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The challenge to the automotive battery industry: the battery has to become an increasingly integrated component within the vehicle electric power system

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Abstract

During the time that the automotive battery was considered to be just a passive component in a vehicle electric power system, the battery industry's answer to all new challenges was constructive improvements. The emerging requirements of even higher function reliability cannot, however be met this way. A battery manufacturer of today has to give recommendations for the appropriate choice of the electrical architecture and has to design batteries that suit best the requirements. In addition, manufactures have to be engaged in the technology of battery management, of battery monitoring and state detection, and performance of prediction under future operation conditions. During service on-board a vehicle, battery performance undergoes significant changes, e.g., loss of storage capability, increase in internal resistance, and changes in voltage characteristics. These ageing processes have to be considered when the electrical architecture is being designed and management strategies are being formulated. Battery monitoring and state detection must be able to identify and quantify battery degradation. Moreover, performance prediction as well as management strategies have to be corrected on account of the changing battery characteristics.

Keywords: Automotive battery; Vehicle electric power system; State-of-charge; State of health; Monitoring; Capacity loss

1. Introduction

1.1. The "automotive battery"

In everyday language, the term 'automotive battery' means a battery on board of a road vehicle. The storage device of energy in the vehicle with an internal-combustion engine (ICE) is the SLI battery, which takes its name from the basic electrical functions of starting (S), lighting (L) and ignition (I). It provides the electric power for cranking the ICE, buffers electrical energy within the vehicle electric power system during operation, provides electrical energy when the engine is off (especially for lighting), and is recharged from an alternator driven by the ICE. The operating mode of automotive batteries is characterised by 'floating' in a medium state-of-charge with shallow cycling, where full recharge and full discharge are never achieved [1,2]. At present, SLI batteries are of the lead–acid type, usually with 12 V nominal voltage and of flooded design. Despite being installed in series-production vehicles back in the late 1980s, valve-regulated lead–acid (VRLA) batteries have not become widespread in large numbers and are still limited to markets with special requirements such as luxury cars, taxis, agriculture vehicles, motorcycles, and military applications [3–7].

Different from the 'automotive battery', vehicle propulsion is the main task of a 'traction battery'. Typical applications are forklift trucks, automatically guided vehicles (AGVs) and electric road vehicles (EVs). From an operation point of view, a traction battery essentially differs from an

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automotive type in that it is recharged at a recharge station, or is exchanged by another recharged battery. For example, the electric energy for vehicle propulsion is not generated on board of the vehicle, but comes from a (immobile) recharge station. In most cases, the operating mode is characterized by deep cycles, starting from a full state-of-charge, and complete recharge (at least from time to time) afterwards.

The batteries of hybrid electric vehicles (HEVs) are operated in an intermediate mode. Early HEV designs were characterized by installation of an independent electrical drive-trains (for emission-free city driving) in addition to the conventional ICE drive-train (for long-distance operation) to provide a dual-mode operation. With combinations of mechanical drive-trains equipped with intelligent gearing and clutches, a single electrical engine may operate for propulsion/acceleration assist of the ICE, for recuperation of braking energy, and for battery recharge. These functions will save both weight and cost. 'Smart hybrid' vehicles have relatively small electrical engines and batteries that are usually used for vehicle propulsion only together with the ICE to enhance the cranking and to improve vehicle acceleration ('launch assist', 'boosting') when the ICE provides little torque. This type of vehicle is sometimes called 'mini hybrid', a 'soft hybrid' or a 'mild hybrid' [8–10]. Recent approaches for 'mild' hybrid vehicles will require some additional battery duty from recuperation of braking energy. This shows that the distinction between traction and automotive batteries will be less sharp.

Future vehicle electric system voltage is expected to be higher than today to reduce ohmic losses in the electric network and to allow for higher efficiency of the components. The introduction of a 42 V level [12–16] is a compromise between increased voltage and avoidance of risk to people. Due to issues of cost and arcing risk, however, to date 42-V systems have been used only in some types of vehicle with low production volume.

For ambitious soft hybrid and for HEV applications in general, a voltage significantly higher than 42 V is required [10]. The first series-production vehicle of this type is the Toyota Prius, the production of which has already exceeded 200,000 units since it was launched in 1997.

1.2. The SLI battery in the 20th century

In the beginning of the development of road vehicles driven by an internal-combustion engine, ignition of the ICE was the only electrical system and was realized by magneto ignition or by primary dry cells. While lighting of luxury cars was provided electrically by storage batteries, it was as late as 1912 that the first electrical starter motor was used in a series-production car. This helped the combustion engine to make the final breakthrough for road vehicles. The SLI battery concept penetrated the whole gasoline vehicle industry within 2 or 3 years, even though the first SLI batteries, designed to provide 24 V for cranking and 6 V for lighting and ignition, weighed about 30 kg [17].

Over the years, the battery and the starter motor, have undergone complete optimization to obtain the best possible torque for the lowest possible manufacturing costs. The vehicle battery was also able to cover electrical requirements during periods when the power supply to consumers was inadequate because the output of the d.c. generator, which suffered from low or even no power output at low engine revs, was too low, or because the engine was at rest. This was not an issue, as for decades electrical ignition, lighting and windscreen-wipers were the only consumers, and features such as radios and electrically driven fans were limited to luxury vehicles. When the electrical window defroster was introduced in the 1960s, this major electrical energy bottleneck was overcome by doubling the battery voltage to 12 V and introducing an adapted 14 V three-phase alternator. This technical concept has remained unchanged to the present day, although many technical requirements have arisen and initiated technological changes to the starter battery that have been scarcely registered by the public.

In previous decades, topping up with water was a regular duty as was checking of the engine oil level and tyre pressure. Successive reduction of the antimony content in the grid alloys allowed for longer and longer service intervals and reduced self-discharge rates. Hybrid batteries with antimony-free negative grid alloys and low-antimony positive grid alloys were an intermediate step ('low maintenance') in the 1980s and 1990s. Today, an antimony-free positive grid alloy, which in most cases is a positive lead–calcium–tin or lead–calcium–tin–silver alloy [18], is demanded by many automotive manufacturers, and represents the state-of-the-art for original equipment starter batteries. With minimal water decomposition, evolution of gasses and acid spilling are no longer critical issues.

Starter batteries with improved double lids may be tilted or even upturned for short periods of time without any acid leaking. The double lid allows the electrolyte to return to the original cell when the battery is turned back to its nominal position.

Independent from grid manufacturing, grid design has been a field of extensive improvement. To achieve higher voltage levels at high discharge rates and to homogenize current distribution, the arrangement, orientation and size of grid wires, as well as size and position of the grid lug, have been optimized [19].

1.3. Interaction with vehicle

Car manufacturers have made use of the above advancements in SLI batteries, especially, with respect to packaging. As space is limited in the engine compartment due to aerodynamic and pedestrian-safe design of the hood, acoustic and thermal insulation of the engine, larger engines and auxiliary components such as air conditioning, the battery is often located in the trunk or in the passenger cabin. Optimization of the weight distribution on the two vehicle axles for best traction and road holding is a further criterion for battery location.

Maintenance-free batteries allow more flexibility in positioning within the vehicle and the absence of acid spillage gives even more flexibility in packaging. Improved battery power capability by grid design optimization, initially aimed at better cranking performance, is used for compensation of ohmic losses from longer cabling (positive terminal side) and from less welding connections and/or glued joints in the car body (negative terminal side), e.g., when the battery is located in the trunk. Improved resistance to grid corrosion and reduced water loss have encouraged the placement of batteries in hot environments.

The technical concept of the vehicle electrical power system has undergone little change since 1960, and the battery is still an absolutely passive energy and power storage device in that:

- it is discharged whenever the current demand exceeds the current provided by the alternator, without any check that the battery is able to provide this energy;
- energy for recharge is offered to the battery if more energy is available than is actually needed, without any check that the battery is able to take the energy. The actual recharge voltage at the battery terminals depends on the actual alternator voltage and on the ohmic losses on their connection, according to the current flowing to or from the battery or to other components.

There is, however, no control of the recharge current, and the state-of-charge (SoC) is hardly a predictable function of electrical loads, driving conditions, alternator and regulator properties, and battery properties including size, design and temperature. This so-called partial state-of-charge (PSoC) operating mode has been, is standard practice, for SLI batteries for decades. Typical SoC levels are about 90% after an extended highway drive in summer, down to less than 50% in traffic jams during winter—or even much less. The latter may generate cranking problems after the engine has been switched off in such a state.

Despite the significant enhancement in power supply, even at low and idle speeds of the ICE, that have been made through the improved characteristics and higher efficiency of the alternator, the rapidly increasing demand for more and more electrical power on board became an issue again in the 1990s. The first problems were encountered in vehicles that featured a multitude of electrical consumers, particularly if only short daily distances are travelled at low temperatures, e.g., in stop–start traffic. In these situations, discharged batteries are being found with increasing frequency in broken-down vehicles. This is due to the decrease in idle speed rpm to achieve less emissions and noise, following improvements in motor control electronics. Even at such low rpm, modern alternators are able to provide the energy that is sufficient for standard demands—but not for all the comfort components at the same time. When the battery is located in the trunk, ohmic losses aggravate the situation (see Section 2.1).

Second, increasing concern has arisen over the battery service-life, particularly if the electrolyte temperature is too high as a result of the location of the battery in the vehicle, or due to climatic influences [3]. This is encountered with improved aerodynamic front–end design, which reduces both space and wind turbulence under the hood, and longer high-temperature operating duties due to increasing traffic congestion. The correlation between battery duty life and climatic conditions has been clearly demonstrated (e.g., [20,21]).

The third class of issues occurs when the cumulative energy throughput exceeds the critical value for lead–acid systems. For standard SLI batteries with liquid electrolyte, this is approximately 100 times the nominal capacity (20 h rate) in a relatively short time. The increased energy throughput a rises from an increasing number of electrical loads that have also to be supplied with energy when the engine is off or on idle. The quiescent loads comprise not only the clock as 20 years ago, but also anti-theft equipment, tele delock, and electronic components such as the engine controller, which is kept in ‘wake’ mode for some period of time after stand-still of the engine to provide a rapid and environmentally friendly re-start. In addition, increased quiescent currents may sometimes be caused by malfunction of devices due to hardware or software failures.

This above considerations show that the requirements of even higher function reliability cannot be met by further constructive improvements by the battery industry. A battery manufacturer of today has to give recommendations for the appropriate choice of the electrical architecture and the design and the packaging of batteries, as well as being engaged in the system technology of battery management, of battery monitoring and state detection, and of prediction of its behaviour under future operation conditions.

2. Functions and situation of automotive battery

Today’s vehicle electric power systems with the battery as an essential component are characterized by the increasing number and associated power demand of electrical consumers, by packaging issues, and by the limitation of the operational voltage of electronic components.

2.1. Dampening of PowerNet against voltage excursion

With the old d.c. generators, the SLI battery had to act as a charge buffer element when the ICE was idling due to their low power output at low revolutions. After introduction of ac alternators of increasing power and efficiency, this was not an issue for many years. Nowadays, however, electronic ICE controllers allow reduced idling rpm to lower emissions, while many comfort components and mechanical devices that are driven electrically require electrical power. Under poor weather conditions in a hot climate, with air-conditioning, headlights and wipers on and the electrical cooling fan of the ICE in operation periodically, the alterna-

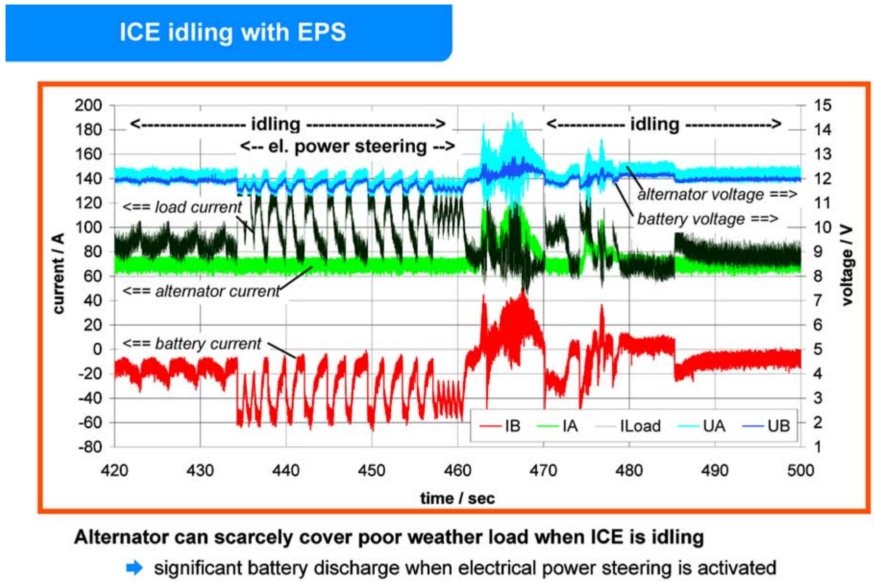

Fig. 1. Battery voltage UB, alternator voltage UA, battery current IB, alternator current IA, and total electrical load current load over time when idling a highly equipped A-size car with many consumers on. When main fan or electrical power steering is activated, the significant lack of alternator power is compensated by the battery.

tor cannot supply sufficient current, as shown in Fig. 1 for a modern highly equipped A-size car. While the alternator provides about 70 A, the overall current load fluctuates between 80 and 100 A, and the battery has to provide the difference. When (electrical power assisted) steering is activated, battery discharge peaks reach −60 A. More current (up to 120 A) is generated when idling is over and the ICE rpm increase. But with increasing alternator voltage, the load current increases as well as many loads have a ohmic-like behaviour. For battery recharge, there is not more than +40 A left in best case and +20 A on average. In this case of load-levelling, charge balance under stop-and-go conditions will be negative, which may compromise cranking capability at the long term.

Negative charge balance, compromising cranking capability, may have other reasons as well, e.g., extended use of comfort components when the engine is off. In all these cases, an intelligent energy management, which uses information from battery state detection, may switch off non-essential consumers, provide appropriate control to the alternator, or even the idle speed and the automatic gearbox, [22,23].

The voltage from the alternator and as well as that at the battery terminals is shown in Fig. 1. The alternator voltage is always higher by several 100 mV due to ohmic losses. Voltage fluctuation at the alternator can bee seen as well. It becomes particularly high when the battery is on recharge, as the recharge characteristic is not as ‘hard’ as at discharge. This shows clearly the dampening effect of the battery on the electrical system (cf., Figs. 3 and 9 in [2]).

2.2. Thermal environment of the battery

The electrical operation of a SLI battery in classical application comprises little high-power duty. Therefore, self-heating of the battery due to ohmic losses is negligible, and the battery temperature is dominated by the environmental temperature, i.e., heat ingress by radiation and air convection. Note, with harsh high-rate cycling operation, especially with start-stop and boost-recuperation duty, the self-heating is significant. For example, start-stop operation with a 600 W electrical discharge load in stop mode and the same total duration of operating and stop periods causes an average power loss of 100 W (total efficiency of 84% of the recharge–discharge), which will heat up a 12 V/80 Ah lead–acid battery within 1 h of continuous operation by 14 K if no heat transfer to the environment is possible [24]. Therefore, the location of the battery with respect to high-temperature components is critical (a comprehensive description of heat-transfer principles applied to batteries is given in [5,6]).

Thermal operating conditions of the batteries of a wide range of series vehicles have been investigated in our vehicle laboratory. A battery adjacent to the pipe-joint of the ICE is scarcely found with modern cars. Car manufacturers have learned that direct heat radiation significantly increases battery temperature, which reduces life due to increases in corrosion rate and water loss. Since the battery parts facing the hot component are especially affected, battery deterioration will proceed inhomogeneously. Many car manufacturers have introduced a (plastic) hood over the battery when the battery is placed in the engine compartment, cf., Fig. 2. This reduces heat ingress from the engine significantly, and maintains a homogeneous temperature within the battery. With extended idling of the ICE at vehicle standstill, without ventilation from driving, underhood temperature may reach very high values. In such cases, a box around the battery will delay and moderate heat ingress, but cannot limit the maximum temperature value. Nevertheless, some manufacturers are go-

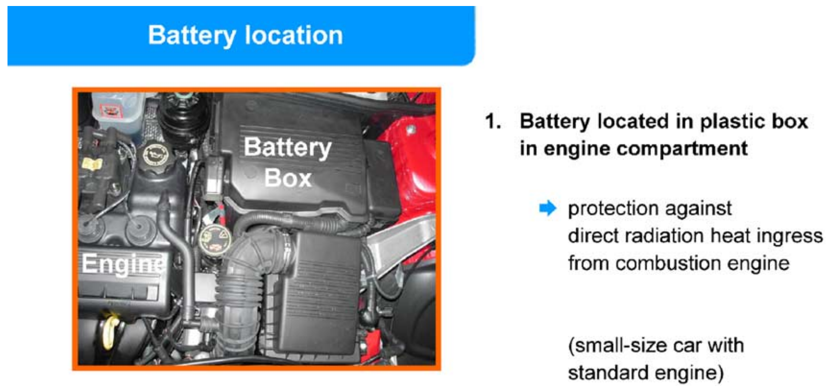

Fig. 2. Battery located in plastic box in engine compartment (small-size car with standard engine) for protection against direct radiation heat ingress from combustion engine.

ing to omit this hood, to save space, weight, and cost. A good underhood location for a battery is within a compartment before the windshield—far away from hot parts of the engine, and the metal sheet construction protects against radiation heat.

With high-power engine vehicles and with luxury vehicles, underhood space is limited and does not allow for packaging of the battery, which is shifted, for example, to the trunk area. From the heat ingress point of view, this is a good choice in most cases. Usually, a battery located remote from the engine should not suffer from any high heat issues. We have, however found a luxury car with the battery located behind the rear axle where the battery temperature increased significantly at medium speed, obviously due to turbulence from hot air from the engine, catalyst and exhaust pipe system between the underbody and the street.

With small cars, space is limited in the trunk area as well. This may have been the reason for the battery arrangement shown in Fig. 3, located in a steel box, but embraced on four lateral sides by the exhaust system. The temperature within the battery and in its direct environment in this box location, as well as outside the box is shown in Fig. 4. Starting at about 20 °C, the outer temperature increases very quickly during driving. The temperature within the steel box increases rapidly by >15° within 1 h and by more than 25° after 2 h of driving. The battery internal temperature rises more slowly and has increased by only 10° after the 2-h drive. It is only the heat capacity of the battery, starting as low as 20 °C, which is dampening its own temperature rise as well as limiting the temperature value within the steel box against the temperature at the outside of the box. After an extended drive, sufficient heat has transferred to the battery, despite of the

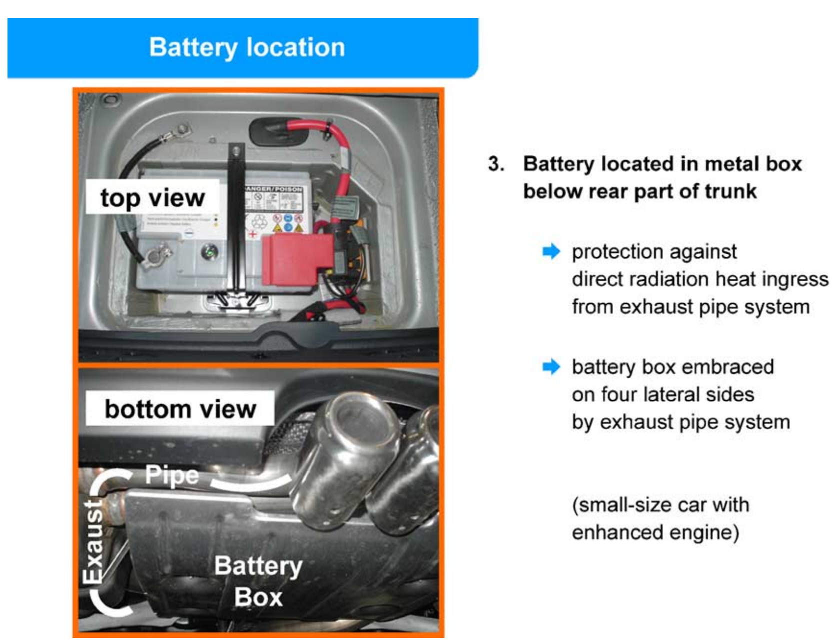

Fig. 3. Battery located in metal box below rear part of trunk (small-size car with enhanced engine) for protection against direct radiation heat ingress from exhaust pipe system; battery box braced on four lateral sides by exhaust pipe system.

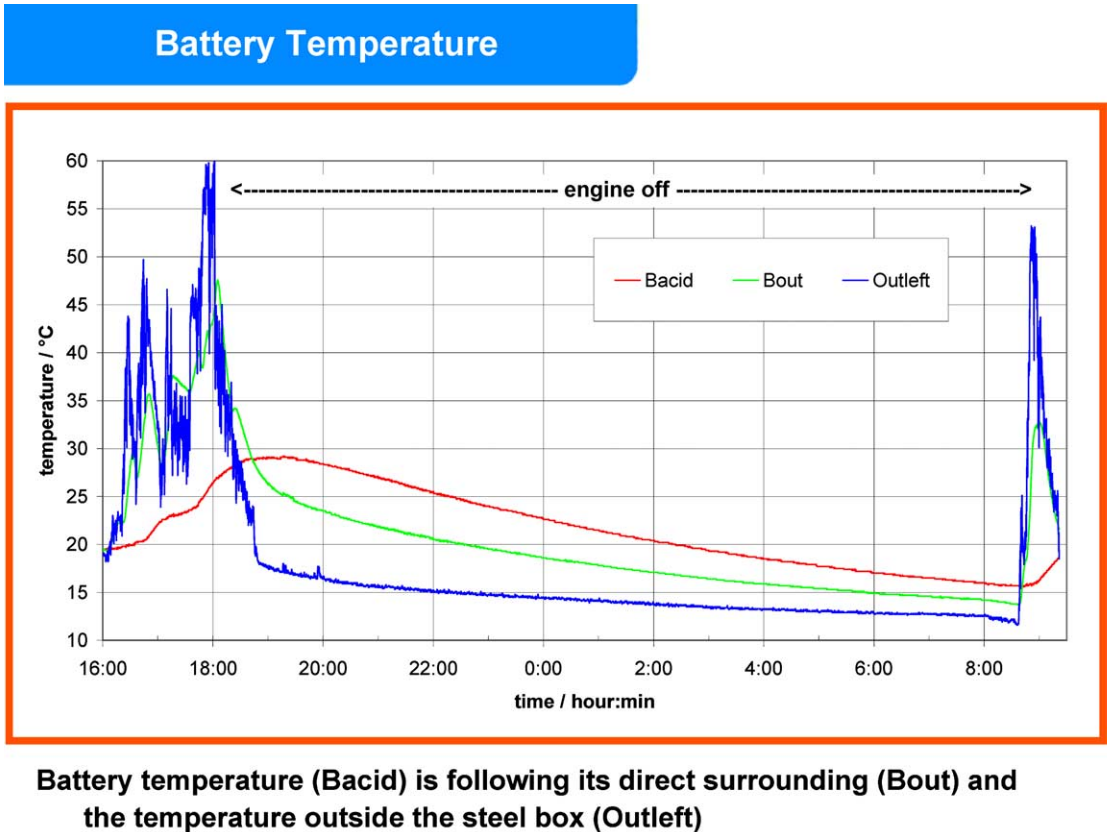

Fig. 4. Battery temperature trend, Bacid, in key-off period follows its direct surrounding trend, Bout and the temperature outside the steel box (Outleft). For battery position, see Fig. 3.

heat shielding, to make its temperature approach that of the environment of the steel box, which is – close to the exhaust – extremely high. Thus, it can easily be estimated what may happen if a test starts at a high ambient temperature (e.g., 35 °C instead of 20 °C) and the driving period is extended to many hours. At the end of driving, the temperature outside the box quickly decreases following ambient cooling over night. By contrast, the battery temperature decreases more slowly due to the insulation provided by the box, and is still 5° higher than ambient in the morning when, after 14 h of standstill, driving starts again.

2.3. Undervoltage at cranking: the battery has to supply both the high-rate starter motor and electronic control units

Before introduction of the electronic engine controller, the battery voltage during cranking under the load of the starter motor was of little relevance: when the current loop was closed, maximum current was flowing and the voltage dipped most, there was no other relevant electrical component. And when battery power was sufficient to make the ICE spin at its minimum rpm for cranking, the voltage had recovered sufficiently to operate the spark plugs. Fig. 5 shows the voltage and the current measured during cranking a 1.8 l

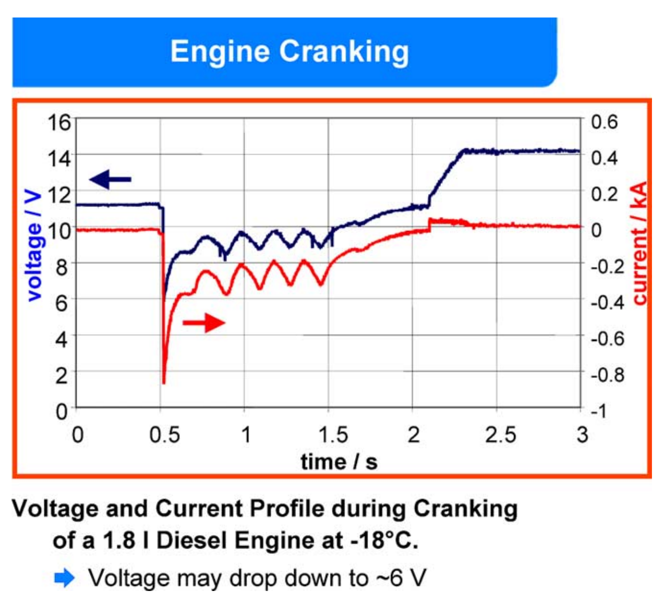

Fig. 5. Voltage and current profile during cranking of a 1.8 l diesel engine (MY 1996) at −18 °C. Voltage may drop down to ∼6 V, but engine will continue to run.

diesel engine (MY 1996) at −18 °C with a battery in medium SoC. The voltage drops below 6 V, but the engine is running within about 1 s.

Today, the electronic engine control unit (ECU) has to be driven by the battery during the whole cranking period; it controls fuel injection and ignition timing to optimize cranking characteristics and to minimise emissions. This ECU requires a minimum voltage for operation. If the voltage falls below this minimum value when the cranking event is initiated, it will work improperly or not at all, and when voltage recovers, it does a logical re-set that takes some period of time. This means a non-optimum cranking even if the voltage has recovered sufficiently when the ICE is going to spin—but the engine will operate if the spinning period lasts long enough.

With many modern cars, the driver turns the ignition key (or presses the cranking button) to give only a ‘cranking request’ signal to the engine control unit, which manages the whole cranking event. The driver no longer has control of the flow of cranking current and the duration of the cranking procedure. The ECU activates a relay, which allows the cranking current to flow to the starter motor. If the short-circuit current through this motor (in stand-still position) causes the voltage to drop below the minimum level for ECU operation (for a period of time longer than the capacitors in the ECU power supply can bridge), the relay will be released and the starting procedure will be discontinued, i.e., cranking is impossible.

Independent of the reason for a deep voltage drop, e.g., low battery SoC, low temperature, other electrical loads (headlights, etc.) activated or battery worn out, the driver will be unhappy as cranking was possible just before (due to the ECU optimizing all parameters) and then there is a ‘digital’ change to ‘no cranking’. With the old technology, cranking became gradually more cumbersome, which even the inexperienced driver could hear. Today, the driver expects to have a reliable indication for cranking capability, and not less information than with the old technology.

3. New functions of automotive battery

New vehicle electric designs are driven by fuel economy and reduced emissions, as well as by new functions for improvement of safety and comfort, reliability, and the availability of the vehicle, i.e., cranking and energy supply to essential functions under all (standard or misuse) conditions. While some of these functions are already established, such as electrically controlled and powered systems for braking, steering and stabilization, others are just being introduced. The stop–start operation mode of the ICE will require even more battery cycling when the electrical system has to be bridged while the ICE is at standstill. The same is true for the torque assist/acceleration assist (boost) mode. Planned generation of electrical energy (only when it is economically meaningful), including electrical brake energy recovery (recuperation), requires knowledge about the capability of the battery to accept charge.

The power demand of luxury vehicles is well exceeding 2 kW, and will further increase. Middle class and compact class vehicles will also follow this trend. For the next decade, automotive engineers predict a dramatic increase to about 10 kW [14,25].

Energy suppliers and environmental scientists predict [26,27] the fuel consumption level for new vehicles to fall by the year 2015 to half that of today’s value of 9 l/100 km. This is thought to be possible only through challenging technical measures which bring up further electrical demands, many with significant current transients such as 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). More powerful batteries with greater cycle stability [26] and storage capacity [28] will be needed.

Dual-battery systems [1] have been established since about 2000 in sports cars, several limousines and, more recently, in a group of SUVs. The systems guarantee the capability to crank the combustion engine and to maintain the mobility of the vehicle even in extreme operating scenarios and in case of failure or misuse of the power-supply system, which is especially important when high reliability is required, e.g., for an electromechanical power steering (EPS) or an electro hydraulic breaking (EHB) system [1,2]. Two batteries and/or an elevated operation voltage of the PowerNet may give some redundancy and may provide the average power demands for which the system is designed, but will not fulfil all the actual and predicted future needs. Only with if the battery has been monitored and its state has been determined can the energy flow be managed appropriately. Thrifty energy housekeeping with an intelligent integration of the battery as the storage medium into the overall concept of vehicle energy management in the vehicle requires a compromise between economy, ecology, safety, and comfort.

3.1. Determination of SLI battery state and capability to improve vehicle readiness

When compared with the operation of traction or stationary types of battery, the specific different situation of automotive batteries becomes obvious. The behaviour is technically impeding battery monitoring in the automotive field because [2]:

- the batteries are rarely ever completely charged, i.e., ‘opportunity charge’ is standard;
- discharge, performed with a wide range of different rates, never starts from full SoC;
- recharge is performed randomly with a wide range of different current rates;

- sometimes full discharge or (unfortunately) even over-discharge may take place;
- operational temperature may even exceed the window from −30 to +70 °C.

Despite the fact that the automotive cost level excludes many solutions that may acceptable in other fields, battery monitoring and state detection, as well as energy and battery management, have found their way into the luxury segment since about 2000, [22,23], and are migrating to the middle class now. Economy concepts will give them another push forward in the next years.

4. Battery state detection—foundation of vehicle electrical power management

The necessary steps to analyze battery status, and to make use of this information, are discussed here in more detail, as the terms used in the field of battery monitoring and energy management are often used in different manner. Especially, there is no unequivocal meaning for the term 'battery management system' (BMS). In most cases, any feedback to the battery is missing, i.e., the battery is only (passively) monitored and information is generated, rather than it is (actively) managed.

Any analysis of an arbitrary system requires information, i.e., input data. In case of the battery, voltage U, temperature T and current i can be measured directly (observable values). Measurements of a sub-set of such data are 'battery monitoring', as battery operation is only (passively) observed.

These data are input information that are being processed during 'battery state detection' (BSD). This term comprises analysis of the state vector P of the battery, i.e., values of internal parameters or properties that may not be accessible for direct measurement (non-observable values), but that determine battery state, property, performance and capability. Examples for such internal battery parameters are acid gravity, active material utilization, and any inhomogeneity of these.

If the state vector P of the battery is known, and furthermore a model of battery performance as a function of P is given, battery behaviour under a hypothetical electrical load can be predicted for the actual point in time t_0, as the actual value of $P(t_0)$ is known (= predictor for instantaneous behaviour). If, for example, the electrical load is a current profile $i(t)$ starting at time $t = t_0$, the battery response voltage $U(t, P(t_0))$ can be predicted. If an even more advanced version of an algorithm is given, which allows prediction of a future state vector $P(t_1)$ from the actual state vector $P(t_0)$ when the operation conditions of the battery in the time period from t_0 to t_1 are known, then battery behaviour under a hypothetical electrical load can also be predicted for that future point in time t_1 (= predictor for future behaviour), see Fig. 6.

The term 'battery management' should be used only if active feedback is given 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. (Electrical) "energy management" means careful housekeeping of the electrical energy, i.e., control of energy generation, flow, storage, and consumption. Without the essential

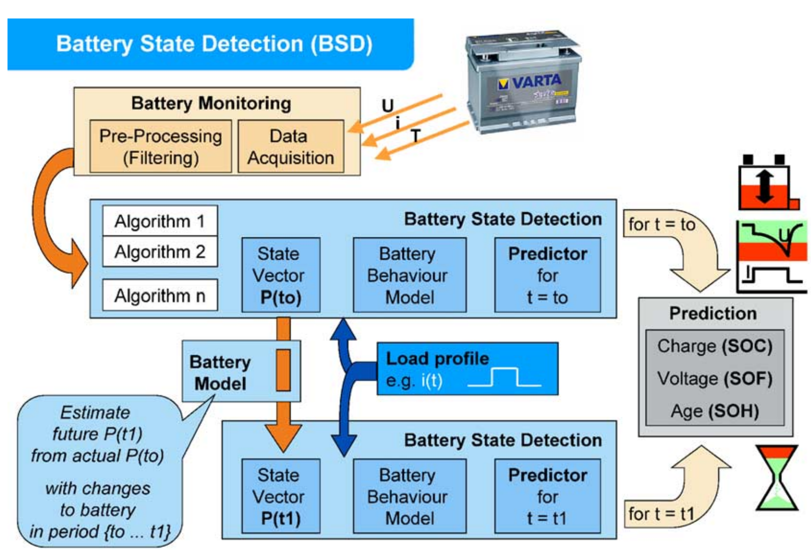

Fig. 6. Steps of battery monitoring, battery state detection, and prediction. Algorithms are used to determine the battery state vector $P(t_0)$ at an actual point in time t_0 from pre-processed measured data. A performance model predicts battery behaviour under a hypothetical electrical load profile for the actual point in time t_0. For prediction of battery behaviour at a future point in time t_1, a future state vector $P(t_1)$ has to be determined, first from the actual state vector $P(t_0)$ considering the change of conditions in the time period from t_0 to t_1. Prediction may be related to SoC (i.e. charge), SoF (e.g. voltage response), or SoH (ageing).

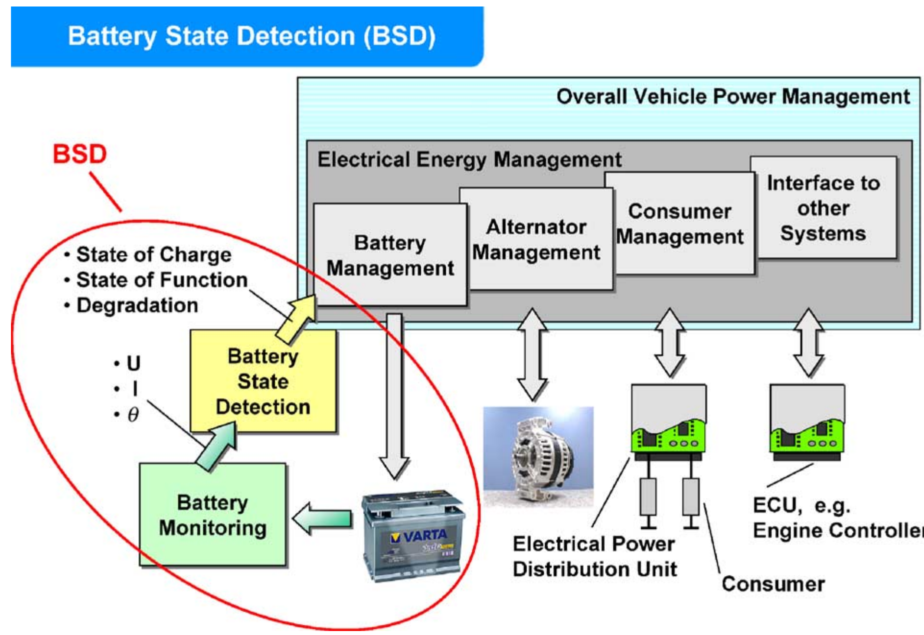

Fig. 7. Layer structure of battery monitoring, battery state detection, battery management and energy management.

information from battery monitoring, energy management may scarcely work. Appropriate battery management may significantly enhance and improve, but is not a precondition for a successful energy management. The layer structure of battery monitoring is shown in Fig. 7. This provides the input that is processed by battery state detection to give valuations and predictions, which is used by the battery management and/or energy management. An even higher layer (vehicle) energy management, comprises also mechanical and thermal energy flows in the vehicle (not shown in the Fig. 7).

4.1. Determination of actual battery status

As battery performance depends on temperature, state-of-charge and state-of-health, it is essential to measure or estimate these properties to guarantee for 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.

Strategies for determination of SoC and SoH have to be chosen according to the goals and should include expected operating scenarios and acceptable error tolerances. Approaches under development include those with and without sensing of battery current. Most probably, to predict short-term or even long-term battery performance, a combination of several methods is required to assure sufficient plausibility and reliability.

Figures of merit are helpful in valuation of the battery status. Definitions have been given for SoC, SoH, and state of function SoF [2]. The SoC and depth-of-discharge DoD = (1 − SoC) give the percentage of the actually stored amount of charge compared with full charge (at reference discharge rate at reference temperature), i.e.,

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

Other definitions for SoC have been proposed (e.g. [29–31]). Practical use is given only for a battery figure of value, which is defined 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 monotonous and unequivocal state function, with a procedure from which it can be calculated from measured data. For the SoC of a lead–acid battery, the well-known dependency of the equilibrium voltage U_{oo} (equilibrated OCV) or of the equilibrium electrolyte acid gravity ρ_{oo} can be used [1,2]. The figure SoC = (1 − DoD) calculated from voltage or acid gravity does not involve over-dimensioning, individual capacity scattering, or loss of storage capability due to degradation over lifetime. Moreover, it should not be mixed up with the battery's charge storage capability CSC ('residual capacity', cf., Section 4.3.5), i.e., the amount of charge that can be drawn from the fully charged battery at nominal current until the cut-off voltage U_{EOD} is reached, taking into account all possible losses of capacity.

The SoH is a figure of merit to describe the degree of degradation of a battery, and should give a quantification that replaces fuzzy statements such as 'fresh', 'aged', 'old', and 'worn out'. For a stationary battery application, often storage capability CSC is the decisive property. In this special case, the SoH may give a number for the degradation of capacity [32]. As a SLI battery comprises more than one relevant property, e.g., cranking capability and internal resistance, which may degrade in different ways, the term SoH should not be limited to storage capability. There may be several types of

SoH that are related to each of these properties and their individual degradation. A battery may be unable to fulfil one specification, but is still ready to achieve another. The type of application determines the particular relevance of a specification [1,2].

For a given duty and operation condition, the SoH can be given easily if a benchmark is set [1,2]. Under the load of a power profile $P(t)$ or current profile $i(t)$, that may depend on time t and has duration t_1, the voltage of the battery will show a minimum $U_{\min}$. In the simple case of a load independent of time, this will occur at t_1. The lowest acceptable voltage under load U_1 for a given application, and the lowest voltage U_{fresh} of a typical fresh battery at the reference (SoC, T) conditions are used to define battery SoH at (SoC, T) [1] (Fig. 8), i.e.,

$$\text{SoH} = \frac{U_{\min} - U_1}{U_{\text{fresh}} - U_1} \tag{2a}$$

If, however, other types of battery duty are been targeted and ageing of performance is to be quantified, other observable values may be used for determination of the SoH. For the amount of charge, Q, that can be recharged within a certain period of time, e.g., in the case of a recuperation process, a definition:

$$\text{SoH} = \frac{Q - Q_1}{Q_{\text{fresh}} - Q_1} \tag{2b}$$

may be useful, where Q is the amount of charge actually recharged, Q_{fresh} the reference value for a fresh battery, and Q_1 is the lowest amount of charge that can be accepted during operation.

In most cases, neither simply the SoC nor its degree of degradation is the figure that decides whether the battery performs as required. As the SoC and the SoH may compensate each other to some degree with respect to battery performance, a poorer SoC may be acceptable for a fresh battery with a high SoH, or an older battery with a lower SoH may fulfil the duty if it is kept at a sufficient higher SoC. To describe the capability of the battery to perform a certain specified duty, the SoF has been defined [2], which is relevant for the functionality of a given target system powered by the battery. The SoF brings together the battery state parameters, i.e., SoC, SoH, temperature and, if needed, also the previous short-term discharge–recharge history.

The SoF is defined in a similar manner to the SoH (2), but is comprised of state parameters (SoC, SoH, T), rather than referring to the reference conditions. When a current profile $i(t)$ is the relevant duty for valuation, the voltage response can be used for calculation, i.e.,

$$\text{SoF} = \frac{U_{\min} - U_1}{U_{\text{fresh}} - U_1} \quad \text{for actual (SoC, SoH, } T\text{) condition} \tag{3a}$$

For other types of battery duty, as with SoH, the appropriate observable values for SoF determination may be others [33]. In the case of braking energy recuperation as the target battery property, the amount of charge Q that can be recharged within a certain period of time will give the relevant information, i.e.,

$$\text{SoF} = \frac{Q_{\min} - Q_1}{Q_{\text{fresh}} - Q_1} \quad \text{for actual (SoC, SoH, } T\text{) condition} \tag{3b}$$

4.1.1. Data acquisition

Data may be collected from the battery via sensors that collect information on internal battery properties (not applicable to SLI batteries due to cost), and on the vehicle, e.g., periods of operation, driving speed, ignition-on information, engine rpm (which are proportional to alternator rpm) and data bus information that provides knowledge about the status of components and control units. Details for data acquisition,

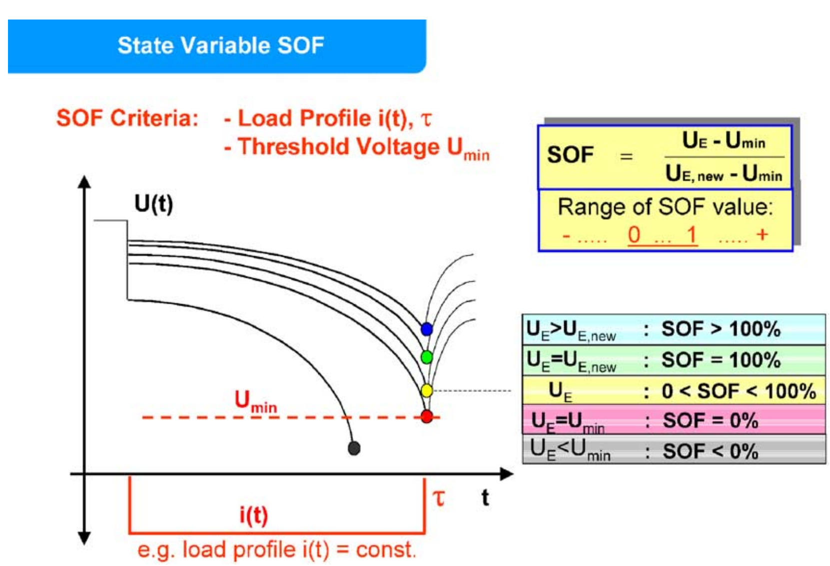

Fig. 8. Example of SoF definition from actual (minute) voltage as response to discharge current profile, compared with behaviour of reference (fresh) state.

including pre-processing such as filtering to suppress noise and extension by models (e.g., if a temperature sensor is not located at the place where the temperature value is needed) have been discussed in [2].

4.1.2. Approaches for battery monitoring

To analyze the battery status, preferably, voltage and current as function of time are evaluated. Determination of temperature is required to compensate for its influence on battery properties. Additional sensors within the SLI battery have not yet been established. Processing of measured data may be done in various ways, following alternative concepts with individual strengths and drawbacks [2]. The precision that can be achieved depends on the precision of the sensor output (including time coincidence, if the case may be), the reproducibility of battery performance and tests, and the algorithms. Any approach may operate with fixed parameter values, or with parameter values obtained from previous operating duty, and needs reference values.

4.1.3. Prediction of battery performance

With the state values (SoC, SoH, T, etc.) having been determined for a point in time t_0, 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 a device requiring a power supply with high reliability, is characterized by the current or power profile needed as a function of time. Usually, a lowest (or highest) allowable voltage level is given to for regular function.

The predictor may predict, for example, the expected voltage level by using characteristic data or a mathematical model. Prediction at time t_0 may be made for the

- short term, i.e., with present battery status (actual state vector $P(t_0)$), for the case when an immediate loading of the battery has to be expected, or for;
- medium term for a future point in time t_1 with an estimated future status (future state vector $P(t_1)$) of the battery, e.g., for a future load (for instance cranking) after an extended stand of the vehicle, with possible changes in state values (like SoC and T) in the meantime.

Any prediction requires a battery behaviour model. If prediction is required for a future point in time t_1, with a state vector $P(t_1)$ different from the actual state vector $P(t_0)$, another battery model is needed to determine the state vector $P(t_1)$ from $P(t_0)$ resulting from the changes (of SoC, T, etc.) which may occur during period between t_0 and t_1. A layer model of information has been presented [2] to explain the differences in predictions to different points in future time.

4.2. Estimation of changes of battery characteristics

In the beginning of operation life, battery characteristics are close to their value at the date of manufacturing and shipping. Therefore, in the early phase, it is a good approximation to assume that battery performance is not significantly changing. It is clear, however, that this is no longer an acceptable approximation from a later point in time. The challenge is to predict the actual status using available information—or, in other words, to find a compromise between efforts for sensing and evaluation and the value and precision of the information obtained.

Battery monitoring and management has to consider the changes in lead–acid battery properties over life. Irreversible changes/degradation of battery properties will be attributed to ageing, like grid corrosion, water loss, loss of active-material availability due to material softening and shedding, or degradation in the microstructure of the positive and negative active-material (inducing softening, shedding, mossing, dendritic growth, reversible capacity decay, deterioration of the expander). Furthermore, flooded lead–acid batteries may show acid stratification. In principle, this is a reversible change in properties, as is sulfation. To date, however, no means has been found to reverse either stratification or sulfation selectively in automotive batteries. Therefore, these effects can be handled in a same way similar to that for irreversible degradation effects.

Any evaluation of battery capability and its changes require a reference value, which may be (i) the respective capability of the fresh battery, and/or (ii) the respective requirement of an application. This is true if some threshold value is considered for the end of (operational) life, or if the degree of degradation experienced from the fresh state to the threshold, usually called the SoH, has been determined. For example, if the actual capacity C_{act} is being considered, i.e., the battery capability for charge storage under reference discharge conditions at the reference temperature following the reference recharge, then either (i) the fresh battery's capacity C_{fresh}, or (ii) the capacity required by the application, $C_{threshold}$, may be used as reference. While option (i) is battery-oriented only and independent of the application, option (ii) does not relate to the individual battery but is dedicated to the application only. The SoH is usually normalized to have a value of one for the fresh state and a value of zero when the threshold has been reached, considering both battery and application, and may be defined in this case (cf. Section 4.1) as SoH = $(C_{act} - C_{threshold})/(C_{fresh} - C_{threshold})$.

4.2.1. Targets for estimation of changes in battery characteristics

For all activities to assess battery ageing, a clear target has to be defined and a clear quantification is needed, i.e., an experiment has to be performed to check if the evaluation is correct. Common statements such as "the battery is worn out" are too much vague.

The user wants to be sure that the battery is still able to fulfil a certain function. If this is going to be questioned, this warning has to be given well in advance, to allow for action. This is true in any case, either if the information is provided to the driver or to the workshop (e.g., to replace the battery), or if the information is handled by the battery management system (BMS) or the electrical energy management system (EEMS) so that, respectively, the battery is changed or the vehicle is allowed to continue operating with an aged battery (possibly with reduced functionality if necessary).

4.2.2. Quantification of changes of battery characteristics—the SoF approach

It is helpful to make use of the SoF terminology [2] to evaluate battery ageing (See Section 4.1). Usually, SoF values will lie within the range of $\{0, 1\}$, with SoF = 1 for a fresh battery and SoF = 0 for a battery that is just at the acceptable threshold value of the application-relevant property. The critical battery property to be used as the relevant criterion may depend on the application. In many SLI applications, this will be cranking capability, but it could also be the residual charge storage capability CSC (residual capacity, Section 4.2), or another performance capability such as charge acceptance, which is especially important for braking energy recuperation.

The SoF terminology also allows a group of several different criteria to be fulfilled simultaneously, i.e., the value of SoF for the overall battery performance is a function of several values SoF_i of different criteria $i = 1, 2, 3, \ldots$, namely:

$$\mathrm{SoF} = f(\mathrm{SoF}_1, \mathrm{SoF}_2, \mathrm{SoF}_3, \ldots) \quad (4)$$

Functions f lead to SoF = 0 if only one of the criteria $i = 1, 2, 3, \ldots$ is reaching the threshold value ($\mathrm{SoF_i} = 0$), and to SoF = 1, if all individual SoF_i are in the fresh state $\mathrm{SoF}_i = 1$, e.g.:

$$\mathrm{SoF} = \min(\mathrm{SoF}_1, \mathrm{SoF}_2, \mathrm{SoF}_3, \ldots) \quad (5)$$

or

$$\mathrm{SoF} = \mathrm{SoF}_1 \times \mathrm{SoF}_2 \times \mathrm{SoF}_3 \times \cdots \quad (6)$$

The SoF values calculated in this way give an assessment of the actual battery performance capability with respect to the functionalities that are required in the given application.

4.2.3. Means for quantification of changes in battery characteristics

Any determination of battery ageing requires some information from the vehicle and/or the battery. This may be a time information, battery voltage, temperature, current, a status information of the vehicle (e.g., key off, engine rpm), a trigger information (e.g., cranking), or any combination of these. In most cases, a sensor is required to provide such information. Discussion of sensing technology and the required precision of sensing is beyond the scope of this paper.

4.2.4. Approaches for quantification of changes in battery characteristics

In the following Sections, approaches are outlined to estimate and quantify the ageing of lead–acid batteries. Drawbacks and steps to overcome them are discussed. So a generic hierarchy of approaches is formed, which will allow for classification and evaluation.

The target is quantification of all of the battery ageing processes, independent from for what and how this information might be used, and how it is forwarded to the user, (garage) service staff, or any intrinsic system of the vehicle.

4.3. Estimation of changes in battery characteristics from operation history

The first class of approaches considers the history of battery life in operation. Conditions and situations are monitored, and conclusions are drawn from these data to estimate battery ageing. There is, however, no test or measurements of battery performance.

4.3.1. Estimation of changes in battery characteristics from time in operation

The easiest approach to estimate changes, and especially wearout, of the battery is just using calendar life, either starting from date of production (this is the start of life of a filled and charged product) or from date of duty in service. As a coarse trend, battery performance decreases with time, and so an allowable period of service time τ_{life} may be set. The period τ_{life} chosen will be based usually on experience with similar products in similar applications. It is obvious that this simple approach, without any feedback from real battery behaviour, is an acceptable route only if the consequences of an erroneous valuation are acceptable, and it may work only if:

(i) the conditions of operation are predictable;
(ii) there is experience with this product and with this type of application.

The operating time may be used to set flags, indicating 100% ... 50% ... 20% ... of expected residual life in duty, and these flags may be shown to the operator. In the automotive case, the driver or the workshop can receive an indication when the battery should be replaced. Also, an electrical energy management may react on such flags, e.g., by cutting back availability of comfort functions the closer the expected period of service time τ_{life} is approached.

In an improved version, state parameters P_i used in the battery state detection procedures could be assumed as a function of service time τ. Possible examples of such parameters $P_i(\tau)$ may be:

- an internal resistance characteristic R (there are many ways to define such a characteristic !), see Section 4.5.1;
- a characteristic for loss of water, or a characteristic for the implication of water loss on the voltage behaviour of the battery;
- a characteristic for the charge storage capability CSC of the battery.

Certain SoF characteristics, depending on such parameters $P_i(\tau)$, may be expressed as $\mathrm{SoF} = f(P_i(\tau))$. Examples for such SoF characteristics are:

- residual capacity (charge storage capability CSC) of the battery;
- voltage behaviour under transient loads;
- cranking capability.

The dependency of a parameter $P(\tau)$ on service time τ may be linear or otherwise. As a decrease in battery performance usually shows progressive behaviour when approaching end of service time τ_{life}, a progressive dependency of such an SoF(τ) characteristic on service time τ will usually describe real life behaviour in a better way.

It is clear, however that even with the progressive dependency of a parameter P_i on service time τ, or of a SoF characteristic on parameters P_i, such a simple approach is scarcely satisfying in automotive applications, as the preconditions mentioned above are not given.

The conditions of operation of a SLI battery are just too manifold, even in a defined vehicle, especially in terms of battery temperature T, cycling and charge throughput, and average SoC during service.

4.3.2. *Estimation of changes in battery characteristics from time in operation considering temperature*

Battery ageing – and degradation of its performance – is accelerated and aggravated by increased temperature. Therefore, consideration of temperature will improve the simple ageing algorithms that measure operating time τ. A straightforward approach is using Arrhenius' law to describe acceleration of a temperature-dependent 'virtual ageing time' τ' (T) against real time τ. If this is done for any real time increment dτ individually, any virtual ageing time increment dτ' (T) is a function of battery temperature T during this real time interval dτ, i.e.,

$$\mathrm{d}\tau\prime(T) = \mathrm{d}\tau \times \exp\left(\frac{a(T - T_0)}{T_0}\right) \tag{7}$$

Usually, the parameter a is chosen in such a way that an increase in T by 8–10 °C generates a doubling of the virtual ageing time dτ' (T) against real time dτ at the reference temperature T_0. This considers the experience that the kinetics of most chemical reactions like grid corrosion, etc., shows such behaviour.

The overall virtual ageing time τ' can be calculated according to:

$$\tau\prime = \int \exp\left(\frac{a(T(\tau) - T_0)}{T_0}\right) \mathrm{d}\tau \tag{8}$$

This approach for estimating service life $\tau' = f(\tau, T)$ looks very plausible, but its implicit preconditions have to be checked for applicability in that:

(i) all ageing processes in the battery follow the same temperature dependency, i.e., the kinetics of the chemical processes have the same activation energy, or
(ii) the dominating ageing process is influential over the whole range of temperature T considered, i.e., there is no switching from one to another degradation process.

While the best results may be achieved if the temperature value T considered is that of the battery, any other temperature value which has some correlation with battery temperature may improve a simple time-based (Section 4.3.1) approach. This may even be the ambient temperature, especially if the battery does not warm up too much during vehicle operation, or if the daily vehicle operation period is short.

4.3.3. *Estimation of changes in battery characteristics from time in operation considering operating voltage*

Besides battery temperature $T(t)$, the virtual ageing time τ' may consider also battery voltage $U(t)$. Battery voltage U determines the half-cell potentials Φ^+, Φ^- (but not unambiguous, however) which in turn determine grid corrosion and water loss. Therefore, consideration of U may also improve estimation of these degradation processes.

An ageing function considering service life time τ with correction for battery temperature T – and possibly also battery voltage U – may be helpful in applications where cycling can be neglected, and the operating voltage is well-defined. This may be true for some emergency stand-by applications with little occurrence of duty, where the dominating ageing processes are grid corrosion, water loss, etc.—processes that show a reasonably predictable dependency on time τ with acceleration by temperature T and voltage U.

After the introduction of antimony-free grid alloys in automotive applications, neither grid corrosion nor water loss are dominating degradation processes. Parallel to the introduction of new grid material, the characteristics of automotive battery duty have changed significantly towards a greater degree of cycling. This is especially true for highly equipped vehicles. Even medium- and lower-class cars now have many comfort components, so that the consequences of cycling duty are also dominating the degradation process of these vehicles. Thus, consideration of cycling is a promising approach to estimate the degradation of automotive batteries either alone or in combination with time of duty τ, temperature T and voltage U, as mentioned before.

The first step to consider cycling operation is to track operating voltage $U(t)$. Battery voltages U below the open-circuit voltage (OCV) are an indication of discharge and very low voltage levels are an indication of (possibly abusive) deep discharge. Consequently, duration of time periods below and above the OCV level allow for estimation of duty periods and the intensity of cycling, while periods with voltage near to OCV indicate key-off periods at which the battery sits without an applicable electrical load. The influence of periods with high temperature, with high recharge voltage, or with a low SoC charge can be quantified to generate an empirical model of battery degradation [34–36].

With a good model of the battery voltage–current characteristic, it is possible to estimate the battery current $i(t)$ from the voltage profile $U(t)$, which allows monitoring of the charge throughput [36]. Approaches considering charge throughput to estimate battery ageing are discussed in Section 4.3.5.

4.3.4. Estimation of changes in battery characteristics from time in operation considering SoC

When the SoC of a lead–acid battery is reduced, the concentration of the sulfuric acid electrolyte is reduced as well. As grid corrosion and water loss depend on the acid concentration, consideration of SoC may improve the evaluation of battery ageing. This is especially true as extended periods of low and medium SoC allow the discharged active material ($PbSO_4$) to recrystallize (sometimes called ‘sulfation’), which will compromise recharge behaviour and storage capability in the long run. This is especially true when in combination with other parameters such as time, temperature, voltage, and cycling charge throughput including DoD.

4.3.5. Estimation of changes of battery characteristics considering cycling and charge throughput

Cycling of a lead–acid battery usually aggravates both grid corrosion and water loss, and causes degradation of the positive and negative active-material due to the dissolution–precipitation processes that the plates have to undergo. Therefore, charge throughput should be considered if active-material degradation is contributing to the failure mode of the battery.

The approaches for estimating battery ageing discussed in previous Sections require a ‘reference’ information about the service life time τ_{life} that can be expected in duty, which will depend on design details such as grid alloy materials, grid manufacturing technology, grid thickness and allowable water loss, but will not depend on battery capacity C_{nom} (size) if the same design is used.

When charge throughput is considered as an alternative failure mode, however, additional ‘reference’ information about the battery is required and should be characteristic of the allowable charge throughput ΔQ_{life}. The value of ΔQ_{life} will depend on battery design like τ_{life}, but also on battery size, i.e., nominal capacity C_{nom}.

Usually, ΔQ_{life} will be approximately proportional to the battery capacity C_{nom}, i.e.,

$$\Delta Q_{\text{life}} = n_{\text{life}} \times C_{\text{nom}} \quad (9)$$

where the cycle-life factor n_{life} is a characteristic given by the battery design. If the decrease in charge storage capability CSC is assumed to be linear with charge throughput, it may be calculated as:

$$\text{CSC} = f(\text{Ah throughput}) = C_{\text{nom}} - \alpha \int i(t)|\mathrm{d}t| \quad (10)$$

Thus, if charge throughput is considered for prediction of residual battery lifetime, the system requires information about battery design and battery size. This information has to be given to the BSD system, or – more ambitiously – has to be ascertained during BSD operation.

With traction batteries, values for cycle-life expectancy n_{life} are summarized in data sheets. The duty cycles of traction batteries are infact usually clearly defined and reproducible (most start from full SoC) and so these data allow for a prediction of operating life. This situation is more complex with automotive batteries given their characteristic operation in a partial SoC, the arbitrary pattern of discharge and recharge, and scarcely ever reaching a full SoC. As they would be of limited value, cycle-life data exceeding those defined in the common standards are usually not given. Without doubt a high-quality, flooded, automotive battery will survive an ampere-hour throughput of about 100 times of its nominal capacity ($n_{\text{life}} \approx 100$), before the actual storage capability falls below 50% of its nominal value C_{nom}. For AGM-type batteries, n_{life} is several 100 times the nominal capacity. This is only true, however, if this amount of charge is put through relatively quickly, e.g., within several months maximum at temperatures not too far different from standard and without reaching too a low charge level (>20% SoC) or even with extended stand periods at such levels, and with regular recharge to least near to full SoC.

It is obvious that all this is a rough approximation only for long established SLI battery technology that are cycled at temperatures between −30 and +60 °C (or even beyond this range) with an unpredictably wide range of DoD. And as they are scarcely or never recharged to a full SoC, they spend nearly their whole life in a partial state-of-charge.

4.3.6. Estimation of changes in battery characteristics from time in operation considering cycle depth

This complex and unpredictable operating mode of SLI batteries makes it difficult to determining the degree of ageing from cycling by just counting the ampere-hour throughput. This is an analogue of the Palmgren–Miner–Rule (‘Miner’s rule’), which estimates residual fatigue life to be reduced linearly by the damage fractions of life that have been used up by an event or a series of (stress) events [37]. As a battery usually ages faster if cycling depth is higher even if the same charge is put through, consideration of DoD may improve the straight–forward approach of counting ampere-hours or cycle numbers to failure. In view of Miner’s rule, the damage fraction increases with cycle depth, and failure is expected when the accumulated damaged fractions exceed a threshold value C, i.e.,

$$\frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + \cdots + \frac{n_i}{N_i} > C \quad (11)$$

If cycle depth is been targeted, the first challenge is to define the term ‘cycle depth’ or better, to identify such a period of operation. Of course, cycle depth means the charge throughput between changes of current direction, but usually current direction is very often changing with SLI battery operation, i.e., cycle duty is an overlay of cycles of various depths. Thus, a group of micro-cycles may form together one cycle with a medium charge throughput, and there may be some of these medium-size cycles that together form a macro-cycle.

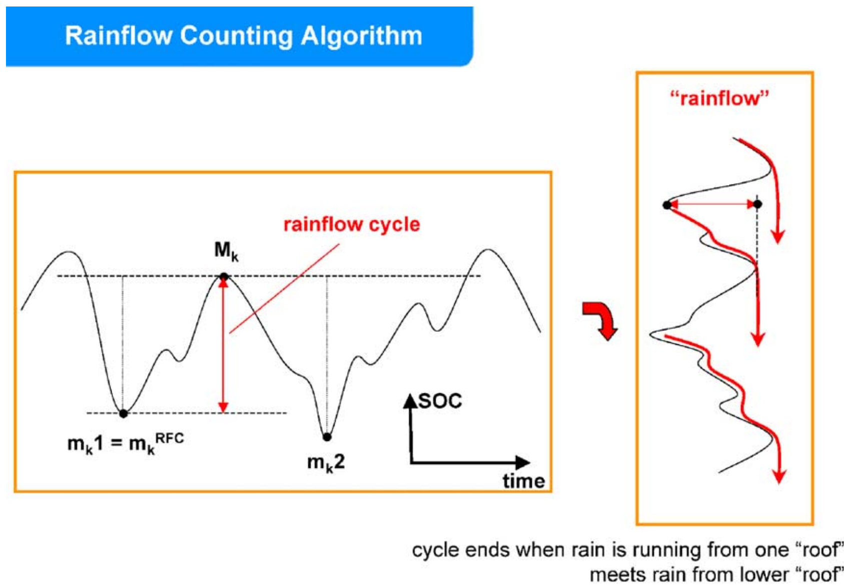

Fig. 9. Visualization of rainflow counting algorithm: cycle ends when rain is running from one 'roof' and meets rain from a lower "roof".

A good algorithm decides where a cycle is starting and where it is completed. A method to define the amount of charge, i.e., the cycle depth, is the Rainflow Algorithm (Rainflow Cycle Counting) that is used in stress and fatigue analysis [38]. Applied to battery cycling, it says that from the kth local maximum M_k of SoC, one shall try to reach above the same SoC level, in the backward and forward directions, with as small a downward excursion as possible. The minima m_k' and m_k'' on each side are identified. The minimum from $\{m_k', m_k''\}$, which represents the smallest deviation from the maximum M_k, is defined as the corresponding rainflow minimum m_k^{RFC}. The kth rainflow cycle is defined as $(m_k^{\mathrm{RFC}}, M_k)$, see Fig. 9. The name 'rainflow cycle' becomes clear when the Fig. 9 is rotated by 90°: there is an analogy with roofs of different width, where rain is falling from one layer to the next.

The challenge is again quantification, i.e., to determine (e.g., by experiments) the dependency of the damage of fraction, DF, on cycle depth, and parameters such as T, etc., the same issue like that arises in fatigue theory.

4.3.7. Summary of estimation of changes in battery characteristics from operation history

The hierarchy of the approaches discussed so far to estimate changes in battery characteristics from operation history is summarized in Fig. 10. While all of them have to consider time, this does not require a high-precision real-time clock. Two types of improvements can be distinguished, namely, consideration of temperature and consideration of battery voltage. Considerations of SoC, of integral charge throughput, and even of depth of cycling results in special and more sophisticated versions, linked to battery voltage considerations. If some of these major parameters of influence are taken together, a strong empirical approach for estimation of battery wearout can be generated [36].

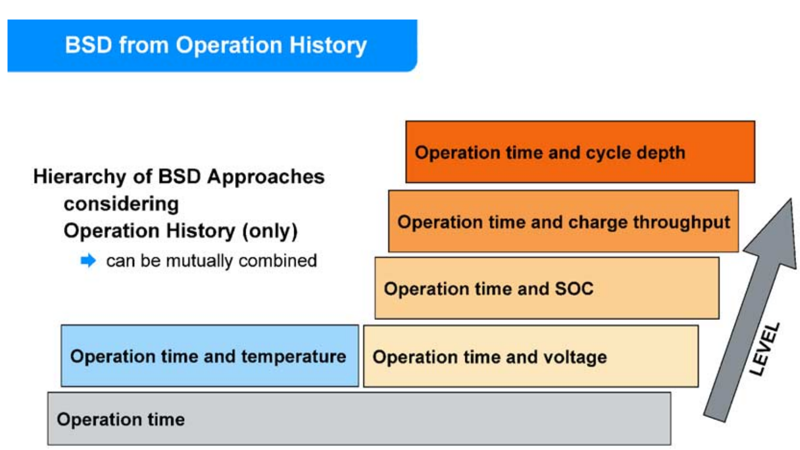

Fig. 10. Hierarchy of BSD approaches, which consider (only) operation history, and which may be mutually combined.

4.4. Estimation of changes in battery characteristics from special events in operation history

The first class of approaches discussed in the previous Section is monitoring conditions and situations in the history of battery life in operation, and draws conclusions to estimate battery ageing. Such approaches may be improved significantly, however, if those events in operation history that are known to be of special influence on ageing, either beneficial or destructive, are also taken into account.

A SLI battery may suffer major degradation under deep discharge, when the active materials are utilized beyond their design specification, and the low concentration electrolyte promotes grid corrosion, recrystallisation of $PbSO_4$ leading to ‘sulfation’, and dendrite growth through the separator. A battery maker may regard it abusive service if more than the battery’s nominal capacity is withdrawn, the OCV falls below 11 V, or a low electrical load forces the battery voltage for extended periods to low values. Such deep discharges can occur during automotive life, i.e.,

- in emergency cases if the hazard warning lights have drawn down the battery;
- due to mistakes of the driver, e.g., forgotten to switch off the headlights or close the bonnet correctly;
- due to design weaknesses of the electrical system, e.g., the radio is working continuously in a key-off condition; or
- due to defects in the electrical components or their software, e.g., a control unit never goes into sleep mode or ‘wakes up’ spontaneously.

Therefore, car manufacturers like to consider deep discharge as regular use and expect the battery to withstand it at least once without any obvious change in performance. Robust designs fulfil such specified requirements. Nevertheless, if deep discharge occurs several times, for extended periods and/or at elevated temperatures, even robustly designed batteries will suffer accelerated ageing. This can be considered in a special ageing routine for deep discharge and is triggered by an abnormal voltage $U(t)$. Experimental experience with the battery product is needed to determine the conditions that have to be fulfilled to define a deep-discharge event. Experimental data can also help to decide how the occurrence of such an event is used to put an extra increment on ‘virtual ageing time’ τ' (like a life penalty in a computer game – this may represent extra wearout of active material) or to accelerate τ' against real time τ (this may represent enhanced corrosion or the growth of dendrites). Experimental experience with the specific battery is essential to decide if and how the occurrence of such an deep-discharge event may be used to modify directly a parameter P_i or a characteristic $\text{SoF} = f(P_i\ (\tau))$.

Another important, but ambivalent, event in battery life may be an extended recharge, either by the alternator in course of an extended (highway) drive, or by a special (external) charger. This will accelerate corrosion and water loss, but may help to overcome some ‘sulfation’ and acid stratification. Further events may take place occasionally in the life of a battery, like extended periods at a medium SoC without operation (vacation ‘airport test’ or waiting in a used-car saleroom). Consideration of these may also improve life estimation for a battery.

4.5. Determination of changes in battery characteristics from direct measurement

The approaches discussed so far monitor conditions and situations during the history of battery life in operation. From these – and possibly also from the occurrence of special events – conclusions are drawn to estimate battery ageing. There are, however, no tests or evaluation of battery performance to check the estimations for correctness.

The most powerful, but also the ambitious class of approaches, makes use of direct measurements from the battery. This is a common method for off-line battery testing in many applications (stationary, traction, SLI) where hand-held battery testers, which put some discharge profile on the battery or which test an impedance information, are well known and offered by various suppliers. A SLI battery is continuously connected to the vehicle, so any test pulse will ‘see’ both the vehicle electrical system and the battery in parallel. Real off-line testing is not welcome even in a workshop, as disconnecting the battery is cumbersome—and vehicle equipment may lose information (engine management, radio, ‘close’ position of electrical window lifter, etc.) when the power supply from the battery is disconnected. Furthermore, the BSD has no control on the operating duty of a SLI battery in most cases. Therefore, it is not possible to put special test load profiles or pulses on the battery, and to monitor the response function—or even to perform impedance spectroscopy. Only in rare cases is there the opportunity to energize a device (e.g., the electrical rear window defroster) in order to put a defined load pulse on the battery. In automotive applications, therefore, the BSD has to analyze the battery while it is connected to the vehicle electrical system, usually using load profiles that are generated by standard vehicle operation, in order to draw conclusions to estimate battery ageing. If, however, consideration is given to the multitude of load profiles that are applied to the battery during the course of the day (cf. Section 3), it becomes clear that most of the information that could be obtained by ‘special’ test load profiles may also be achieved by the ‘natural’ duty profiles. On the other hand, they are not always updated at the point in time they are requested, and possibly they have to be determined one after the other. Therefore, for algorithms that require more than a single type of information at a point in time, some information may have to be extrapolated from the time that it was obtained until these algorithms can be used.

All this makes high-level BSD in automotive applications a special challenge. Some examples of the measurements that allow estimation of battery ageing are discussed in detail below.

4.5.1. Determination of changes in battery internal resistance

Estimation of a dynamical battery impedance R_{dyn} by differentiating measured voltage by current $R_{dyn} = dU/di$ is mathematically an easy approach, but creates many difficulties, as discussed in [2]. The dynamical impedance R_{dyn} enables for prediction of battery load voltage under short load currents i that differ not too much from the current that had been used to determine R_{dyn}. This is possible only if the battery status has not changed significantly, i.e., in immediate paste, while long-term predictions may carry significant deviations, as R_{dyn} may change rather rapidly under high dynamic battery duty [39]. Depending on the way in which R_{dyn} has been determined, the value will comprise both ohmic contributions from conductive lead and electrolyte and non-linear contributions from the charge-transfer reaction. The ohmic resistance of lead depends on temperature and possibly increases during operating life due to corrosion. The ohmic resistance of the electrolyte depends on both its temperature and density; the latter is a function of actual discharge depth. Changes during operating life may arise from water loss and from inhomogeneity of relative density due to acid stratification. The non-linear, charge-transfer reaction resistance depends on temperature and actual utilization of active material, and may change significantly with operating life, depending on ageing mode (e.g., active material change of structure and softening). Therefore, valuation of R_{dyn} with respect to ageing requires at least compensation of its dependency on temperature and DoD. Residual changes (usually increase) of R_{dyn} may be attributed to ageing if the SoC is not too low. Such changes of resistance R_{dyn} are a convolution of many effects. Only if the relevant battery quality is directly controlled by this entity R_{dyn}, as with voltage under cranking current load, changes in this parameter provide a useful measure of ageing. Otherwise, these contributions have to be deconvoluted using expert knowledge on the interaction of ageing modes, usually using different types of measurements which are influenced in a different manner by the various modes of ageing.

4.5.2. Determination of loss of capacity

Following the introduction of antimony-free grid alloys, grid corrosion has become a common failure mode that limits battery use in hot environments. In moderate environments, the ohmic part of a R_{dyn} value is only then a helpful indication for battery degradation if electrolyte resistance is a relevant failure mode, e.g., with AGM batteries that suffer of dry-out. On the other hand, reduced grid corrosion together with increased cycling duty have resulted in loss of capacity (i.e., charge storage capability measured at the standard low rate) due to active-material degradation being very often a prominent failure mode.

In many cases, the limiting process of active-material degradation from cycling is softening of the positive active-material. This soft material is still in place but is so poorly connected to the grid that discharge is significantly impeded at technically relevant rates. There is, however, some electrical connection of this soft active material to the grid and this is why it is charged to PbO_2. This view is supported by the fact that even shed material has been found to be charged PbO_2 rather than discharged $PbSO_4$ [40]. If there is no significant sulfation at the negative electrode, then electrolyte is not involved in this type of storage capability loss, i.e., the electrolyte specific gravity would be the original value for a (hypothetical) full recharge. This conclusion is demonstrated in Fig. 11 in which the upper part of sketch (a) shows a stor-

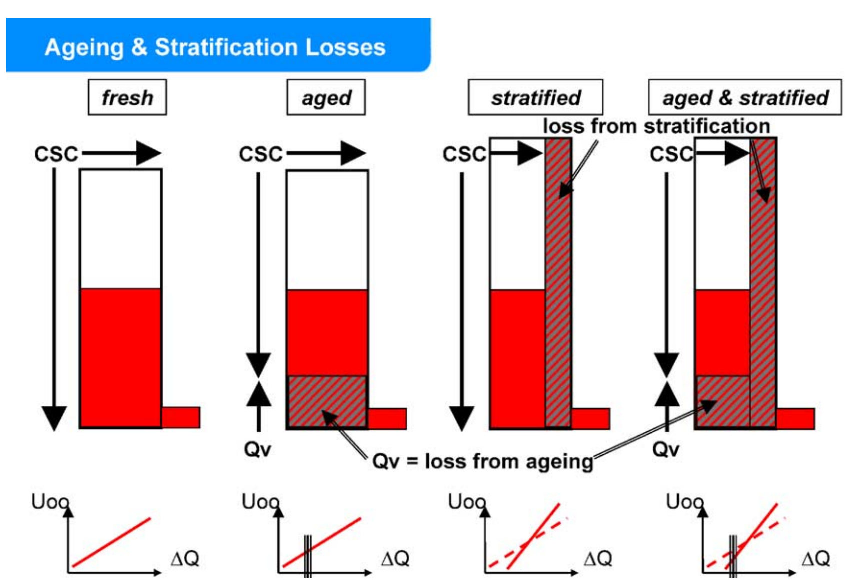

Fig. 11. Visualisation of consequences of (b) ageing (c) acid stratification and (d) combination of both compared with (a) fresh state of battery. Upper row: battery charge storage capability (CSC) as a water tank with limitations. Lower row: impact on characteristics of equilibrium voltage U_{oo} vs. charge throughput ΔQ.

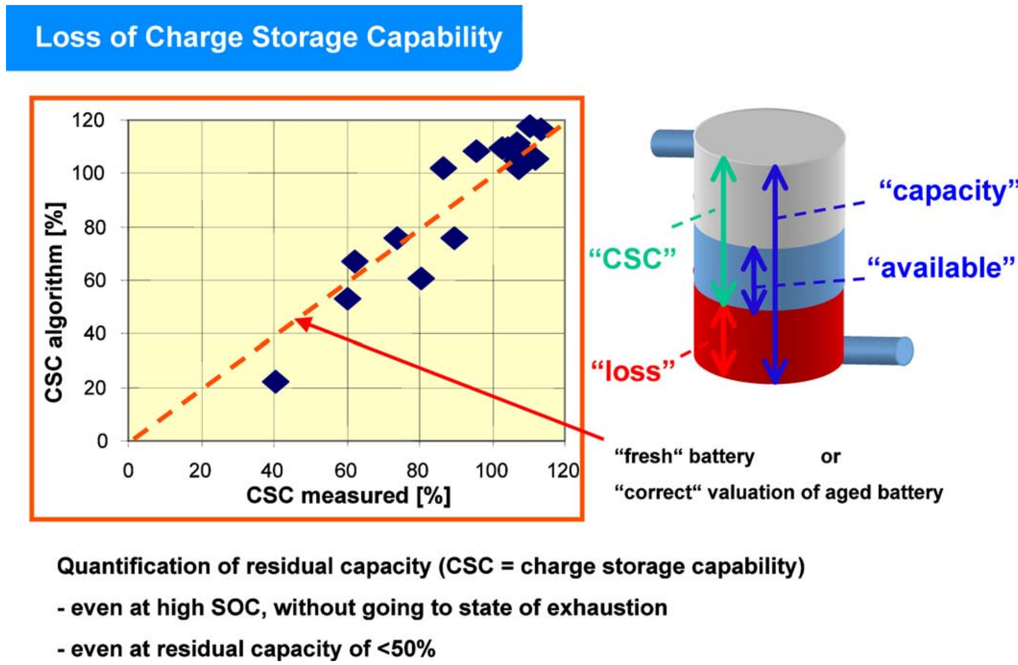

Fig. 12. Capability of algorithm to predict loss of charge storage capability (CSC) from battery behaviour even at high SoC, i.e., without discharge going to state of exhaustion.

age tank for a liquid as an analogue of a storage battery, with an outlet at the lowest point. The amount of liquid that can be stored in the tank (its charge storage capability CSC) is represented by the height times the width of this 2-dimensional representation. Change in the height of the liquid level represents the change in actual pressure (i.e., the equilibrium voltage U_{oo}), and the width the amount of liquid (i.e., charge throughput ΔQ) that is drawn from the tank when the height is changed by a certain amount. The characteristic for U_{oo} versus ΔQ is sketched in the lower part of Fig. 11(a), and is an approximation of the lead–acid battery characteristic (cf., Fig. 5 in [2]). From the considerations given above, the capacity loss due to active-material degradation does not use up electrolyte, i.e., the electrolyte relative density in the fully charged state is the same as that for a fresh battery. If the battery is discharged at a low rate, negligible changes are observed until the available portion of the active material is consumed. This situation is illustrated in Fig. 11(b) with a set of 'stones' on the bottom of the storage tank. The storage capability above these 'stones' is unchanged, and the existence of the 'stones' is scarcely obvious before the level of the liquid falls to their level. Then, the pressure in the tank decreases suddenly. This is indicated by the cut-off of the voltage versus ΔQ characteristic in the lower part of Fig. 11(b).

Knowledge of this loss in capacity, or of the residual storage capability, or of the actually available amount of charge is very helpful for energy management to guaranty starting capability, as well as other functions at some future point in time, with some energy being consumed in the meantime. It is essential, however, that the method providing this information is working at any (also at relatively high!) SoC and not only near to voltage breakdown. In addition, it must not comprise discharge of a relevant amount of energy. The capability of such a procedure to estimate the actually available (dischargeable) amount of charge Q_{act} [41] is shown in Fig. 12. The precision is typically better than about 10% of the total nominal (fresh) storage capability C_{nom}. If the amount of charge missing to full SoC, Q_{dis}, is known (which can be estimated from the equilibrated OCV), the actual charge storage capability CSC = $Q_{act} + Q_{dis}$ can be calculated, which is a good measure for capacity ageing when compared with the nominal (fresh) storage capability C_{nom}.

4.6. Determination of changes in battery characteristics using models

Models are mathematical descriptions of expert knowledge. A good model is able to predict the actual or future value of a parameter, and it may be able to replace direct measurement of this parameter. Non-observable parameters can only be accessed by models.

Electrical equivalent circuits that comprise the electrical components (resistor R, impedance L, capacity C, Warburg term Z_W, constant phase element CPE, etc.) and describe the battery's internal processes are favoured. Different from other approaches, understanding of the electrochemical processes [42] is essential to assess the validity and to recognize the limits of relevance of appropriate equivalent circuits that may depend on the operational situation. To fit the parameters of the equivalent circuit to measured data, usually algorithms from control theory are used, especially filter functions such as the Kalman filter approach [43,44].

Models are very helpful to obtain values for parameters that cannot be measured directly. This may mean that: (i)

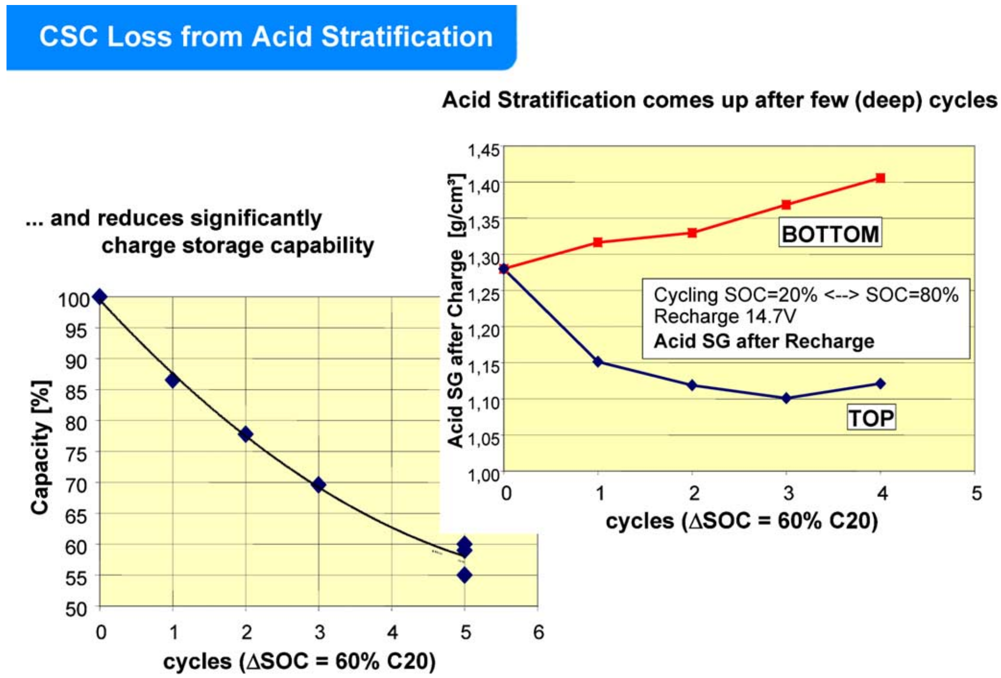

Fig. 13. Acid stratification may occurs in SLI batteries after a couple of cycles with 60% DoD (between 80 and 20% SoC) without returning to full SoC. Residual charge stored is lower than 70%. Acid specific gravity in upper and lower part of cell may differ by more than 0.25 g ml^{-1}.

sensing of the given parameter is technically impossible; (ii) it would be too expensive to establish an appropriate sensor; or (iii) the parameter cannot be measured at a given point in time when a value is required as an input for an algorithm. Typical examples for these cases are: (i) local sulfation of an area of one of the electrode polarities, as is described for the negative electrode of (especially AGM) batteries under PSoC cycling [45]; (ii) acid stratification in flooded batteries that have been cycled under medium or deep discharge and never reach a full state-of-charge; (iii) open-circuit voltage OCV. Two of these examples are discussed more in detail in the following section.

4.6.1. Quantification of acid stratification

Acid stratification is a consequence of the participation of sulfuric acid from the electrolyte in the electrochemical reactions. Convection of the free electrolyte is generated by differences in local concentration, i.e., specific gravity of the electrolyte, and results in electrolyte concentration being higher in the lower part of the cells than in the upper part. Suppression of this electrolyte convection is one of the major benefits of electrolyte immobilization in VRLA batteries.

To date, acid stratification has received little attention in the case of SLI batteries. Due to the usual rather shallow cycling operation, generation of stratification is limited, and mechanical movement of the battery in the vehicle, as well as some gas evolution during charge at elevated temperature (when the battery is located under the hood), supports equilibration. Cycling operation is more harsh today and generates more stratification, while there is less electrolyte mixing due to the use of battery designs with low-gassing grid and closer plate packaging, and to better vehicle suspension.

The reduction in the storage capability of a SLI battery (12 V/110 Ah) when cycled between 80 and 20% SoC at the C20 rate is shown in Fig. 13(a). Already after six cycles, the charged battery (14.7 V for 24 h) provides less than 70% of its nominal capacity (Note, when the battery was turned upside down several times and recharged at 16 V, stratification was overcome the and capacity was fully recovered). This demonstrates the relevance of acid stratification for battery state detection.

Acid stratification generates a local imbalance between available active electrolyte and active material: in the upper portion of the cell there is a lack of sulfate ions in the electrolyte to discharge the active materials as designed. By contrast, in the lower portion there is a surplus of sulfate ions that cannot be put to use as the amount of active materials is unchanged. This imbalance is the reason for capacity reduction, and the voltage starts higher but reduces faster on discharge than without stratification. This is because discharge commences in the lower part of the cell due to the higher electrode potential (higher electrolyte relative density) there, and a smaller portion of electrolyte is involved. The upper part of Fig. 11(c) represents the situation by a tank that is somewhat higher (higher voltage at full charge corresponding to higher pressure), but contains a body at the side of the tank that displaces liquid volume. Thus, the battery CSC is reduced by reduction of tank width when acid stratification is present, which dominates the somewhat increased tank height. The corresponding characteristic of voltage versus ΔQ is steeper than without stratification, as sketched in the lower part of Fig. 11(c). The situation when both capacity loss due to active-material degradation (Fig. 11(b)) and acid stratification (Fig. 11(c)) are present is shown Fig. 11(d); two effects of capacity loss overlap.

The relative density of the electrolyte above the plate stack SG_{top} and in the lowest part of the container SG_{bottom} is shown in Fig. 13(b). The difference between these values exceeds 0.25 g ml^{-1}. If the battery voltage, which is dominated by the highest acid density SG_{bottom} in the cell element, is taken as a measure of the SoC, then the latter would be overestimated significantly as the gradient of voltage against specific gravity dEMF/dSG, is about 920 mV g^{-1} ml^{-1} per cell, i.e., ∼5.5 V g^{-1} ml^{-1} per six cell battery [5].

Direct sensing of the degree of acid stratification is not economical; it is a classical case for modelling. Theoretically, all the information required to estimate the degree of stratification is available (i.e., the acid concentration profile as a function of cell height $c(z)$):

- acid concentration in the fully charged state (when homogeneous);
- the amount of electrolyte and active materials in the cell;
- cell design data like such as electrode number, thickness, height and width;
- separator characteristics, including rib height to calculate electrolyte flow;
- viscosity and diffusion constant of diluted sulfuric acid as a function of concentration and temperature, etc.

(*Note*, the acid concentration profile perpendicular to the electrode plane $c(x)$ may be modelled as well, but is not considered here.)

When the battery is being operated, i.e., a current profile $i(t)$ is applied, all electrochemical processes such as charge transfer and all physical processes like diffusion, convection, as well as all thermal effects, can be simulated. The output is the acid concentration profile $c(z)$ together with the distribution of positive and negative active-material utilisation over cell height z. With this information on state parameters, battery behaviour can be modelled completely. The precision of all this prediction depends of course on the quality of the model for stratification and electrical battery behaviour, as well as on the correct data for describing the design of the battery. This is not an easy task from the mathematical and numerical point of view, but it has been addressed successfully for more than 10 years [46–48]. A simplified approach may provide a coarse estimation of the degree of acid stratification, and will allow for correction of the battery voltage reading as an input for the estimation of the stored amount of charge.

4.6.2. Determination of open-circuit voltage

The equilibrated open-circuit voltage (OCV) of a lead–acid battery is a good value to estimate the SoC (if acid stratification is not relevant) [2]. If the battery is under electrical load, however, a direct measurement of OCV is not possible. And even after the battery is released from all electrical loads, the battery requires some time for relaxation until the OCV reaches an equilibrated value. This value can, however, be predicted earlier [49].

A good approach to the estimate the OCV while the battery is under electrical load is a model using an electrical equivalent circuit that comprises at least: (i) an electrical element representing a voltage source which is operating at the actual equilibrated OCV; (ii) a linear resistor representing the ohmic losses within the conductive lead and the electrolyte; (iii) a non-linear resistor representing the charge-transfer reactions. The model would be similar to that of Shepherd [42] and others [50,51]. The actual values of the parameters of the equivalent circuit can be fitted to the measured voltage and current data by using filter procedures from control theory, e.g., the Kalman Filter [2,52]. An example for such an approach is shown in Fig. 12 of [1]: within 1 min of typical vehicle driving condition, the filter algorithm, intentionally set to a wrong starting value for U_{oo}, is able to find the correct parameters of the equivalent circuit and to capture the correct value of U_{oo}. From this modelled U_{oo} value, a modelled SoC value was determined shown in comparison to the 'true' SoC value. Such modelled state parameters are used to predict battery behaviour under a potential future load profile (see Fig. 6).

4.7. Classification of approaches for determination of changes in battery characteristics

Four classes of approaches for the determination of changes in battery characteristics have been discussed so far. They may also be combined in a BSD if the required information is available, which means suitable sensing devices with appropriate data sampling rates and precision, and storage capability (Fig. 14) by:

(i) monitoring of battery operating history (e.g., time, temperature, charge throughput, etc.);
(ii) consideration of special events (e.g., deep discharge);
(iii) direct measurements of battery behaviour, e.g., on cranking, load transient, etc.
(iv) use of models.

These classes have their equivalent in the world of life and health insurance economics. And there are several analogies with that field, as follows:

(i) Monitoring of battery operating history has its equivalent with a life or health insurance company, handling a new unknown customer. They will ask for his/her age, and if they want to estimate his/her personal health risk or expected residual life, to calculate the monthly insurance premium, they will try to monitor his/her life conditions more precisely. Education and profession, family status, number and age of children may allow better estimation of health and life risks, and the customer's health awareness. The same is true for sporting activities, which may be ambivalent due to higher fitness

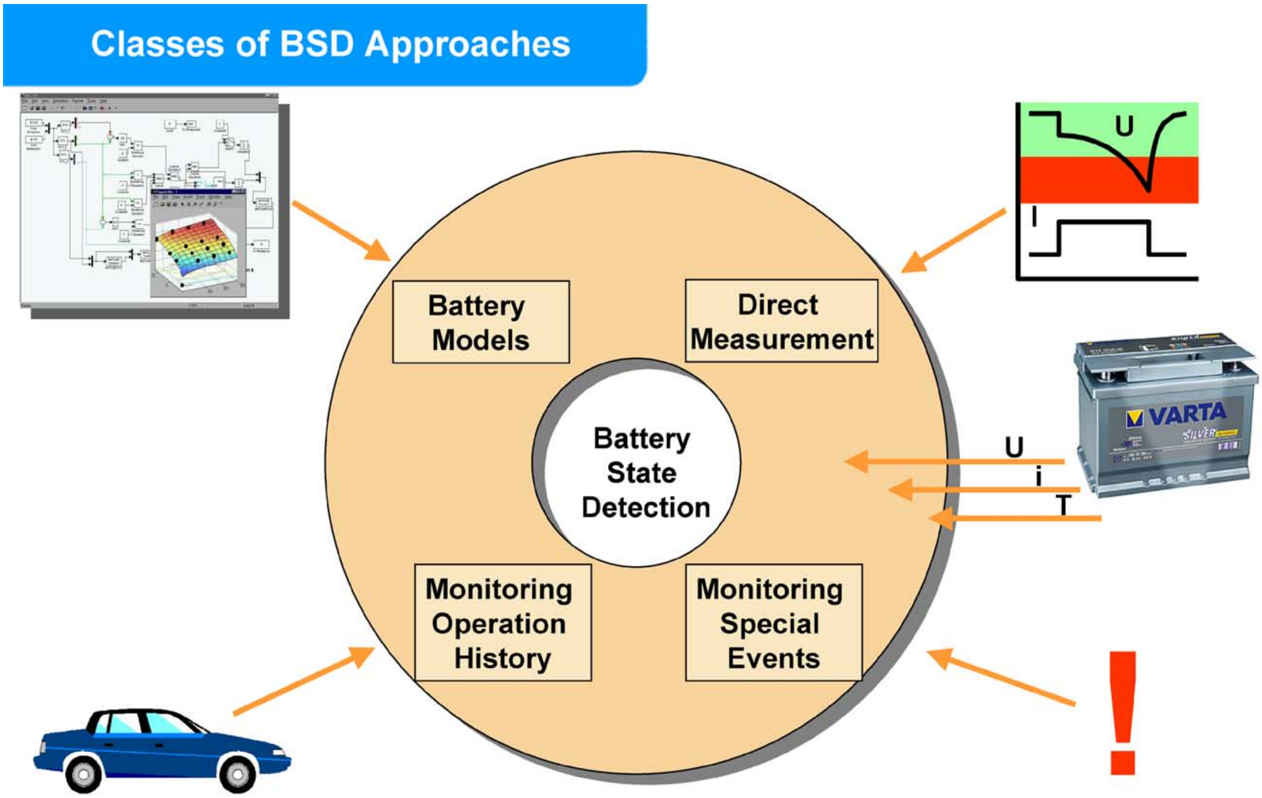

Fig. 14. The four classes of approaches of battery state detection, which may be combined to make the best compromise between capability and precision of prediction, effort, and cost.

but also increased risk, as well as the use of medicine, smoking and drinking alcohol. (Note, the acquisition of some of these personal data may not be in accordance with legal regulations, but they would improve the precision of a prediction. Of course the comparison of battery ageing with health and ageing of human beings should not be over-stressed.).

(ii) Consideration of special events will also allow the insurance company to improve their estimation. Diseases, accidents, surgery, changes in profession and relocation, as well as wedding and divorces—will all allow for better prediction of risk for future health and life.

All of the estimations discussed so far are of pure statistical manner. They only enable the prediction of a statistical probability for the occurrence of an illness and the cost generated, or a residual life expectation. A prediction for the future of an individual is not possible at all. The individual may die tomorrow, or may live for many more years. For the insurance company this may be an acceptable uncertainty because the expenses for a chronically ill person are compensated by a dynamic senior who never needs to see a doctor.

For the estimation of battery performance and residual life, this may be not the case. A driver of a car will not be satisfied if told after the breakdown of his/her car that unfortunately he/she was one of the 100 ppm of cases in the left tail of the distribution function. Therefore, a BSD in automotive applications should make use of the stronger classes of approaches, using direct measurement and models.

(iii) Direct measurements of battery performance have their equivalent in health care in precautionary health checks. They do not avoid health issues, but allow for early detection and cost saving. This is the motivation for the health system to promote regular health checks. The same is true for direct measurement of battery performance. And these measurements look at the battery individual, not at the statistical situation!

(iv) Using models (i.e., an expert system) for some aspects of battery state allow for estimation of parameters P_i that are not accessible for direct measurements, or the cost would be too high to measure, but relevant for ageing. Insurance companies also follow this route. If they have no access to data, their expert knowledge is used to make the prediction.

This classification of approaches to estimate battery ageing compared with the respective activity of an insurance company gives a strong hint of the type of approach – and the level of precision – that should be followed in a certain case. The decision between increasing the cost for data detection of appropriate precision and for the hardware and software to operate the algorithms, and the precision of prediction and risk for malfunction of a sub-system or the whole vehicle has to made individually on a case-to-case basis.

4.8. Precision of algorithms

The precision of any algorithm depends on the level of simplification, i.e., the intended decision to neglect certain effects, or – to save cost or complexity – not to measure certain data even if technically possible. Errors in input data, from sensing devices and scattering of an individual battery property, 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 prevent erroneous sets of data from influencing battery monitoring, [2]. Algorithm quality is more than precision, i.e., a robust procedure is needed with mathematical stability, unequivocal parameterization, and correct separation of variables.

To avoid unexpected results, the input data to battery monitoring, and the output generated, should be checked for plausibility before they are used, e.g., by an energy management system. Results may be checked against their range of plausible values, which may depend on parameters such as temperature, SoC, or vehicle status. More simple approaches (cf. Section 4.7), while possibly not being satisfactory in terms of reliability on their own, provide an excellent means to cross-check more ambitious algorithms. The handling of possibly detected discrepancies depends on the relevance of the result, the goal of the function, and the capability of the system.

5. Summary

Nowadays, vehicle electric systems are driven by fuel economy, ecology, and by new functions for improvement of safety, comfort, and reliability. Electrically driven components that require electrical power of high reliability are penetrating the mass market, and the emerging start–stop systems will bring new challenges. Overall the requisite electrical performance is increasing with much higher fluctuations of the load demand. This cannot be accommodated simply by scaling up today's components.

All of the above also applies to the battery, especially as packaging of the rather bulky battery within the vehicle is becoming more and more of an issue for designers. Consultation with the battery manufacturer for packaging and possibly partitioning into two batteries may be helpful in many cases.

While there is still potential for the further technical improvement of automotive batteries, procedures are needed for optimum use of the battery resource, i.e., knowledge of actual SoC, power capability, and quantification of the degradation of the battery performance as an input for energy management. Early detection of possible restrictions of reliability by battery state detection allows for actions by the energy management system well in advance. The expertise of the battery manufacturer is challenged by this task.

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