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Issue	v04
Topic	**Bosch Battery State Detection BSD Software**
Description	Technical Description Bosch BSD Software

Technical Description

for the

Battery State Detection

Software

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1 Introduction

Since 1992, Bosch has been working in the area of development of algorithms for battery state detection for lead-acid batteries (wet and fleece batteries). The state-of-the-art technology is a battery diagnostic system consisting of algorithms that are implemented onto a Bosch ECU. Bosch sees a trend towards a compact sensor hardware, which is assembled in the battery pole section. The software of this sensor contains the battery diagnostic functions.
The task of the battery diagnostic function is the on-line calculation of information about the current battery state, taken from the measured physical variables such as battery current I_{Bat}, battery voltage U_{Bat} and battery temperature T_{Bat}.

The information thus obtained from the vehicle battery is

- battery voltage U_{Bat}, battery current I_{Bat}
- battery temperature T_{Bat}
- state of charge (SOC)
- actual performance capability of the battery (SOF)
- degree of ageing (SOH)
- battery parameters, e.g. internal resistance (R_i)

This information will be provided in a broad range of output variables that may be customised according to the OEMs needs.
Using a bus system (LIN) it is possible to transport the variables – relevant to the electrical energy management EEM – to an ECU. In the ECU, further processing of this information will take place.

This document

- gives a short description of the SOC, SOF and SOH definition used
- describes the structure and the components of the BSD Software
- lists output variables that may be provided by the BSD Software and how they can be used within Electric Energy Management

Using the battery sensor EBS, regular transmission of temperature T_{Bat} , current I_{Bat} and terminal voltage U_{Bat} of the battery to an ECU, as well as information about the actual state-of-charge (SOC), the performance capability (SOF) and the degree of ageing (SOH) in a variety of specifications can be provided.

2 Operation Principle of Battery State Detection

The basic principle, how the Battery State Detection Software works, is shown in figure 1:
The *real vehicle battery* is observed using the electronic battery sensor EBS by measuring current, voltage and temperature nearby the battery pole. The BSD software contains a *battery model* that covers all main electro-chemical features of the battery, e.g. acid capacity, internal resistance, diffusion and polarisation. A feedback unit ensures that the parameters and the state variables of the battery model of the BSD software describe the real battery inside the vehicle with a high accuracy. This self-learning process uses the mathematical method of the *Kalman Filter*.
Using this method, changes of battery parameters, e.g. ageing effects are considered.
Based on the battery model of the BSD software, simulations can be carried out using predictors in order to determine state-of-charge of the battery (charge predictor), voltage drop of the battery responding to current profiles (voltage predictor) or maximum current that can be drawn from the battery (power predictor).

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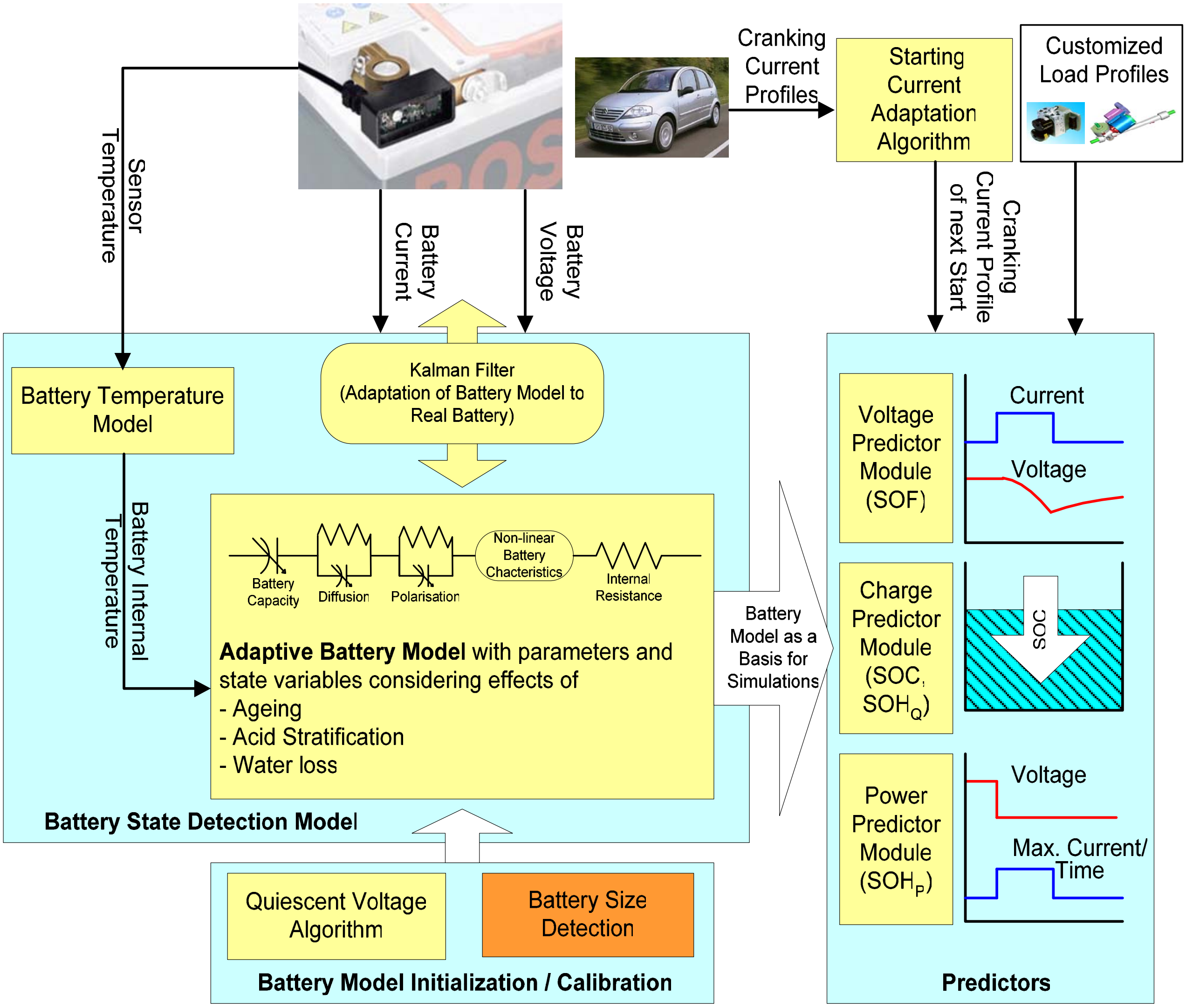

Figure 1: Structure of the BSD algorithm

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3 SOC as a Measure of Deliverable Charge

3.1 Background

For the vehicle operation, deliverable charge of the battery is of relevance for strategies of the electrical energy management.

Bosch uses the deliverable charge from the battery as an input variable for SOC calculation related to the battery capacity. This charge quantity is dependent on the load profile. Hence, Bosch uses a standardised profile of discharge current with an amplitude I [A] = 1/20 * K20 [Ah] at room temperature, where K20 is the nominal capacity of the battery.

From the Bosch viewpoint, the SOC determination as deliverable charge under nominal and actual environmental and loading conditions can be meaningfully realised only on taking into consideration the losses of capacity as a result of ageing and acid stratification (SOH_Q).

The correlation between nominal capacity according to the type specification (K20), the deliverable charge (Q_{ist}), the usable capacity (Q_{akt}), the loss of capacity as a result of acid stratification and ageing (SOH_Q) can be derived from the illustration in.Figure 2.

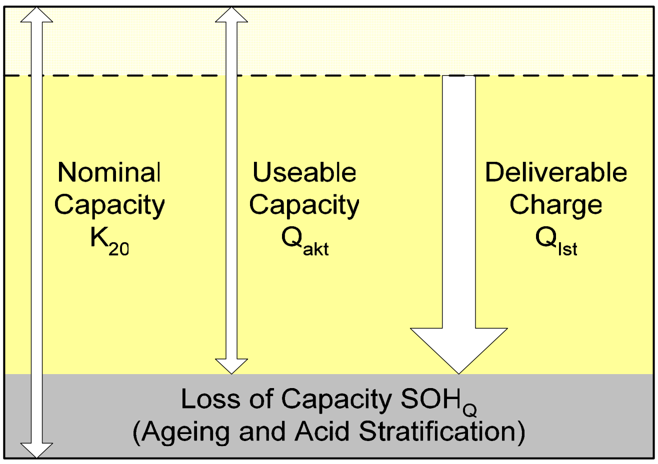

Figure 2: Correlation between nominal capacity K20, useable capacity (Q_{akt}), deliverable charge (Q_{ist}) and the loss of capacity (SOH_Q)

Currently, there are two different reference variables used for SOC calculation in series projects:

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1. SOC related to nominal capacity K20

$SOC = Q_{ist} / K_{20}$

Benefit: The absolute value of deliverable charge is indicated directly.

2. SOC related to useable capacity Q_{akt}

$SOC = Q_{ist} / Q_{akt} = Q_{ist} / (K_{20} – Q_{ist} – SOH_Q)$

Benefit: The SOC can reach 100 %, even if a part of the battery capacity can no longer be used as a result of ageing or acid stratification. This benefit is useful in display concepts, for example, for panel instruments.

3.2 Algorithm for SOC Determination

Basis for the SOC determination are the SOC calibration of during vehicle standstill by quiescent voltage algorithm and on the other hand the current integration using the *model of the battery* adapted by the Kalman Filter during vehicle operation.

Effects of ageing and acid stratification are considered.

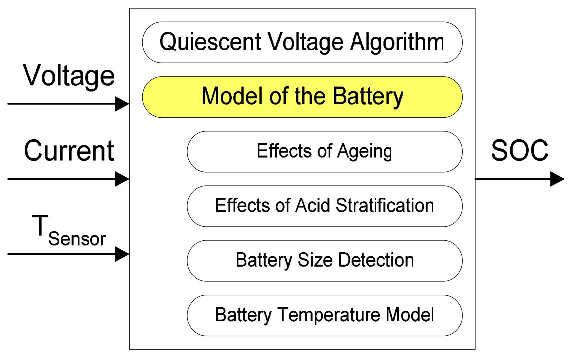

Figure 3: Algorithm structure for SOC determination

The *quiescent voltage algorithm* module, consideration of ageing and acid stratification, battery size detection module and the battery temperature model are described in 3.2.1 to 3.2.5.

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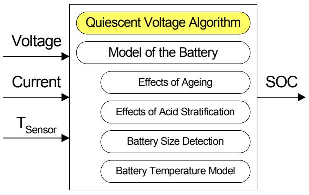
When calculating deliverable charge of the battery using the charge predictor module (see Fig.1), the SOC can be universally related to various temperatures and discharge current profiles (AH_K20, SOC).

3.2.1 Basic Principles of the U_{00}-Algorithm



The functional correlation between the ideal quiescent voltage (U_{00}) and the state-of-charge (SOC) of a new battery which shows no acid stratification is essentially simple and well-known since a long time.

However, neither the pre-requisites for acquisition of the ideal quiescent voltage nor the conditions of a new battery without acid stratification are met in the vehicle.

Decay of all electrochemical balancing processes within the battery is present at low temperatures only after 30 h.

Apart from that, due to ECU power consumption, power consumption of comfort loads etc., there exist no real battery quiescent phases even at vehicle standstill.

The quiescent voltage algorithm allows estimating the value for the quiescent voltage (Uoo), which would be present in case of an ideal rest phase. This value is necessary for a precise determination of the state of charge (SOC).

Performance features

The strength of the Bosch quiescent voltage algorithm lies

1. In the process of delivering an exact estimation of the ideal quiescent voltage even in short standstill phases of the vehicle. Thus, a first estimation occurs after a 1 h quiescent phase, and after 8 h, the estimation already corresponds nearly exactly to the ideal value.
2. In the process, to even compensate the deviation due to remaining quiescent currents up to 200 mA during standstill phase.
3. In the process, even to compensate disturbances due to high current pulses during quiescent phase (pulses < 10 s, I < 100 A).

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Range of application

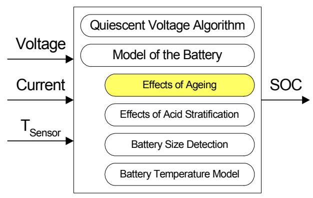
The quiescent voltage determination by the Bosch algorithm has been specially developed for application in vehicles and has been successfully integrated in customer series projects.
It allows for application on various electrical system configurations and dynamics.
Measurement of battery voltage, battery current and battery temperature in the vehicle standstill phase must take place every hour. If a parameterisable current threshold is exceeded, measured values are required at short intervals.

Internal output variables

Output variable of the U_{00} algorithm is an estimated value for the ideal quiescent voltage of the battery.
This voltage could be measured on the battery terminals in case of an unloaded battery after aligning all electro-chemical balancing processes.

3.2.2 Ageing effects that influence SOC (loss of capacity)

Background of SOH_Q



The limiting of the battery life to 2 - 5 years of durability is caused by physical and electro-chemical ageing processes such as sulphurisation. These processes lead to loss of capacity SOH_Q of the battery , see Fig. 2
After 2 years of driving the vehicle, SOH_Q would be in the range of several 10 % of nominal capacity. Hence, for useful SOC determination, it is essential to take into consideration the resulting loss of capacity SOH_Q.

Performance feature

The algorithm to determine SOH_Q is in development. It is based on online-monitoring of all battery parameters by the Kalman filter, see Fig. 1. Changes within the vehicle battery (e.g. internal resistance, acid capacity, diffusion coefficient) during lifetime (e.g. due to sulphation, corrosion,

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acid stratification, water loss) are monitored and the parameters of the *battery model* are modified accordingly.

Simulations using the *charge predictor module* allow to quantify the capacity of the real battery in Ah assuming nominal discharge conditions. On the other hand, the value in Ah for the new battery at nominal condition is known. The difference of the two values is the irreversible loss of capacity.

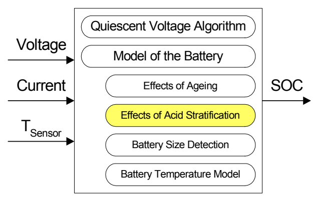
Range of application

The SOH_Q algorithm can be implemented in EBS for starter batteries, if the measured variables such as battery current, battery voltage and battery temperature are available.

The algorithm is part of the Kalman filter controlled battery model. The result contributes to the loss of capacity SOH_Q of the battery in Ah. It is used to modify output of all SOC related output values.

3.2.3 Acid Stratification Effects that influence SOC calibration

Background



Non-homogenity in the acid density distribution of the battery will result in case of strong charging of wet batteries starting from a low SOC level. This effect is known as acid stratification.

Measuring the quiescent voltage in this case can lead to a too high U_{00}-value and will lead to incorrect SOC determination.

Range of application

For this purpose, this effect of acid stratification is considered in the Kalman Filter by modifiying the the battery model parameters. The algorithm does not deliver a value for the loss of capacity due to acid stratification. Acid Stratification is considered in the calculation of SOH_Q described in 3.2.2.

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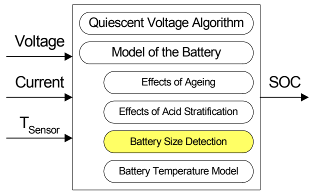
3.2.4 Algorithm for Battery Size Detection



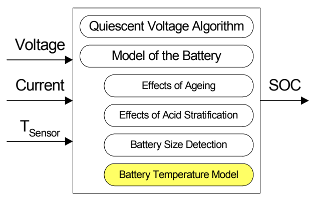
High precision of the BSD algorithm is provided by battery coding leading to high precision through battery and manufacturer-dependant assignment of parameters. During the BSD development phase, a set of parameters for a broad range of possible battery types (e.g. 60 Ah to 110 Ah) is selected with the car manufacturer. Battery coding will be done by the car manufacturer and by service stations at each battery change. This method is practice in several series projects.

However, with respect to the event of unauthorised change of the battery, an extension of the algorithm is in development to identify the battery size automatically without coding of parameters.

It is foreseen that the process of automatic identification will not be finalized immediately after a Terminal-30-Reset. It is expected that at least several motor starts and a slight discharge of the battery will be precondition for a fully automated battery identification. During this period of time, where identification is not terminated, output values of the BSD will not be valid and a strategy for the case has to be developed between OEM and Bosch (e.g. assumption that no battery change took place, neglection of ageing output, etc.).

By adapting the battery’s acid capacity, the battery nominal size will be determined and a mismatch with the coded battery size will be clearly identified. In case of battery change without coding the battery parameters, a selection of the nearest parameter set dependant on battery nominal capacity will be done.

3.2.5 Model for Battery Temperature Estimation



With respect to the strong impact of temperature to the electrochemical processes inside the battery influencing the overall electrical behaviour, the temperature determination of the battery plays an important role. Battery temperature will be estimated by measuring the temperature on the EBS (nearby the battery pole) and processing the measured value with the *battery temperature model* algorithm.

Part 1 of the temperature model compensates the deviation between measured sensor temperature and environmental temperature caused by self-heating of the ECU. Part 2 of the model determines the battery temperature with an typical accuracy of 3..5 K (max ±6 K) for an environmental temperature between -40 °C and 80 °C. This accuracy is sufficient for the BSD algorithm. There is no application necessary, however to guarantee this accuracy in series projects, the battery temperature model is validated using a measurement cycle in an OEM vehicle.

3.3 Range of Application and Precision of the SOC Determination

The SOC determination with the available algorithm can be applied to various electrical system dynamics and battery types. The SOC calculation using the charge predictor,
Figure 1, provides information about the deliverable charge for individual load profiles and covers the full temperature range. The universal charge predictor will be used to provide information about the load-specific requirements from the OEM specification.

The precision of the output variable SOC is dependent on the temperature as well as on the ageing state of the battery.

The error determined in the vehicle for all SOC-related values is typically ±10% in following conditions:

- After a first standstill phase of at least 4 hours, and
- one standstill phase of 4 hours regularly (at least one time per day) and
- battery temperature range between -10°C and +45°C

SOC accuracy in the other cases: ±15%

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4 State-of-Function (SOF)

4.1 Background

The universal voltage predictor allows the calculation of the voltage sag due to an expected current profile (SOF). The current profiles are designed to be adaptable according to the OEM needs. The SW module *voltage predictor* (Fig. 1) is used to provide information about the OEM SOF-requirements. The SOF determination is based on the battery model determined by the Kalman filter and ageing effects such as increased internal resistance of the battery are included.

4.2 Startability of the Vehicle

The algorithm allows to determine the voltage drop for a certain current profile. Most useful in electric energy management is the information about the voltage drop during engine cranking. Load profiles depending on the temperature can be offered for stop-start applications (cold cranking current, warm cranking current). Application to real starting profiles is done using the Bosch *starting current adaptation algorithm* where the prediction load profiles will be based on the history of cranking currents of the engine starts.

4.3 The Starting Current Adaptation Algorithm

The *starting current adaptation algorithm* is part of the BSD-algorithm. This algorithm requires some engine relevant data (engine characteristic data) provided by OEM via LIN and additional application effort. The starting current adaptation algorithm is used to identify parameters for prediction of a warm start current profile and a cold start current profile. With this self-learning algorithm, better accuracy than with fixed current profile, is achieved, because the calculation is based on real cranking profiles.

The error determined in the vehicle for all SOF-related values is typically below 5 % related to 12V if the temperature assumptions for the prediction remain valid.

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4.4 Ageing related to Startability (loss of power performance)

In order to consider the ageing effects that influence startability of the vehicle, the *power predictor* (Fig. 1) is used. The voltage drop during engine cranking is strongly influenced be battery parameters, e.g. internal resistance of the battery. Ageing effects of the vehicle battery are continuously monitored by the Kalman filter and parameters of the battery model are modified accordingly.

The *power predictor* calculates the maximum cranking current of the battery in the vehicle with its actual ageing values and compares it with the initial values of the new battery. The output variable SOH_P hence gives a good indication of the state-of-health (SOH) of the battery.

5 Validation of Battery State Detection Algorithm

Test specifications have been created for individual algorithm modules and for the entire algorithm. The validation takes place in different phases of the development process, for instance, in the early phases of algorithm development (simulations), up to the final system tests on the D-sample ECU.

There exists an on-board testing cycle for validation of the battery state detection in series projects. This was conceptualised and mutually agreed upon with various OEMs:

Validation of individual algorithm modules:

- offline (processing of recorded measurement data in simulations)
- online through measurements in the vehicle or on the test-bench

System test cycle available for BSD-Software on EBS, suggestion Bosch:

- Duration: 5 days
- Test can be run on a test bench without a battery using recorded data as input stimuli or with a battery
- Temperature range: –18°C, 0°C, +60°C
- Contains phases of high dynamics and rest phases

6 Concept for Integration of BSD Algorithms on Hardware

Bosch is offering the BSD algorithms integrated in the sensor EBS.

Features:

- Standardised interface of SOC, SOF and SOH using a low bus data rate. LIN bus can be used also for generator communication
- EBS as optional component in vehicles and suitable for aftermarket
- Availability of battery data U, I, T to host-ECU is provided
- Low application work and clear responsibility (no SW integration in foreign ECUs required)

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7 Output variables

This listing shows possible output functions, that can be offered for a series project. If necessary, further functions and output variables can be offered separately. Further details of the output variables may be discussed.

A suggestion is given, how the OEM may make use of the variables as an input for the OEM electric energy management.

Name	**Description**	**Remarks**	**Development Status**	**Usage within Electric Energy Management**
I	The measured electrical current, flowing either into or out of the battery: positive current is defined as charging current (*i.e.* current flowing into the battery), negative current is defined as discharging current (*i.e.* current flowing out of the battery).		In series in previous Bosch battery sensor projects (EBM/EPM) EBS: M2006	Quiescent current management, dynamic energy management, OEM specific energy management functions
T	Battery internal temperature	This signal is generated by the battery temperature model BTM, aplication of battery in vehicle is required	In Series in previous Bosch battery sensor projects (EBM/EPM) EBS: M2006	OEM specific energy management functions, e.g alternator control
U	The voltage that is measured across the terminals of the vehicle battery.		In Series in previous Bosch battery sensor projects (EBM/EPM) EBS: M2006	OEM specific energy management functions
AH_K20	Deliverable electrical charge of the battery by 20-hour rate test current at actual battery temperature	This signal is generated by the charge predictor	M2006	Quiescent current management or battery diagnosis (deep discharge logging)

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Name	Description	Remarks	Development Status	Usage within Electric Energy Management
SOC	Battery SOC at present temperature (Deliverable charge related to the battery size)		In Series in previous Bosch battery sensor projects (EBM/EPM) EBS: M2006	Quiescent current management and dynamic energy management, e.g. load control or alternator control
SIZE	Battery capacity of the used battery in the vehicle	This signal is generated by the charge predictor	M2007 (no accuracy statement yet available)	Internal use
SELF_LEARNING_FLAG	After an unknown battery is installed in the vehicle, the self-learning process of the battery requires a certain time; during this time, the flag is 1 else 0		M2007 (no accuracy statement yet available)	Battery diagnosis
BAT_OLD	After self-learning process, it was learned that the battery health parameters are not in a good condition	This signal is based on SOH_P or SOH_F- Signal	M2007 (no accuracy statement yet available)	Battery diagnosis
OCV	Prediction of the battery terminal voltage after 0.1 s if the battery current was set to zero from the present instant on. This is the open-circuit voltage in the electrical sense (I=0), not the thermodynamic equilibrium voltage.		M2007	Alternator Control
SOF_AIRPORT	This signal calculates how many days can cranking of the vehicle can be possible at actual temperature and quiescent current. Basis: Automatic Starting Current Adaption (leads to self-learning system, hence the cranking current used for the prediction is the vehicle cranking current)	This signal is generated by the voltage predictor and makes use of the automatic cranking current adaption	M2007	Quiescent current management
SOF_COLDCRANKING	This signal calculates the voltage drop of the following engine cranking. It indicates, if engine cranking can take place after a quiescent phase of duration x with a current amplitude of y mA. Basis: Automatic Starting Current Adaption	This signal is generated by the voltage predictor and makes use of the automatic cranking current adap-	In Series in previous Bosch battery sensor projects (EBM/EPM) EBS: M2006	Quiescent current management, ensure startability and maximum availability of comfort loads

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Name	Description	Remarks	Development Status	Usage within Electric Energy Management
	(leads to self-learning system, hence the cranking current used for the prediction is the vehicle cranking current)	tion		
SOF_NOMINAL	Prediction of the maximum cranking current, that can be drawn during 3 seconds from the battery with fully charged battery and a temperature of –18°C after a rest period of 24 hours. During the cranking pulse the voltage must not fall below a voltage limit, e.g. 7 V.	This signal is generated by the power predictor an includes ageing effects of the battery that influence the cranking capability of the battery	M2007	
SOH_P	Maximum cranking current of the actual battery related to the maximum cranking current of the new battery → degree of ageing This signal includes ageing processes of the battery (e.g. internal resistance, change of Co)		M2007	Ageing information, indicates battery check for service
SOF_WARMCRANKING	Calculates the voltage drop of the following warm cranking current assuming a vehicle standstill phase of n sec. with y Amp-standstill load Basis: Automatic Starting Current Adaption (leads to self-learning system, hence the cranking current used for the prediction is the vehicle cranking current)		M2007	Dynamic energy management of start-stop vehicle
SOF_AH_LEFT	Ah that can be delivered by the battery at the actual condition to reach the limit of startability. This signal includes ageing processes of the battery (e.g. internal resistance, change of Co)		M2006	Startability, dynamic energy management
RI_ACTUAL	Actual internal resistance of the battery		In Series in previous Bosch battery sensor projects (EBM/EPM) EBS: M2006	OEM specific dynamic EEM function

Name	Description	Remarks	Development Status	Usage within Electric Energy Management
SOH_Q	Irreversible loss of capacity of the battery in Ah		M2007	
RI_T25_SOC100	Internal resistance that would be measured, if the ambient temperature was 25°C and SOC was 100%		In Series in previous Bosch battery sensor projects (EBM/EPM) EBS: M2006	OEM specific dynamic EEM function