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A Novel Electrical Energy Management System in Automated Battery Electric Vehicles

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Summary

For an automated battery electric vehicle, equipped with a four-times redundant electrical power supply system, an electrical energy management system based on service-oriented communication needs to be developed. Additionally, the electrical energy management system shall provide information about the internal state of the power supply system. The value of state of function is introduced that is based on self-perception of the electrical supply system. By the use of this approach a concept of an electrical energy management system is presented that suits the demands for automated battery electric vehicles by incorporating machine-learning algorithms. Thus, this paper illustrates new approaches for the electrical energy management in automated mobility concepts.

Keywords: Autonomous vehicle, battery management, BEV, diagnosis, energy

1 Introduction

In the project UNICARagil, funded by the German Federal Ministry of Education and Research, battery electric shuttles are developed that shall reach SAE level 4 automation [1]. Due to elevated requirements in terms of reliability and safety, these kind of vehicles will contain a very different approach towards the electric power supply (EPS) compared to standard electric architecture layouts. In addition, the service-oriented communication architecture (SOA) differs from function based vehicle architecture. Embedded within these constraints a new approach for the electrical energy management (EEM) system has to be taken to ensure reliability of power supply and system operation during failure events.

Thus, in the following section, main features of the EPS system of UNICARagil shuttle and possible faults in any EPS are looked into. Furthermore, state of the art features of EEMs are presented as well as the SOA communication approach in UNICARagil.

1.1 EPS in conventional Battery Electric Vehicles

In conventional battery electric vehicles (BEV) there is one traction battery, usually a high voltage (HV) battery that delivers power to the electric drives. An additional low voltage (LV) power net that is supplied by the HV battery via DC-DC-converter is powering electronic control units (ECU) and other LV consumers. An example for this kind of conventional EPS is shown in Fig. 1. Accordingly, other components in the HV power net are HV consumers and on-board-charger. The main difference between HV and LV power net is the need for direct contact protection of the HV components. Thus, both HV plus pole and HV minus pole are not connected with vehicle chassis and isolation guardians are required.

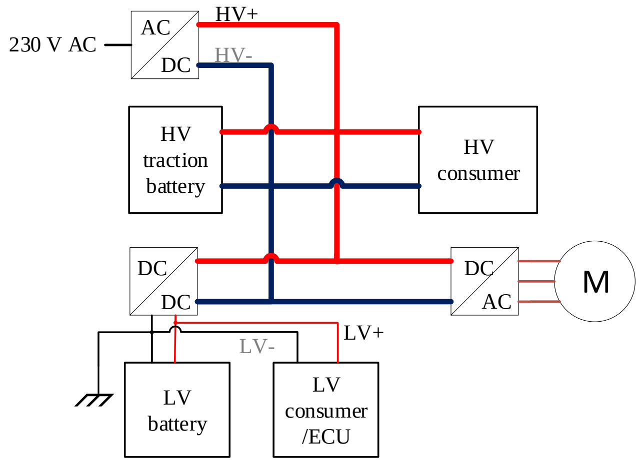

Figure 1: Conventional EPS system with HV traction battery

1.1.1 Faults in EPS System

Different faults in the EPS system can occur during operation leading to different consequences for the overall functionality of the vehicle. These faults can be voltage loss of traction battery, connection faults, short circuit and component failure.

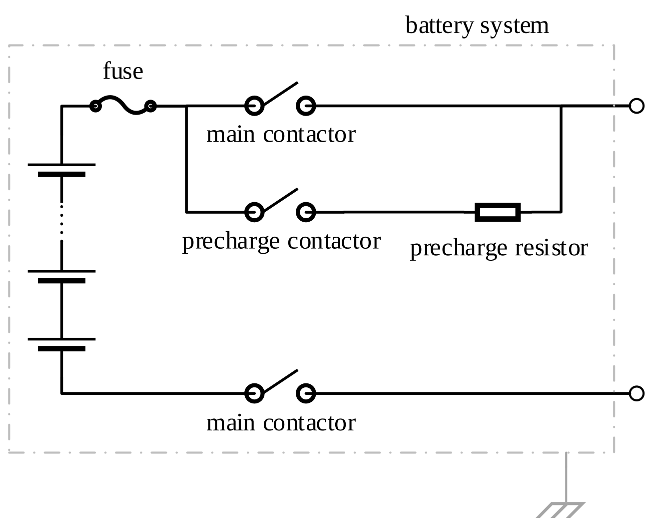

Figure 2: Electric circuit within battery system [2]

The voltage loss of the traction battery, either HV or LV, can have different reasons. Therefore, it is necessary to understand the battery system, which is shown in Fig. 2. Additionally to the battery cells, the battery system also contains a main fuse, contactors and a battery management system (BMS). The BMS is an ECU within the battery system, that is monitoring measurement data from current, voltage and temperature sensors that are also part of the system. Furthermore, the BMS is computing data such as state of charge (SoC) and state of health (SoH). For that reason, the battery system is a complex system whose operation is relying on many different components. Voltage loss can result from open contactors or blown fuses. Contactors may open due to safety reasons, e.g. high temperature, over-current or reaching cut-off-voltage. A blown fuse may result internal or external short circuit. Sensor faults and contactor defects may also result in open contactors. Typical sensor fault modes include sensor values being out of range or stuck in range, offsets, slope faults or oscillations [3]. Furthermore, the BMS ECU is powered by external voltage source such as LV batteries. Failure of external power supply for BMS will also cause contactors to stay open.

Connection faults can manifest through poorly installed plug connections that may lead to accelerated corrosion of contacts due to aging. Thus, connection faults result in an increase of contact resistance and increased voltage drop. Voltage drops may provoke ECUs to shut down. At 48 V, loose or intermitting contact provokes voltage arcs causing danger to surrounding components.

Short circuits are a consequence to insulation defects. In a properly set up power supply the corresponding inline fuse will blow and prevent extensive heat generation within the cable. Fuses are installed at every cable connection. However, in order for the fuse to blow, the current needs to reach a certain threshold. Therefore, any short circuit below that threshold may not be detected immediately.

A component failure such as a fault within an ECU or an electric consumer may lead to either high or low resistance. High resistance will result in decreased current flow. A low resistance causing a current below fuse threshold will result in heating of the defect component. Depending on the fault condition, the component may as well still be able to change between different states of failures towards the electric supply interface, which means it can appear as either low or high resistance at different times.

1.1.2 EPS UNICARagil

The EPS system of UNICARagil is designed for the requirements of reliability to prevent dangerous situations during automated driving mode. There are certain requirements and specific design elements that have shape the EPS architecture:

- The UNICARagil vehicle is propelled by four corner modules that can drive and steer each wheel individually [4].
- There are four sensing units within the vehicle that can monitor 270° of the vehicle environment at each vehicle corner [4].
- Single faults within the electric system must not result in complete shutdown of automated driving functions.

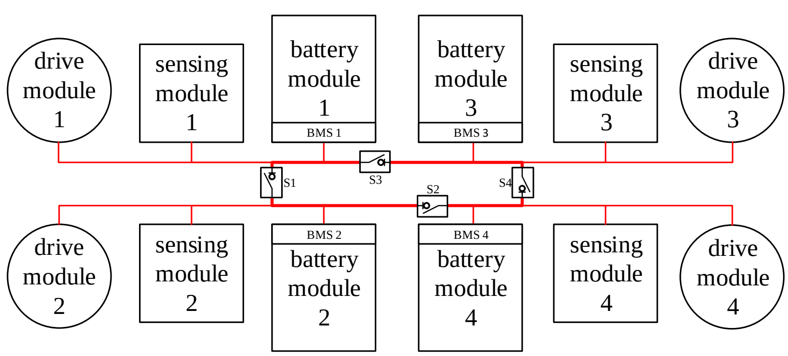

Figure 3: Layout of EPS in UNICARagil vehicle

These design factors lead to a fault-tolerant EPS ring topology shown in Fig. 3. Thus, the topology of EPS has four times redundancy due to the four battery modules in the four part nets. Four contactors connect the four part nets. In fault free condition, all contactors are closed, which means the batteries are connected in parallel. In fault condition, the four part nets can be separated for reasons of fault isolation. This way, a single fault in any part net will not result in complete failure of the overall power supply. Due to the distributed driving and sensing abilities, the vehicle will still be able to maintain functionality for safe locomotion, if one part net might stop operation.

The voltage level of the four battery modules is 48V. Each battery is equipped with a complete BMS and contains 12 kWh of energy. The batteries are air-cooled. There are also four 12 V part nets, that are all supplied by one 48 V part net individually due to the fact that certain electric consumers only run on 12 V. The BMS is not part of the SOA environment due to the fact, that commercially available batteries are not equipped with the SOA interface that has been developed for UNICARagil.

1.2 EEM in BEVs

In conventional BEVs, the right operation of the traction battery is the EEM's focus. In this regard right operation means maintaining the battery within the safe operations limits during environmental influences in coordination with thermal management [5 p. 12]. According to [6] an EEM consists of energy supply, a diagnostic system and an information system. In that work the EEM's main task is to control power flow towards energetic consumers by categorizing and prioritizing power flow to different consumers. In [7] a trip-based energy management is proposed that focuses on estimation of maximum power demands in order to guarantee the vehicle to reach destination. Thus, research results illustrate that there are many different approaches for EEM systems that exceed basic functionality by providing optimized operation strategies in certain regards.

1.2.1 EEM for Automated BEVs

For automated BEVs, an EEM is proposed in [8] that shall optimize energy distribution in fault tolerant power supply systems, predict energy demands for electric drives based on trajectory planning information as well as predict energy resources. In that work, the EEM is based on the assumption that all DC-DC-converters are bi-directional allowing for completely controlled energy flow. In addition, different faults are considered such as electric faults in power link, power sources and power load. During fault condition, the EEM shall apply strategies to meet certain safety goals and maintain specified degrees of operation during faults. The detection and evaluation of the different faults are not further specified or only proposed marginally [8 p. 117]. Thus, this work doesn't offer complete insight into an EEM for automated vehicles, as according to [6] a diagnostic system may be part of an EEM.

1.3 SOA

Whereas the conventional function based communication architecture for ECUs in vehicles prohibits to master any increasing complexity that may be introduced by future functions such as automated driving functions etc., a service oriented architecture can cope with these challenges [9 p. 31]. In SOA different functions are being encapsulated in services that can be accessed by any client [10 p. 2]. Furthermore different services can be linked together for accomplishing tasks. This approach allows flexibility in accessing information from different domains within the vehicle as well as communication with out of vehicle services [11].

1.3.1 SOA Concept UNICARagil

In UNICARagil, every service contains a defined input and an output interface based on a predefined interface database. As illustrated in Fig. 4, inputs can also be both data inputs and service demands. Subsequently, outputs can also be service guarantees. The service itself consists of source code for computation. Service integration is happening during operation time. [11]

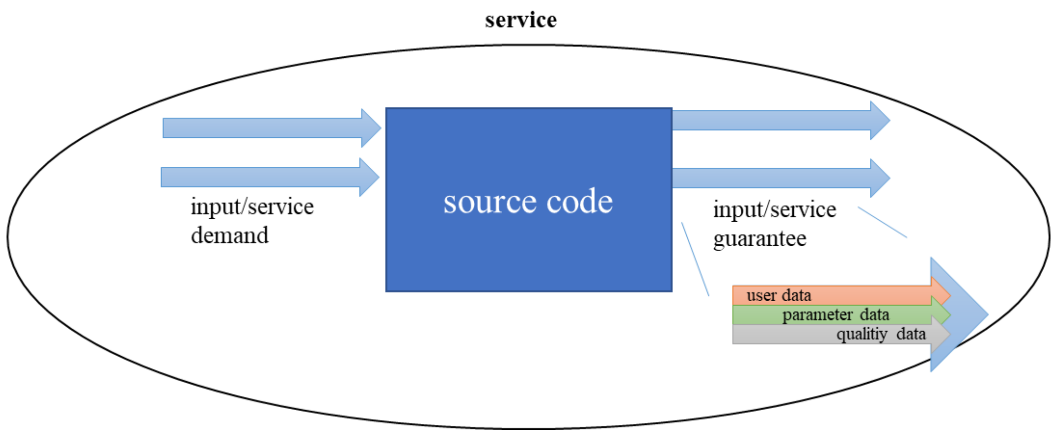

Figure 4: Service interface according to [11].

According to [11] every input and output contains three different kind of data:

- User data: data describing physical or logical values
- Parameter data: interface specific data for compatibility tests for integration during operation time and communication of non-changeable data.
- Quality data: evaluation of quality of user data

1.3.2 Concept of EEM in SOA

For EEM requirements about input and output, data have already been made. Inputs are supposed to be power requests and data from trajectory planning for power demand prediction purposes. Output data are computed values such as state of charge (SoC), state of health (SoH), state of function (SoF), and information whether the batteries are charging or discharging and measurement data such as temperature of traction batteries, voltage, and current. In this context, SoF represents a nominal value for the performance capacity of the battery system, based on the internal state of EPS.

1.4 Aim

The safe operation and control of any system in an automated vehicle can only rely on knowledge about the internal state of a system, which requires certain abilities of perception and data fusion. Current EEM methods do not provide these abilities nor do they show ways for sharing this information with the remaining vehicle functions. Furthermore, there is also no concept for adapting EEM as part of a SOA system in an automated vehicle. Therefore, this work shall present a feasible concept for an EEM that shall diagnose and evaluate the inner state for the fault-tolerant EPS in UNCARagil project. In a first step, the focus of diagnosis and internal state evaluation will be on the traction batteries as these components are both the most complex systems and the core of any EPS. In the second part, possible ways of translating the results of diagnosis and internal state evaluation into output values for the SoA interface are presented.

The remainder of this paper is structured as follows. Section 2 deals with requirement analysis for the proposed EEM system. In section 3, the concept for developing the required functionality of the EEM system is presented, where section 4 provides an outlook for future steps that need to be accomplished.

2 Requirements Development for EEM

In the following section, requirements for the EEM in UNICARagil shall be presented. According to the previous section, the EEM system needs to be implemented in a SOA environment but shall also provide functions about self-perception. Thus, there are both implementation and functional requirements.

2.1 Functional Requirements

The main functional requirement to EEM is the perception of internal state of the EPS. The internal state perception serves as basis for computation of the state of function value as well as for any decision-making algorithm that is supposed to enable safety measurements in the power supply system during fault condition. Thus, providing the remaining vehicle domain with a value that represents the internal state as well as the ability to react upon certain fault events are additional requirements. Therefore, these requirements can be divided into diagnosis functionality and fault strategy management.

2.1.1 Diagnosis Functionality

The diagnosis functionality serves to monitor BMS input data in order to detect irregularities, evaluate these irregualties for their criticality and match them with distinct faults. Thus, EEM needs to be equipped with classification methods and knowledge about faults associated to EPS.

2.1.2 Fault Strategy Management

Fault strategy management is about using the knowledge from the diagnosis functionality in order to adapt the computation of EEM output values such as SoF and their assigned quality data as well as taking actions such as shutting down single batteries if necessary. Different faults can be divided into treatable and non-treatable faults. Hardware faults are typically non-treatable faults. Either they can be tolerated by loss of functionality or the overall system can be shut down. The only treatable hardware faults may be sensor faults such as offsets or gain faults. When diagnosed correctly, the faulty sensor data can be corrected by post processing.

2.2 Implementation of EEM

According to the SOA concept, the inputs and outputs are predefined, but the EEM is also depending on BMS data, that are not part of SOA. Thus, the EEM serves as interface between the data provided by BMS and the SOA vehicle environment, which is illustrated in Fig. 5. Inputs are power demands and trajectory planning data. Output data are SoC, SoH, SoF, temperature, voltage and current, as well as general state of operation.

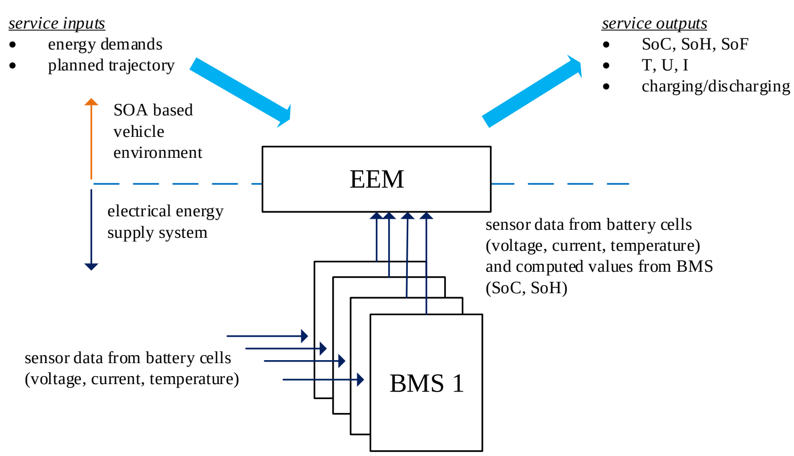

Figure 5: Communication architecture of EEM and BMS.

According to Fig. 4 and according to the predefined signals the EEM needs to provide, basic implementation requirements for the EEM are about BMS data processing. The four data sets from all four BMS need to be simplified into one data set for the output so that there are only single values for SoC etc. This way, the EPS is viewed as a system with a single battery by the remaining vehicle domains. However, individual approaches for data processing need to be taken for different values. Basic methods for incorporating multiple values into one value can be done by either choosing the minimum, maximum or average value. Possible ways for the handling of different BMS data are presented in the following sections.

2.2.1 Voltage Measurement

The voltage value indicates both the energy that is left in the battery cells as well as the load that is applied. As shown in Fig. 5, all four traction batteries are connected in parallel, when all contactors in the main supply ring are closed. Thus, it is to be expected that the measured data should be equal at any time. Therefore, in normal operation mode, the average value should be equal to any single value. However, in fault mode, when at least two contactors are open, measured voltage values may start drifting apart, due different power consumptions in different main part nets. In this situation, the chosen data processing methods may have greater implications. From a safety point of view, choosing the minimum value from any measurement would be the most conservative way during fault condition.

2.2.2 Current Measurement

The current values indicates the load applied to the batteries. Due to the parallel connection of all four batteries in normal operation mode, current measurements should be equal to each other at all times. In fault mode, with two contactors isolating one part net, equality of current load is not guaranteed. Thus, choosing the maximum value in order to indicate the largest power demand would be the safest method but probably not the smartest one.

2.2.3 Temperature Measurement

Lithium-ion batteries require a certain temperature range for operation. Exceeding the maximum temperature will lead to hazardous situations. Furthermore, operating at high temperatures will also decrease lifetime. Thus, the highest temperature that is measured at any time should be used to avoid safety critical situations.

2.2.4 SoC Computation

The SoC values are computed by all four BMS individually and indicate the amount of the energy that is left in the batteries. Due to four identical batteries connected in parallel, all four SoC-values should be equal. Again, only open main contactors may lead to diverging values. Thus, as already mentioned for the measured voltage values, choosing the lowest SoC value may result in the most conservative value but not the accurate value. During fault free mode, the average SoC value does represent the correct amount of energy in the batteries. In fault condition, with open contactors in the main supply ring, the lowest value represents the amount of energy that can be guaranteed at any time in all four batteries, without provoking the shut down of one part net. Thus, SoC computation should depend on operation mode.

2.2.5 SoH Computation

The SoH value indicates the actual battery capacity in relation to the nominal capacity. The actual capacity will reduce over time due to aging effects. All four batteries are located in different sections of the vehicle and thus temperature effects differ slightly for all four batteries. The SoH value is not operation safety critical, as it is a time depending value. Thus, using the average value of all four batteries is sufficient.

3 Concept

In the following section a basic concept is presented, that shall fulfil the requirements to EEM in terms of diagnosis functionality and fault strategy management.

3.1 Diagnosis Functionality

The diagnosis functionality is supposed to be the core of the internal state estimation of the EPS system. As already mentioned in previous sections, the four independent BMS are continuously sending measured and computed data that describe the internal state of every battery system. Due to the parallel connection of all four batteries, these data are supposed to be very similar at any time. Thus, any measured and computed irregularity in any battery will translate into BMS data diverging from those of the other BMS. Subsequently, the data need to be monitored and evaluated continuously in order to detect irregularities. For this task, data processing algorithms are required to classify whether or not a certain data set is irregular. However, if a certain data set could be identified, further steps should be done to achieve a complete diagnosis as it is shown in Fig. 6.

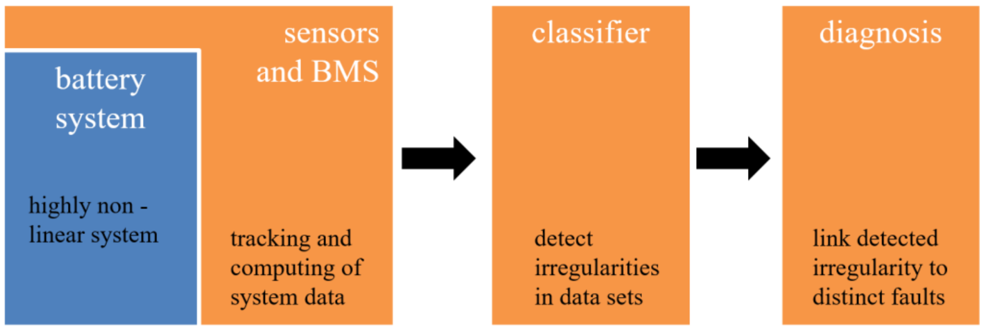

Figure 6: Steps in diagnosis functionality.

3.1.1 Classification

For the classification step machine learning (ML) algorithms shall be used. ML algorithms can be divided into supervised and unsupervised learning methods. Supervised learning methods require known input and output data in order to train the algorithm to be able to predict future outputs. Unsupervised learning methods are used to explore unknown data sets in order to find patterns among the data points. [12]

Currently, there are no data sets available that could have been recorded from a four-time redundant EPS, especially during fault condition. Thus, there are no historic data that may be used to train any machine-learning algorithm. This lack of available data can be partly solved by generating data through simulation models. The advantage of simulation based data generation lies in the cost efficiency due to the fact that also hardware faults can be simulated. The downside of simulation-based data is the fact, that data need to be generated for a huge bandwith of operation conditions combined with many different fault conditions.

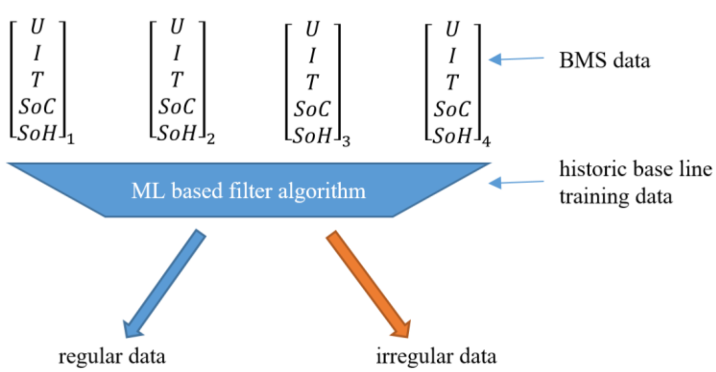

Figure 7: Classification algorithm for filtering BMS data.

However, one key element of this EPS is the permanent comparability of all four BMS data. Thus, the inevitable lack of complete training data set can be partly compensated by real time data comparisons. As shown in Fig.7, a ML filter algorithm will be established that has been trained by a simulation-based data set.

This baseline data set shall support the filter algorithm in the regard, that every single input data vector will not only be compared to the other vectors but will also receive a general evaluation. This approach shall enhance the filter robustness against permanent measurement noise. With a comparison only approach, the input vector with the largest distance will always be sorted as the irregular vector suggesting an unusual operation condition.

In another step, it may also seem possible to update the filter algorithm permanently by feeding data inputs that were recognized as regular input vectors. This may be useful to compensate for aging effects of the battery system that are happening over time.

3.1.2 Diagnosis

As a result of the classification step, irregular data sets are singled out. In the diagnosis step, these data sets shall be matched to distinct faults. Thus, similar to the ML filter algorithm, there needs to be an algorithm accomplish to link the singled out data to a certain fault. This process requires a profound base of knowledge about the certain faults.

Figure 8: Exemplary illustration of faulty data set patterns and associated faults.

One way of linking irregular BMS data sets to certain faults can be done by using simulation data of fault conditions. As shown in Fig. 8, this data can be analysed by pattern recognition algorithms. Thus, it is possible to define the boundaries for different fault patterns. However, it is also obvious that boundaries between certain patterns may be fluent leading to uncertainty. In theory, additional support can be drawn from stochastic methods that evaluate the probability of a certain fault in order to enhance the uncertainty problem. In reality this would require both experience and at some point huge testing efforts of individual hardware components. Therefore, in a first step the differentiation between sensor and hardware faults may be major result for the fault strategy management step. As hardware results may not necessarily be resolved in the way that sensor or computation faults may be resolved, this differentiation already provides decisive information about the internal health state of EPS.

3.2 Fault Strategy Management

The strategy application management part of this process shall use the information from the diagnosis step in order to apply suitable strategies in case of fault conditions. There are several ways for the EEM to react to any fault occurrence: it can either apply hardware-based actions to prevent further risks, resolve the fault conditions and adapt computation of output values.

3.2.1 Hardware based Actions

Hardware based actions can either be fault isolation by splitting up a quarter of the EPS supply or shut down of any battery by opening the contactor within the battery. Reasons for battery shut down may be necessary to protect the battery against overheating or other operative limits.

3.2.2 Resolving Fault Conditions

Some faults such as sensor related issues can be resolved when correctly diagnosed. For example, gain or offset faults in the voltage or current sensors can be corrected by using the comparative data sets from the other BMS under the assumption of identical system behaviour.

3.2.3 Computation of Output Values

By adapting the computation of output values, the EEM is supposed to provide at the SOA interface, the EEM can take indirect measures to reduce the operative strain on EPS. This way, the SoF value can be reduced in order to implicate the maximum power that can be drawn from the system. Furthermore, the diagnosis result shall be translated into the quality data. In Fig. 9, three exemplary different states of the EPS are shown as well as the possible corresponding output values for SoF and quality data.

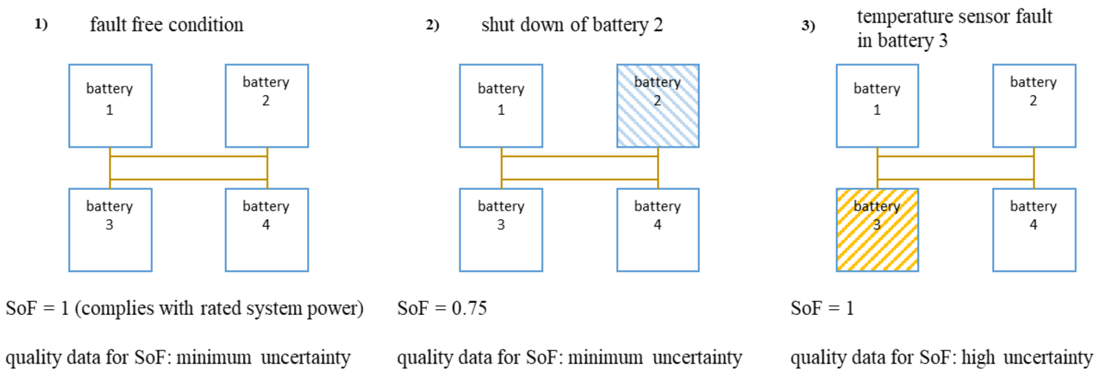

Figure 9: Different states of EPS and affiliated values of SoF and quality vector.

Thus, the possible translation of diagnosis into quality and output data becomes obvious. In the fault free state, the EPS may be able to deliver rated output power with minimum uncertainty, hence the minimum uncertainty in the quality data. The second case shows the shutdown of one battery due to internal faults. Thus, the SoF value will be reduced by 25 % and certainty of this state is clear. In the third case however, a faulty temperature sensor has been diagnosed. Thus, the performance of the system remains unaffected. Nevertheless, the quality data will show increased uncertainty. This way, the remaining risk of a false diagnosis about the temperature sensor, whose data information is critical for safe battery operation, is mirrored in the quality data.

4 Future Work

This paper has given insight in to a concept for inner state evaluation of an EPS for an automated vehicle by EEM. Thus, additional work has to be done before being able to implement the proposed system.

Therefore, the next step will be the setup of a simulation model of the EPS system. This will include the simulation of different faults that have been mentioned in this work. At the end of this simulation step, a first test set will be available that shall be used to train a machine learning algorithm, that itself has to be validated with another test data set.

The strategy application management needs to be developed in detail. Furthermore, a method needs to be defined, that incorporates quality data for the SoA environment out of the diagnosed inner state. This will require studying implications of different approaches for quality data computation on the overall vehicle system.

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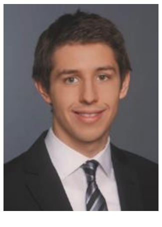

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