What makes things easy is the relative reproducibility of initial SOC and T. But for an automotive battery, neither charge state nor duty temperature is fixed, and there may be several types of duty, e.g. cranking and bridging. A battery may be unable to fulfil one specification, but is still ready to do another.

However, SOH can be defined rather easily if the duty and operation condition is precisely known and a benchmark is given [1]. Under the load of a power profile $P(t)$ or current profile $I(t)$, which may depend on time t and have duration t_0, the voltage of the battery will show a minimum U_{min}. In the simple case of a load independent of time, this will happen at t_0. The lowest acceptable voltage under load U_1 for the particular application, and the lowest voltage U_{fresh} of a typical fresh battery at reference (SOC, T) conditions are used to define battery SOH at (SOC, T) [1] (Fig. 6):

$$\text{SOC} = \frac{U_{\text{min}} - U_1}{U_{\text{fresh}} - U_1}, \quad \text{at reference (SOC}, T\text{) conditon} \qquad (2)$$

NB: For recharge duty power or current profiles, U_{min} has to be replaced in (2) by the maximum battery voltage U_{max} under this load, and U_1 is the highest acceptable voltage under recharge.

SOH according to (2) is a monotonic state function with distinct values, which can be used for mathematical treatments, instead of fuzzy states. A fresh battery is given a nominal $\text{SOH} = 1$, a battery just meeting the threshold criterion is named $\text{SOH} = 0$, and negative SOH values are given to batteries which fail the specified duty. The characteristic dependence of SOH on temperature T and SOC can be used to deduce SOH values at other (T, SOC) combinations.

Any discharge duty power profile $P(t)$ or current profile $I(t)$ of duration t_0, with a lowest acceptable voltage under load U_1, has its own SOH figure. It is the $\text{SOH}^{\text{crank}}$ for cranking which decides if the battery may give enough power to crank the engine, while, e.g. another figure $\text{SOH}^{\text{bridge}}$ for short-term bridging, with different profile $I(t)$, duration t_0, and lowest acceptable voltage U_1, predicts the battery capability to bridge a sudden discharge current.

If a battery has several duties, all the respective SOH figures can be checked, and the minimum SOH value is the figure of merit for the battery under this set of duties.

3.1.3. Definition of state-of-function (SOF)

In most cases, neither simply the state-of-charge nor only its degree of degradation is the figure which decides if the battery performs as needed. As SOC and SOH may compensate each other to some degree with respect to battery performance, a poorer SOC may be acceptable for a fresh battery with high SOH, or an older battery with lower SOH may do its duty if it is kept at sufficient higher SOC.

To describe the capability of the battery to perform a certain specified duty, a new figure, the state-of-function (SOF), is defined, which is relevant for the functionality of a system powered by the battery. SOF brings together the battery state parameters, i.e. state-of-charge, state-of-health, temperature, and if needed also the short-term previous discharge/recharge history.

SOF is defined similarly to SOH (2), but comprising state parameters (SOC, SOH, T), i.e. the number of SOF equals that of SOH for a certain battery state under investigation, characterised by (SOC, SOH, T):

$$\text{SOF} = \frac{U_{\text{min}} - U_1}{U_{\text{fresh}} - U_1}, \quad \text{for actual (SOC, SOH}, T\text{) condition} \qquad (3)$$

Any discharge duty power profile $P(t)$ or current profile $I(t)$ of duration t_0, with a lowest acceptable voltage under load U_1, has its own SOF of merit (cf. with SOH, Section 3.1.2).

Fig. 7 sketches qualitatively the dependence of SOF for a discharge load on SOC and SOH at a given temperature. To sketch SOF for a recharge load, the SOC axis has to be inverted in Fig. 7, and in (3), U_{min} has to be replaced by the highest voltage under load U_{max}, and U_1 stands for the highest acceptable voltage under recharge load.

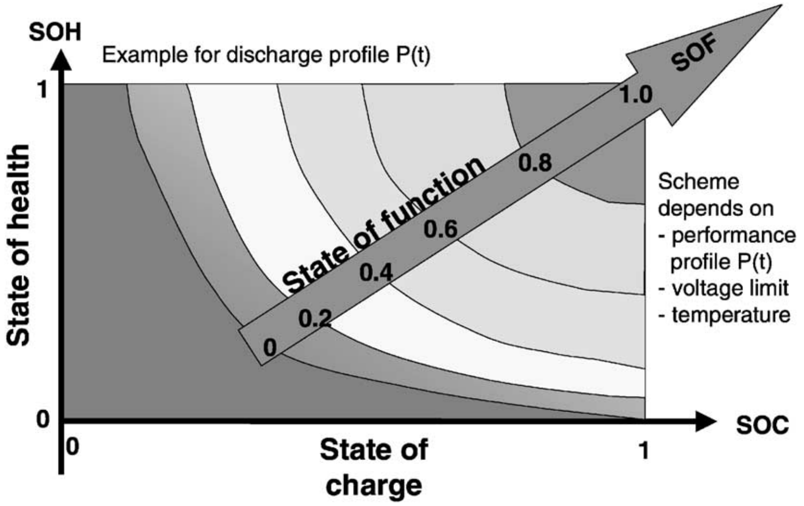

Fig. 7. Qualitative dependency of SOF for a discharge load on SOC and SOH at given *T*. Within limits, SOC and SOH may replace each other for securing a given SOF value.

3.2. Approaches for Battery Monitoring

To analyse the battery status, preferably voltage and current as function of time are evaluated. Determination of temperature is needed to compensate its influence on battery properties. Additional sensors within the battery have not yet been adopted (cf. Section 3.3.2).

Processing of measured data may be done in various ways, following the alternative concepts, e.g.:

1. balancing of current flow for tracking of changes of state-of-charge,
2. comparison with a characteristic pattern,
3. input to a mathematical model, describing the characteristic behaviour of the battery,
4. estimation of a dynamical battery impedance,
5. valuation of battery voltage at point of zero current,
6. valuation of battery open circuit voltage.

All approaches may operate with fixed parameter values, or with parameter values learned from previous operating duty, and need reference values.

Balancing of current flow allows for tracking of changes of state-of-charge, but does not provide an absolute SOC value. Therefore, a reset for calibration of absolute state-of-charge is needed. Further practical handicaps of current integration over time are the accumulation of sensing and calculation errors over time (cf. Section 4.4), and the unknown recharge efficiency (recharge factor >1.0). Therefore, a reset for calibration is needed not only once but periodically.

With current integration, only a SOC value can be generated, but no prediction of battery performance SOF at other than nominal test conditions (nominal discharge current and cut-off voltage, nominal temperature), nor any figure for battery ageing SOH can be made.

Comparison with a characteristic pattern, which may be given as a characteristic diagram or as a functional dependency, is a pattern recognition approach, i.e. knowledge and understanding of battery processes is not essential. The quasi-stationary battery voltage U under current load i is sketched in a characteristic diagram (or mathematical function) as a function of battery temperature T and SOC.

This approach can be applied directly for monitoring of batteries which are being operated mostly under quasi-stationary conditions, i.e. with limited relative current changes $(1/i)(\mathrm{d}i/\mathrm{d}t)$.

However, in automotive applications, many current transients and reversals disturb the quasi-stationary state, and voltage cannot be evaluated by comparison with tabled quasi-stationary values. Tabling of transient behaviour is scarcely possible due to the manifold transients. Therefore, a filter function has to detect when the voltage $U(t)$ has become quasi-stationary after a current transient $i(t)$, and if the procedure is applicable. In many cases, a voltage $U'(t)$ filtered by a low frequency (PT1) pass filter (or by a combination of several filters) from $U(t)$ is evaluated to allow for evaluation sufficiently often.

If characteristic voltages U are tabled for the whole (i, T, SOC) manifold needed, SOC figures are obtained, and SOF predictions can be made. To obtain information of battery ageing SOH, battery degradation has to be introduced as a further table parameter besides (i, T, SOC), and a procedure has to be provided to distinguish influences from SOC and from SOH.

A mathematical model, describing the characteristic behaviour of the battery, needs to have model parameters correlated to all the battery properties about which information is wanted. As a model, electrical equivalent circuits [22–24] are favoured comprising electrical components (resistance R, impedance L, capacity C, Warburg term Z_W, constant phase element CPE, etc.) describing the battery's internal processes (Fig. 8).

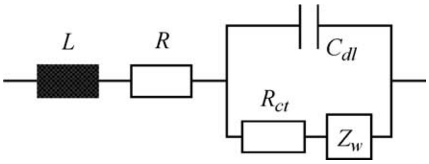

Fig. 8. Equivalent circuit for lead-acid battery with impedance L, resistor R, double layer capacity C_{dl}, charge transfer resistance R_{ct}, and Warburg term Z_{W} proposed by [24].

Apart from recognition approaches, understanding of the electrochemical processes (e.g. [25]) is essential to assess the validity and to recognise the limits of relevance of appropriate equivalent circuits, which may depend on the operational situation. However, switching of equivalent circuits under operation is a challenging task for numerical stability.

To fit the parameters of the equivalent circuit to the measured data, usually algorithms from control theory are used, especially filter functions like the Kalman filter approach [26–28].

Parameter fitting is facilitated by changes of the system, i.e. the typical current transients of automotive duty are highly useful.

Equivalent circuit approaches both provide SOC figures and allow for predictions of battery performance (SOF) under arbitrary conditions. To include SOH figures to obtain information of battery degradation, the equivalent circuit has to be extended accordingly. However, this increase of the number of free parameters may harm numerical stability if parameters are strongly correlated.

Estimation of a dynamical battery impedance R_{dyn} by differentiating measured voltage by current $R_{\mathrm{dyn}} = \mathrm{d}U/\mathrm{d}i$ is mathematically an easy approach. However, the R_{dyn} value depends not only on battery temperature T and SOC but also on battery current i, as the electrode charge transfer reactions are strongly non-linear. Therefore, filter functions are needed to assess R_{dyn} only if appropriate. Limited sensor precision (cf. Section 4.4), ac ripple from the alternator, and electromagnetic interference (EMI) are further hurdles to be overcome.

Dynamical impedance R_{dyn} allows for prediction of battery load voltage under short load currents, i, which differ not too much from the current with which R_{dyn} had been determined. This is possible only if battery status has not changed, i.e. for the very near future, while long-term predictions may carry significant deviations, as R_{dyn} may change rather quickly in highly dynamic battery duty.

Some SOC information may be gained from R_{dyn} using the well-known dependence of electrolyte resistance from SG and SOC [29], if appropriate reference values are given. However, additional information is needed to distinguish influences from electrolyte resistance from those originating from electrolyte inhomogeneity, grid resistance, etc.

Valuation of battery voltage at point of zero current in dynamic operation is motivated by the perspective of a procedure working without a current sensor, which is a significant cost issue. Only a trigger is needed providing a signal when current equals zero when changing from recharge to discharge or vice versa. The higher $U(i = 0)$, the higher SOC and the higher a voltage under load i is expected (cf. Fig. 7 in [1]).

Valuation of battery open circuit voltage OCV uses, different from that at point of zero current in dynamic operation, the quasi-equilibrium voltage when for extended periods no or only a marginal (e.g. quiescent) current is flowing. After complete equilibration, this provides a excellent SOC information based on its correlation with electrolyte SG. However, equilibration takes about 1 h after discharge, and may take more than 1 day, at low temperature even longer, if an extended recharge phase preceded the OCV phase. This issue is overcome by advanced procedures assessing the shape of the OCV(t) curve to predict the true equilibrium value instead of taking non-equilibrated voltages [30].

Valuation of OCV is an excellent procedure to assist other approaches, e.g. for re-calibration of current integration procedures, or for plausibility checks.

Table 1 summarises the most important properties of the different approaches and makes clear that a single method will be scarcely sufficient to cover all demands. However, an intelligent combination of several procedures may compensate the mutual weaknesses.

3.3. Data acquisition

Data may be collected from

- the battery, especially voltage $U(t)$, current $i(t)$ and temperature $T(t)$ as a function of time,
- sensors taking additional information about internal battery properties, and
- the vehicle, e.g. about periods of operation, driving speed, ignition-on information, engine revs (which is proportional to alternator revs), and data bus information providing knowledge about status of components and control units, etc.

While some of these data may be available already in a modern vehicle via a data bus, an additional sensor is required for most of the information. The cost related to additional sensors is the first hurdle to be overcome. All strategies monitoring automotive batteries aim to work with a minimum number of sensors at a minimum of component cost: reduction of need for precision or acquisition frequency is a development goal by itself.

3.3.1. Input data from battery

Taking voltage U, current i and temperature T of the battery is the most direct monitoring approach and requires no change to the battery. Voltage should be taken as near as possible to the terminals to avoid Ohmic losses, and the current sensor should register the total battery current. For

Table 1
Battery Monitoring approaches—summary of key properties

#	Approach	SOC	SOH	SOF	Pros	Cons
1	Balancing of current flow/current integration	+	−	−	Works for discharge and recharge phases; independent of engine status; no mathematics	Needs periodical re-set (e.g. by #6); no prediction; no information about degradation
2	Comparison with characteristic pattern	+	−/(+)	+	Works for discharge and recharge phases; limited mathematics; option for continuous improvements	Large data set for precise operation; handling of degradation very difficult; interference by short-term history → poor in erratic dynamic situations
3	Mathematical model/ equivalent circuit	+	(+)	+	Limited data set; very flexible; option for continuous improvements	Complex equivalent circuits require high calculation power; learning required → poor in static situations
4	Dynamical impedance R_{dyn}	−	−	(+)	Limited mathematics	Prediction for actual SOF status only; no separate SOC and SOH information; dynamics required
5	Valuation of voltage point of zero current	(+)	−	(+)	No current sensor (only trigger at $i = 0$)	Limited precision; poor in recharge phase; no degradation information; needs many $i = 0$ situations
6	Valuation of open circuit voltage	+	−	−	Excellent SOC information; limited mathematics	No degradation information; extended rest periods required

+/−: information achieved/not achieved; (+): information only achieved in special situations/for short-term prediction.

calculation of derived figures like battery impedance, simultaneous acquisition of U and i data is very important for the dynamic vehicle electric system. The frequency of data acquisition depends on the necessity of the algorithm in use.

Temperature should be taken as direct to the battery as possible. As battery temperature follows rather slowly to changes of the environmental temperature, and internal battery heating can be neglected in most cases, temperature taken near to the battery may be sufficient, possibly being improved by a thermal model of the heat exchange with its environment [31].

Due to variations of loads and especially the rectification of the alternator ac current, battery voltage and current is overlaid with a lot of noise signals (cf. Fig. 9). Appropriate analogue and/or digital filtering may be necessary to suppress such noise for analysis. However, evaluation of just such noise may provide valuable information [29].

3.3.2. Special sensors

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 [32], refraction [33,34], vapour pressure, or of property changes of the active materials [35,36], etc. However, as most of them perform only a local measurement in a single cell, the relevance of such data for the behaviour of the overall SLI battery (with today six cells and possibly in

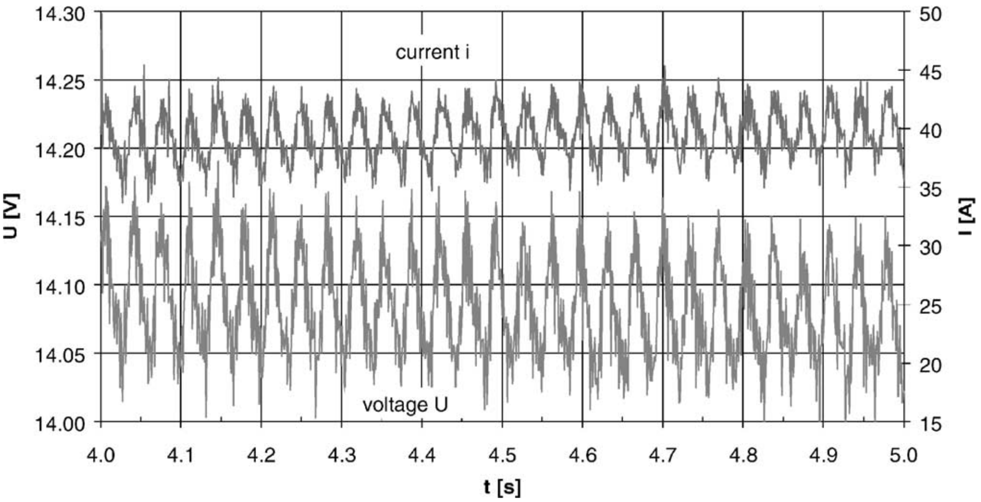

Fig. 9. Battery voltage and current overlaid with noise signals from rectification of the alternator ac current; high-end class vehicle with idling engine.

future even more cells in series) is limited. In addition, cost considerations give a harsh limit to such sensors in the automotive industry.

So far no special sensors integrated into SLI batteries measuring internal properties are established, and at least for lead-acid automotive batteries, this is not expected in the near future.

A temperature sensor within the battery may provide more precise data than sensors attached from the outside or modelling of battery temperature from other temperature information [31]. But as temperature may be inhomogeneous within a battery, the potential benefit of an integrated temperature sensor is limited and has to be critically assessed against cost for this sensor and for reliable data transfer. The same is true for individual cell voltage monitoring or at least for a voltage balance, taking the mid-point voltage of the cell chain. Information about cell imbalance is a valuable indication of improper battery status, which, however, needs combination with means for cell equilibration to provide full benefit.

However, the more dynamics are imposed on the battery, with harsh high-rate cycling operation, with ac ripple loading, and especially with start/stop and boost/recuperation duty, the more benefit may rise from temperature and voltage sensors inside the battery due to imbalances and electrical self-heating as input for battery thermal management and individual cell voltage control, as is done already with hybrid vehicle batteries.

3.3.3. Input data from the vehicle

While vehicle data do not directly provide information about battery status, they may be very helpful for valuation of battery data. Ambient and/or engine temperature may help for estimation of battery temperature and of power demand for engine cranking. If the engine is off, battery voltage is not influenced by the alternator, and after the vehicle is locked, the vehicle will go to sleep mode after a limited period of time, with only quiescent currents loading the battery. Such periods are especially suitable for valuation of open circuit voltage. Engine rpm data provide information about alternator capability, and vehicle speed allows for estimation of power demand if electrical power braking or steering components have to be supplied.

3.3.4. Transfer of Input data

Analogue data are directed from the sensors to analogue digital converters (ADC), which should be arranged as close as possible to avoid electromagnetic interference (EMI). Generated digital data are directed to the processing unit, which is either arranged nearby, too, or via a digital link. This link is either an individual data bus, or a data bus used also by other components, in which case potential delay in data transfer has to be considered as the Battery Monitoring data are competing with other vehicle data for transfer priority. This may injure real-time capability and synchrony of U and i data.

So far, data processing for Battery Monitoring and Energy Management is performed by special control units, which comprise also most (if not all) of the necessary I/O components. However, for cost reasons, a distributed realisation of Battery Monitoring and Energy Management may be desirable in future, with data processing and I/O being performed in control units shared with other vehicle functions. Data transfer within these distributed functionalities will be a challenging issue.

3.4. Data analysis

Which type of data from which period of time, at what precision, acquisition frequency, and other criteria, are needed, and what is calculated from these data, depends on the monitoring algorithms (cf. Section 3.2), and finally on the type and precision of information needed. All types of algorithm need some information about the battery properties and the load profiles for which performance prediction is requested. If battery type and properties including degradation, and load profiles, are completely fixed, these data can be stored as constants. Otherwise, these values have to be learned while (or before) the Battery Monitoring algorithm is operating.

While input data have to be acquired at the location they can be measured with least effort and highest precision, and output data have to be transferred to the location where use shall be made of them, opinions about the best location of the analysing hardware for Battery Monitoring are diverging. If hardware were mounted to the battery side, the battery's characteristic parameters could be stored already upon battery manufacturing, making "burn in" phases and "pairing" of battery with control unit obsolete. On the other hand, load conditions for which performance prediction is requested are given by the system, i.e. the vehicle, and this information would have to be transferred from the vehicle to the control unit at the battery, which means "burn in" phases and/or "pairing" of battery (including the control unit) with the vehicle.

The automotive battery of today is a commodity product, which is replaced not only by qualified personnel in a workshop but also unqualified personnel. It cannot be excluded that a battery different from the unit provided by the vehicle manufacturer is mounted. As any monitoring algorithm uses some characteristic battery information for reference, independent of self-type, procedures are needed to estimate the essential reference data.

Reference values, e.g. nominal capacity or R_{dyn}, may be "learned" during a "burn in" operation phase after battery mounting, when it is in a well-defined state. However, any lack of precision of this state may generate significant consecutive errors.

The most important information is nominal capacity, which can be estimated from the characteristic dependency of equilibrated open circuit voltage U_{00} on SOC. When the nominal capacity has been completely discharged from full a state-of-charge (i.e. $\Delta\mathrm{SOC} = 100\%$), U_{00} of a 12 V battery decreases by about $\Delta U = 1.2$ V (the precise value depending on battery design). Therefore, when U_{00} is known before (U_{00}^{1}) and after (U_{00}^{2}) a significant charge throughput ΔQ, a good approximation for nominal capacity K_{20} within a family of batteries with similar layout is

$$K_{20} = \frac{1.2\,\Delta Q}{U_{00}^{1} - U_{00}^{2}} \tag{4}$$

Default values are used as starting value for the "burn in" phase—and as values for fall-back situations. However, learning procedures suffer from some suppositions like scaling of battery parameters with nominal capacity. Storage of battery parameters at the battery is an elegant way to overcome this issue. As world-wide exchangeability of batteries is requested, an electronic device is not yet an adequate cost-saving solution. A good compromise is a bar code label comprising the essential data. Battery and control unit are "paired" when a battery is been mounted at production or in a workshop. If this is not done, the system may operate in a fall-back mode.

The electrical requirement of the system, i.e. the load condition for which a prediction is requested from Battery Monitoring, is usually well defined. However, especially for ICE cranking, load demand is rather complex, depending not only on temperature, but also on individual engine, engine oil type, and on ageing of the engine. Therefore, continuous learning of the electrical load requested for cranking may further improve prediction of cranking capability.

3.4.1. Determination of stored electrical energy and charge storage capability

In many applications, the actually available amount of stored energy is needed, starting from a SOC value until U_{EOD} is reached, or the charge storage capability (CSC), i.e. the amount of charge which can be drawn with nominal current from the fully charged battery until the cut-off voltage U_{EOD} is reached.

SOC may be calculated from the equilibrium open circuit voltage U_{00} using Eq. (1), providing input for calculation of the electrolyte contribution to battery resistance for prediction of voltage under load. However, SOC information is sufficient for prediction of available energy for a fresh battery only, where CSC should be $\geq 100\%$ of nominal capacity. With progressive capacity degradation, CSC can be estimated either from battery history, or from changes of battery performance. The operational window of an old battery may be reduced due to capacity losses at low state-of-charge values (e.g. due to active material degradation) and at high state-of-charge values (e.g. due to non-rechargeable lead sulphate, "sulphation"), e.g. to 20, ..., 90% SOC, i.e. the charge storage capability (CSC) left is only 70% of nominal capacity.

Observation of the battery operational condition history may help to estimate battery ageing, i.e. changes of its characteristic properties and especially its degradation. The influence of periods at high temperature, at high recharge voltage, or at low state-of-charge, can be quantified to generate an empirical model of battery degradation [37,38].

Crucial input data for estimation of battery ageing are, e.g. integral charge throughput, battery voltage, and the time profile of battery temperature, e.g. collected in a histogram-like structure. These allow for estimation of active material degradation, grid corrosion, and water loss, using a functional dependency of battery parameters, e.g. based on the results of field trials.

Estimation of battery status and prediction of battery performance is done using these dependencies. To give an example, a linear degradation of charge storage capability (CSC) with charge throughput $i(t)$, starting at nominal capacity C_{nom}, may be estimated similar to

$$\mathrm{CSC} = f\ (\mathrm{Ah\,throughput}) = C_{\mathrm{nom}} - \alpha \int |i(t)|\,\mathrm{d}t \tag{5}$$

With all such approaches, the *typical* property change of a "true to type" battery is estimated from the operational history the battery has suffered, and this is supposed to be correct also for the *individual* battery under test. As individual battery performance is not measured and properties of the individual battery are ignored, those approaches are inherently limited in precision. However, they can be easily established, may serve as a rough estimation of degradation, and may support more sophisticated approaches as a check for plausibility.

The strengths of such approaches are the limited effort with respect to number, precision and acquisition frequency, i.e. limited cost of sensors, memory, and processing capability.

3.4.2. Prediction of battery performance

With the state values (SOC, SOH, T, etc.) determined, the behaviour under an assumed (hypothetical) future load profile can be predicted, i.e. the power capability of the battery with respect to a known electrical demand. A load profile, e.g. that for cranking of an ICE or for operation of EPS or EHB, is characterised by the current $i(t)$ or power $P(t)$ needed as a function of time, and by the lowest (or highest) allowable voltage level. The predictor may predict the expected voltage level, using characteristic data or a mathematical model.

The prediction may be made for the

- short-term, with current battery status, for the case when an immediate loading of the battery has to be expected, or for
- medium term with an estimated future status of the battery, e.g. for a future load (for instance cranking) after an extended stand still of the vehicle, with possible changes of state values (especially SOC and T) in the meantime.

The following layer model of information explains the differences for predictions to different points in future time completely sufficient as input parameter for air conditioning control.

	Case A	Case B
Point in time from now	Right now/near future	Medium future
Application	For supply of EHB, EPS; for cranking capability right now for stop/start mode, ...	For cranking capability at a later point in time t', e.g. with some engine off discharge, in several days at potentially lower SOC and other T, ...
1st step	Estimate actual SOC, T, SOH	Estimate actual SOC, T, SOH
2nd step		Make prediction for SOC, T, SOH at later point in time t'
Predict SOF = voltage $U(t)$	At defined electrical load profile $i(t)$ of duration t_0 with actual ($t = 0$) values of SOC, T, SOH	At defined electrical load profile $i(t)$ of duration t_0 with later point in Time ($t = t'$) values of SOC, T, SOH
Criterion (e.g. special case of discharge load)	$U(t) >$ threshold voltage U_1 for $0 < t < t_0$	$U(t) >$ threshold voltage U_1 for $t' < t < t' + t_0$
Comment	SOC, T, SOH are *internal calculating* parameters only, i.e. their definition is free and needs not to be standardised	SOC, T, SOH are *exchanged with the vehicle system* → common understanding for design specific definition required

3.4.3. Determination of battery degradation

For a service check of the vehicle in the workshop, or for a replacement strategy for the battery, an assessment of wear and tear of the battery and information about if and when a battery should be replaced is requested. While determination of battery performance is related to an actual battery status, degradation means performance under (hypothetical) reference conditions, i.e. SOH with respect to a certain load profile (cf. Eq. (2)), e.g. cranking. However, a figure of merit SOH describes the actual battery status only. For prediction of the residual battery lifetime, until the lower threshold (e.g. SOH = 0) is reached, a special life model is needed.

4. Precision of Battery Monitoring

4.1. Precision—what is possible and meaningful

In discussions about Battery Monitoring, precision is one of the key points—and sometimes it seems to be rather a political one, without deeply specifying the term "precision" and the potential benefit.

For established vehicle instruments, like fuel gauge, cooling water temperature (boiling), engine oil pressure and temperature, rather coarse gauges are accepted. Relative error of about 5% in residual fuel is state-of-the-art. Ambient temperature is precisely measured, but due to a poor position of the sensor (the vehicle's front bumper temperature may differ significantly from that of the bridge 100 m ahead), the value of the information is rather limited for ice warning—but

The same is true with precision of Battery Monitoring: any number, and any effort, has to be analysed for its significance for the purpose under discussion.

4.2. Demand and technical necessity for precision

Precision with Battery Monitoring is governed by an area of conflict, comprising

1. Needs to achieve a given technical goal.
2. Effort due to
    - ○ Limited reproducibility of battery and battery performance.
    - ○ Precision of sensing and data acquisition.
    - ○ Model/algorithm quality and scope of its applicability.
3. Cost.

Considering marginal cost and marginal utility for any effort increase, needs and cost have to be balanced, to maximise benefit for the customer.

Valuation of needs for a defined technical goal comprises risk analysis for erroneous prediction, possibly a Failure Mechanism and Effects Analysis (FMEA), definition of acceptable residual risk, and—if the system has to be oversized, threshold values to be chosen more conservatively, or means for redundancy have to be taken—valuation of extra cost to do so.

4.3. Reproducibility of batteries and battery performance

Reproducibility of battery performance has to take account of the principal limitation of measurement of lead-acid battery data. No algorithm can exceed the ideal case: an experiment to measure what is being predicted. However, when repeated, the result of this experiment will not be the same: battery state is characterised by electrode microstructure and its spatial distribution, overlaid by many details of operational history, which cannot be covered by macroscopic figures like SOC, SOH and temperature.

Reproducibility of battery experiments depends on the type of experiment, and on the effort to reproduce the initial status. Depth-of-discharge and discharge rate of the previous cycle influence the actual capacity due to the ‘‘reversible capacity decay’’ phenomena, cf. [39]: while continuous deep (full) cycling decreases capacity, a preceding deep discharge at low rate (a so-called ‘‘recovery cycle’’) may improve capacity by several percent [40].

Valuation of capacity requires taking the time t_{EOD} until voltage $U(t)$ falls below a threshold voltage U_{min}. The precision depends on the gradient $\mathrm{d}U(t)/\mathrm{d}t$ at this point U_{min}: with a steep decline, the threshold area is passed through very quickly, giving a precise point in time. However, with a flat decline, the voltage passes slowly, and the experimental fuzziness creates more uncertainties in time t_{EOD} and capacity value.

The same is true if the voltage $U_{\mathrm{load}}(t_0)$ under a load after a certain period of time t_0 is requested.

Acid stratification is another potential source of error: if the specific acid gravity SG is higher in the lower portion of the battery, this creates a higher electromotive force EMF than at the upper portions with lower concentration. However, the battery terminal voltage, dominated by the highest EMF in the cell, simulates an overall EMF which is correct only for the lower portion, which may affect estimation of battery properties calculated from terminal voltage.

Automotive batteries are cycled but scarcely ever completely recharged. With modern antimony-free grids, gassing is very much reduced providing freedom from maintenance, and the limited recharge voltage (about 14 V, …, maximum 15 V) does not overcome acid stratification. With narrow electrode plate stacking and optimised vehicle suspension, stirring of electrolyte by vehicle motion is reduced, too.

The good message is that significant acid stratification has scarcely been found in the field. This is most probably due to limited cycling in most applications. The bad message is that in vehicles under intensive battery cyclic duty, a difference in acid density between the top and the bottom regions of several 0.01 g/ml can be observed. And such vehicles become more and more popular.

The gradient dEMF/dSG is about 920 mV/(g ml) per cell (~5.5 V/(g ml) per six cell battery) [41]. For automotive batteries the gradient dSOC/dSG is about 400–500%/(g ml), depending on design, i.e. 1% SOC change is equivalent to a change in EMF of about 11–14 mV.

If the ‘‘true’’ acid gravity SG (=average over the whole battery) is assumed to be the average of the ‘‘bottom’’ value $\mathrm{SG}_{\mathrm{bottom}}$ and the ‘‘top’’ value $\mathrm{SG}_{\mathrm{top}}$, overestimation of SOC from EMF will be about 2% for any difference in acid gravity ($\mathrm{SG}_{\mathrm{bottom}} - \mathrm{SG}_{\mathrm{top}}$) of 0.01 g/ml. In this calculation, potential latent reduction in storage capability due to the inhomogeneous distribution of acid over cell height is not currently considered.

Besides acid stratification, sulphation, i.e. discharged $PbSO_4$ active material (‘‘hard sulphate’’) which is not reconverted to PbO_2 or Pb(met) under extended recharge, is claimed to mislead Battery Monitoring. However, as far as SOC estimation from EMF is considered for valuation of ‘discharge’ capability only, ‘‘hard sulphate’’ behaves like ordinary discharged $PbSO_4$ material. On the other hand, for valuation of ‘recharge’ capability, sulphation is an issue, as ordinary $PbSO_4$ can be recharged much better than ‘‘hard sulphate’’.

Reproducibility of the battery itself deals with the deviation of the individual battery from the ideal type of this design, which comprises variations in the amount of active and non-active materials, active material density, inhomogenities over electrode area and from electrode to electrode, or among cells connected in series, etc. According to [42], electrolyte SG of SLI batteries shall be in the range from 1.27 to 1.30 g/ml, if not specified differently by the manufacturer. Usually, SG is in the range of 1.28 ± 0.01 g/ml when they are shipped.

Variations in electrolyte specific gravity SG have two consequences:

1. A deviation of 0.01 g/ml in SG will mislead the SOC value derived from battery open circuit voltage or any voltage under load measurements by about 4%.
2. A deviation of 0.01 g/ml in SG induces a deviation of $M(H_2SO_4)$, the amount of H_2SO_4 available in the cell, by about 4%.

Another source of deviations is variation of the amount of electrolyte filled into the cell, which may vary $M(H_2SO_4)$, too. When the battery is fully charged, SOC estimation from terminal voltage is not influenced by variations of $M(H_2SO_4)$. However, when H_2SO_4 has been consumed during discharge, its EMF is determined by the amount of H_2SO_4 which is left. Variations of the total amount of electrolyte have to be considered relative to the residual amount of H_2SO_4. Therefore, errors generated by such variations become the more relevant the lower the SOC, as sketched in Fig. 10. The absolute value depends on battery design.

An example for the consequences of variations of the amount of electrolyte is as follows:

If 60% of nominal capacity has been discharged, a 1% variation of the amount of acid results in a SOC variation of about 0.6%. If variation of the amount of electrolyte follows a normal distribution with a variance of 1%, then the variation in SOC at about 40% is about ±1.2% with a reliability of 99.7% (3σ value).

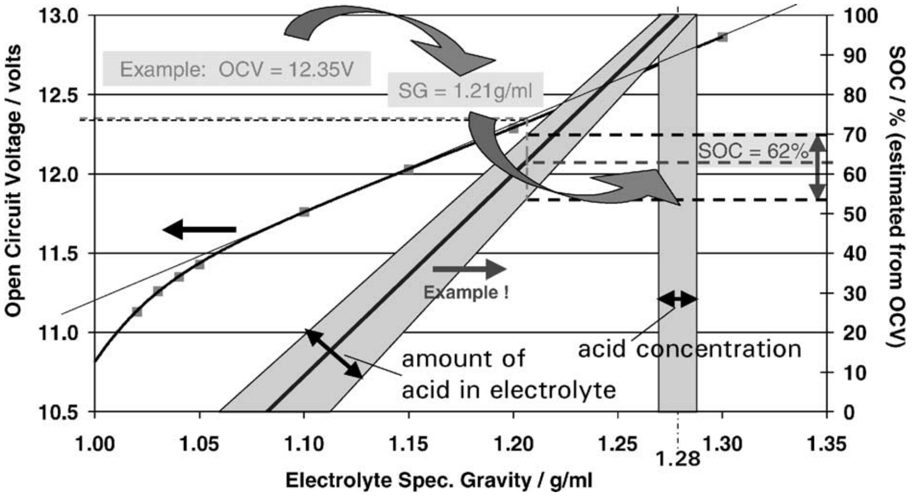

Fig. 10. Errors generated by variations of total amount of electrolyte are the more relevant the lower the SOC, while errors from electrolyte SG are independent from SOC. Absolute values depend on battery design.

Table 2
Expected divergence of SOC (%) estimated from EMF, for a battery with state-of-charge of ∼100 and ∼40%, respectively

SOC divergence	SG (g/ml)					
	1.27[a]		1.28[a]		1.29[a]	
	∼100	∼40	∼100	∼40	∼100	∼40
$M(H_2SO_4) = 99\%$	−4	−4 − 2.4 − 0.6 = −7	0	−0.6	4	4 + 2.4 − 0.6 = 5.8
$M(H_2SO_4) = 100\%$	−4	−4 − 2.4 = −6.4	0	0	4	4 + 2.4 = 6.4
$M(H_2SO_4) = 101\%$	−4	−4 − 2.4 + 0.6 = −5.8	0	0.6	4	4 + 2.4 + 0.6 = 7

[a] Estimated from EMF at different percentages of SOC.

The values in Table 2 shows the expected divergence of SOC estimated from EMF, for a battery with state-of-charge of ∼100 and ∼40%, respectively, for the combinations of

- various acid SG (1.27, 1.28, and 1.29 g/ml), and
- various weights of filling acid (99, 100, and 101% of designed value).

Table 2 shows that divergence of SOC may range from about −4 to about 4% for ∼100% (full) state-of-charge, and from about −7 to 7% for ∼40% state-of-charge.

Variations in SG of filling acid have two consequences in SOC calculated from EMF, namely

- parallel shift of EMF with increasing SG,
- change of the slope of the EMF versus SOC curve, which influences SOC at SOC < 100%,

while variations in the amount of filling acid only, and

- change the slope of the EMF versus SOC curve, which influences SOC at SOC < 100%.

Both amount and SG of filling acid will follow a distribution curve. If, for simplicity, Gaussian (normal) distributions are assumed with variance of 0.002 g/ml in acid SG and 1% in acid weight, respectively, and with 1.28 g/ml of acid SG average value, and if both parameters are assumed not to be correlated, convolution of these distributions using a Monte Carlo procedure gives the probability functions as shown in Fig. 11.

This makes obvious that prediction of the *average* behaviour of a *large sample* of batteries at a specified test can be made with high-reliability, but not the behaviour of one individual battery.

A similar situation is found when one single battery undergoes repeated tests: the behaviour in one single test cannot be predicted so precisely as the average in a series of tests.

4.4. Precision of sensing

Precision of sensing and data acquisition comprises sensor resolution, drift with temperature and ageing, appropriate location of the sensor, and—depending on the information derived from the raw data—sample rate frequency and constancy, and co-incidence of data from various sensors. Error types and acceptable sensing and acquisition errors are strongly linked to the type of algorithm applied, the figures calculated, and the consequences drawn are as follows:

- Absolute error, e.g. of absolute voltage, which is relevant if SOC is estimated from EMF.

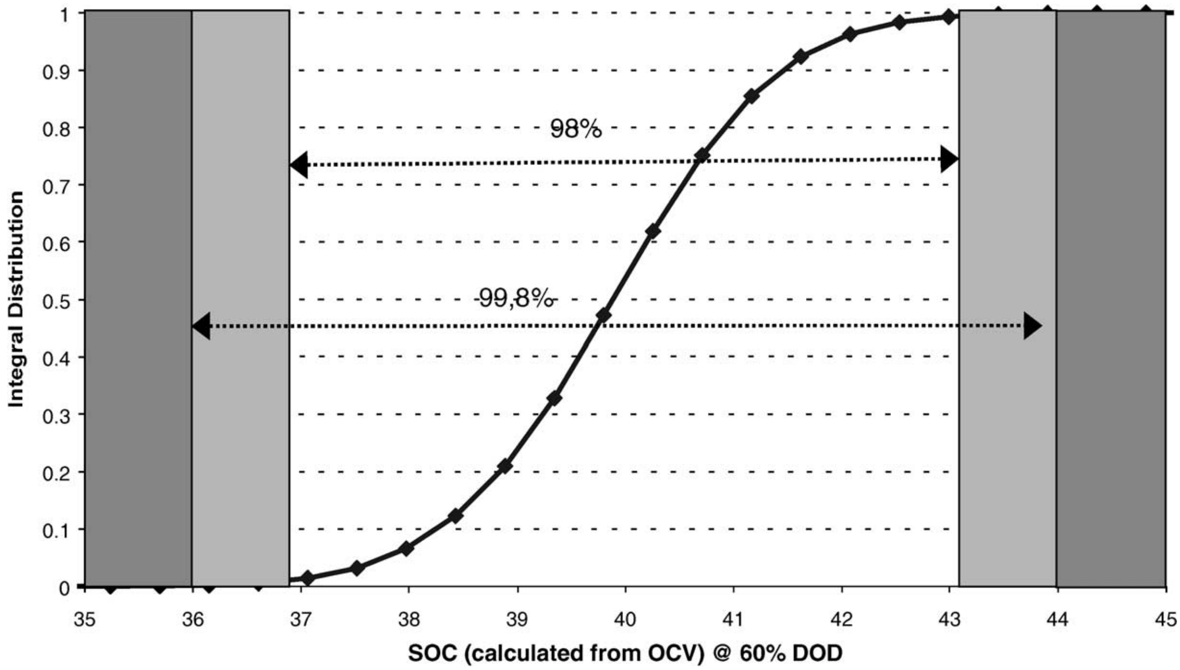

Fig. 11. Probability function generated by convolution of distribution curves of amount and SG of filling acid using a Monte Carlo procedure (cf. text).

- Relative error, i.e. deviation in difference between two acquired values, e.g. between two voltages or two currents, is relevant if a figure like $\Delta U/\Delta i$ is calculated.
- Repetitive error is a measure for the reproducibility of sample values taken several times.
- Co-incidence errors, i.e. shift in point in time of sensing data of two figures, which should be taken exactly synchronously, are especially important with transient processes.
- Systematic error means deviations caused by non-optimised acquisition, e.g. non-optimal location of a sensor; mostly those deviations can be estimated using a model.

Voltage is usually measured using an analogue to digital converter (ADC). With commercial 12-bit types, the two least significant bits (LSB) being uncertain, a relative resolution of about $2^{-10} \approx 0.001$ is achieved. With about 15 V maximum battery voltage, this is an accuracy of ±15 mV. If EMF is used to estimate SOC, this corresponds to $\pm 1.1, \ldots, 1.3\%$ in SOC.

For current measurement, either a shunt or a current transducer is used. Precision of these components varies in a wide range following the manufacturers' specifications. Typically, the error comprises a relative (proportional to actual value) and an absolute contribution (independent of actual value).

Besides the usual deviations of the sensor and the related ADC, the measurement of battery temperature is handicapped by the potential temperature inhomogeneity within the battery, and by the fact, that at least today, there is no temperature sensor within the battery. Positioning of the temperature sensor apart from the battery creates a systematic error (v.s.), which may be compensated by a temperature model, e.g. [31].

4.5. Precision of algorithms

The precision of an algorithm depends on the level of simplification, i.e. the degree of neglecting of effects. Any error in input data, from sensing devices and scattering of individual battery properties, should not be attributed to the algorithm. Such errors cannot be compensated even by a highly-sophisticated model or a very detailed characteristic pattern. At best, intelligent filter functions and checks for plausibility allow the exclusion of erroneous sets of data from influencing Battery Monitoring.

Ambiguity is a principle problem with characteristic patterns and models. With model approaches, better results may be achieved by more detailed consideration of battery processes. On the other hand, more detailed models usually work with more parameters, the values have to be correctly chosen, or fitted to measured data. For strongly correlated parameters, a correct separation and choice of parameter values from measured data becomes more and more difficult, i.e. observability may be rather poor. If a high level in detail results in occasional numerical instability, a more coarse but robust algorithm may be the better choice.

Algorithm quality is more than precision: a robust procedure is needed with mathematical stability, unequivocal parameterisation and correct separation of variables. To check this capability, extensive laboratory and road tests are necessary.

4.6. Battery degradation

Battery Monitoring and Management has to consider the change of lead-acid battery properties over life, including grid corrosion, water loss, changes of active material properties, loss of active material availability, etc.

Energy throughput, i.e. battery cycling, is gaining in importance with new vehicles, but the dissolution/precipitation process as the main reaction of the lead-acid system is a fundamental handicap for cycle life for all lead-acid batteries, with both flooded and immobilised electrolytes, and in both prismatic and in spirally wound designs:

1. Structural information is lost upon cycling, as electrode morphology changes during operation (inducing softening, shedding, mossing, dendrite growth, reversible capacity decay, etc.).
2. The sulphuric acid electrolyte is involved in the main reactions, and depletion processes show up at high discharge rates.

Valuation of the actual SOF does not necessarily need to distinguish between short-term (reversible) influences like electrolyte depletion effects, and long-term (irreversible) degradation, e.g. from mass shedding or corrosion, while predictions of battery performance in the medium or far future can be made only if these effects are handled separately.

An actual increase of battery impedance helps prediction of reduced short-term high power capability. For prediction of long-term behaviour, at another battery status (SOC, T), permanent origins from grid corrosion have to be separated from those from active material loss, as their dependence on SOC and temperature T is different. And these permanent origins have to be distinguished carefully from momentary concentration polarisation effects and especially the influence of SOC and T.

4.7. Cross check and plausibility

To avoid unexpected results, the input data to Battery Monitoring, and the figures generated, should to checked for plausibility before they are used, e.g. by Energy Management.

Figures may be checked against their range of plausible values, which may depend on parameters like temperature, SOC, or vehicle status.

- With engine off, voltage is scarcely >13 V, and current cannot flow in the recharge direction.
- Battery voltage and current may change rather quickly, but more or less synchronously.
- Battery temperature, SOC, and SOH cannot change abruptly.
- CSC or a parameter comprising grid resistance should correlate with battery duty history, like charge throughput and/or operational temperature. Otherwise something is wrong—with the output of Battery Management, or with the battery.

The handling of possibly detected discrepancies depends on the relevance of the figure, the goal of the function, and the capability of the system.

5. Energy and Battery Management

The technical goal of Energy Management is to guarantee the electrical power supply of a component, in all or only in special situations, e.g. with the ICE running or the vehicle moving. Power supply is usually provided by the alternator when the ICE is running and this has to be considered.

If the expected voltage under an estimated future load becomes critically low, or the available amount of charge is too low, energy balance may be improved by a decrease of energy consumption or by an increase of energy generation.

Especially the first is very helpful to improve the short-term energy situation, e.g. to guarantee the power to supply critical loads by reduction or disconnection of non-essential loads, which can be done in a stepwise manner, until all but the real essential components have been switched off.

More comfortable for the user, but technically more ambitious, is an increase of power generation by alternator stimulation (increasing of the generating magnetic field), by triggering of the engine control to increase idle speed, or by increase of the rpm switch points of the automatic gear shift control.

Usually, a higher state-of-charge is sought to meet discharge demands. Therefore, Energy Management is closely linked to battery performance and properties like charge acceptance, etc.

Medium term Energy Management considers the situation several hours or days ahead, when the battery state-of-charge and temperature may have been changed. Cranking capability is the main goal in most cases. With an estimated temperature at the point in time under consideration, the power or current profile $P(t)$ or $i(t)$, and the minimum voltage U_1 (cf. Eq. (3)) needed to crank the engine can be calculated. From this information, the minimum available amount of energy Q_{min} necessary to provide this power profile at $U > U_1$ can be deduced. This corresponds to a minimum value $\mathrm{SOC}_{\mathrm{min}}$.

If the actual SOC is higher than $\mathrm{SOC}_{\mathrm{min}}$, Energy Management may keep house with the excess $(\mathrm{SOC} - \mathrm{SOC}_{\mathrm{min}})$ to cover both quiescent loads and additional comfort loads like radio etc. However, if the actual SOC is lower than $\mathrm{SOC}_{\mathrm{min}}$, immediate means to increase SOC have to be activated to maintain future cranking capability.

A schematic flow chart for Energy Management to provide cranking capability several days ahead is shown in Fig. 12.

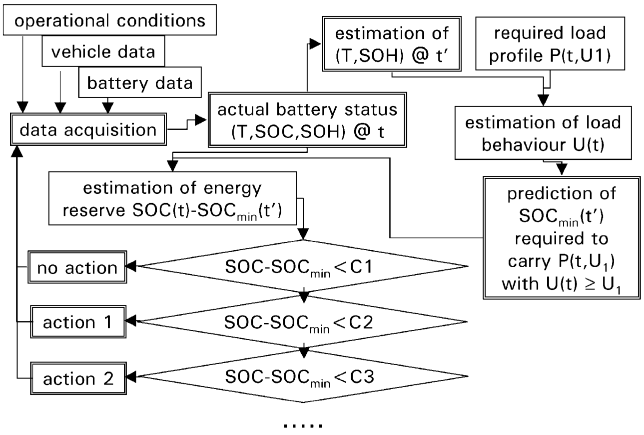

Fig. 12. Schematic flow chart for Battery Monitoring and Energy Management to provide cranking capability several days ahead.

6. Summary and outlook

Vehicle electric systems will be further driven by fuel economy, ecology, and by new functions for improvement of safety, comfort, and reliability.

Electrically driven components needing electrical power with high-reliability will penetrate the mass market soon, and start/stop systems will reduce ICE idle speed running.

The automotive industry and its suppliers are aiming at solutions comprising the 42 V PowerNet [4,7,11–13,43–45] to be open for technical solutions with very high power demand like new cranking technologies [46–48] and other components (cf. e.g. [12,13,46,49]). Standardisation of the "42 V PowerNet" with the ISO is under way [50,51].

In advanced "smart hybrid" designs, the drive modes (ICE only, electric only, both, recharge battery, braking by mechanical brakes or by recuperation, etc.) are chosen by an intelligent drive control system, which considers energy consumption (fuel and electric), emissions and battery status. This includes keeping the battery state-of-charge within an optimal operating window.

In the long-term future, the role of the ICE may be taken by a fuel cell which directly provides electrical energy for driving. This will change but not revolutionise the battery operating conditions, as a fuel cell is normally not able to operate as an electrolyser. So an electrical storage device is needed for peak power shaving, for consumers at stand still, and for recovery of braking energy.

However, changes of the vehicle electric power architecture are expected to proceed evolutionary rather than in a revolutionary manner. Due to cost considerations as well as uncertainties with respect to the availability and reliability of newly designed components [10], modifications will be introduced stepwise only when really needed. This process is expected to last many years.

Battery Monitoring and Energy Management becomes even more essential when new types of duties are imposed on the batteries, changing from a passive component to a pivot unit which has to be monitored, supervised and managed to maintain the vehicle functionality and safety—for both present 14 V and for future 42 V PowerNet levels.

After high initial enthusiasm, a date for introduction of 42 V systems is not yet fixed. But there is already demand for Battery Monitoring and Energy Management. Solutions for series vehicles launched in years 2001–2003, operating at a 14 V level, have been developed and are being further improved.

Whatever the final design of the vehicle electrical system may look like

- there will be more electrical power needed on board than today,
- this will be the case even when the vehicle is at a standstill,
- the alternators are chosen for the average rather than the maximum power demand, and
- the battery will have to bridge even more than today.

For systems needing a highly-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 in order to keep the battery in a good operational range, to check its actual state, to predict its capability, and with multiple battery systems, to control the mutual energy exchange.

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