

Development and Validation of an Energy Management System for an Electric Vehicle with a split Battery Storage System

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Abstract - Within the project 'e performance' supported by the German Ministry of Education and Research (BMBF) an electric vehicle, powered by two lithium-ion battery packs of different capacity and voltage has been developed. The required Energy Management System (EMS) in this system controls the current flows of both packs independently by means of two individual dc-dc converters. It acts as an intermediary between energy storage (battery management systems-BMS) and the drivetrain controller on the vehicle control unit (VCU) as well as the on-board charger. This paper describes the most important tasks of the EMS and its interfaces to the BMS and the VCU. To validate the algorithms before integrating them into the vehicle prototype, a detailed Matlab / Simulink-model was created in the project. Test procedures and results from the simulation as well as experiences and comparisons from the real car are presented at the end.

Keywords: Electric vehicle, Li-Ion battery system, Energy management system, Battery management system

1. Introduction

Energy management systems (EMS) for vehicular applications control and optimize the power flow between electric consumers and power sources in the system. The strategies primarily aim at maximizing driving range and power of the vehicle. In case of more than one energy source in the vehicle, the EMS ultimately becomes more complex, as there are more control options. Previous publications consider hybrid energy storage systems consisting of batteries and ultra-capacitors [1] or batteries and fuel cells [2]. These systems are designed to gain best performance out of a high energy density source combined with a more powerful peak power device. For full electric vehicles such a system has not been brought to market yet. Most electric vehicles (EVs) that can be purchased today are powered by one single lithium-ion battery pack, for example the Mitsubishi i-MiEV [3].

A battery pack internally consists of a series connection of single battery cells to reach a voltage level required by the power electronics and the engines. High voltages are preferred to minimize currents and so the required copper in the vehicle. In some cases parallel connection of more than one string are used to extend the capacity [4]. An alternative approach is to divide the desired battery capacity into more than one battery unit. This results in

greater flexibility when distributing the battery in the vehicle chassis and brings further advantages which will be discussed later on. The simplest way is to hardwire the single packs in a parallel or a series connection, as accomplished in [5].

This paper presents a vehicle concept which has been developed in cooperation with Audi AG, Audi Electronics Venture GmbH, Bosch, Bosch Engineering Group and RWTH Aachen University. The battery system is made from two individual battery packs located at different places in the vehicle. Furthermore the packs have different voltage and capacity to fit best into the available space. The battery packs are connected via dc-dc converters to the drive train. The project aims at investigating several innovative concepts and approaches in the electrical drive train which may improve future EVs by means of driving performance, safety, driving range, reliability and costs. The construction of the prototype vehicle was completed in the end of 2012 allowing test drives in the real car.

2. Drivetrain and Battery Topology

The developed car is based on the Audi R8 chassis and is driven by three electric machines which provide a peak power of 50 kW each. One drives the front axle differential and two machines independently propel the rear wheels. The drivetrain is powered by two completely independent Li-Ion battery packs which are housed in the tunnel between the two seats and in the rear of the car (see Fig. 1). Each of the two battery units is equipped with its own battery management system (BMS) and is electrically connected to the HV-DC link via an independent

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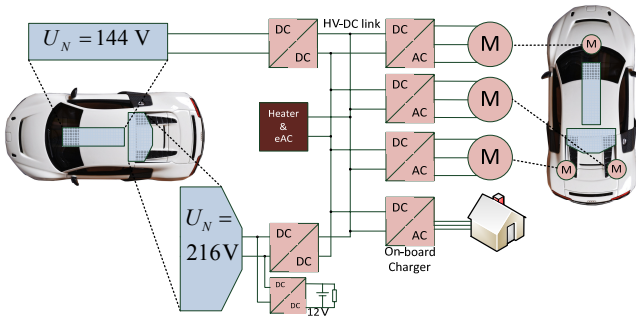


Fig. 1. Topology of HV system

dc-dc converter. The battery system offers a combined capacity of 40 kWh. As the car can be driven with one pack only in a reduced power mode, this concept directly leads to a higher overall reliability besides offering more flexibility on placing the battery in the car and on choosing the voltage level of the battery units. A failure in one pack does not affect the remaining pack. Due to the different available installation space, the battery packs consist of a different amount of cells which leads to unequal nominal voltages. The battery packs are designed and located in order to maximize crash safety [6]. Also connected to the DC link are the three traction inverters, an electric heat pump, an electrical air condition compressor and a 20 kW on-board battery charger. Ultimately a more complex and adapted EMS is required for such a vehicle concept.

3. Description of the Energy Management System

The major task of the EMS is to control the power flow between the batteries and the drivetrain during acceleration, braking and recharging the batteries from the grid. In charging mode the EMS controls the individual battery charging currents. A further task of the EMS is the adaption of the voltage-level of the HV-DC link to the speed dependent voltage requests of the inverters in order to minimize switching losses in the converters [7]. To prevent the drivetrain from overloading the batteries, the EMS also calculates a power limit which must not be exceeded while accelerating or braking. The above mentioned functions are described in the following chapters.

The EMS algorithms are executed on a rapid prototyping electronic control unit (ECU) as this guarantees maximum flexibility during software development in Matlab / Simulink. The ECU also provides a CAN bus interface, which is used by the EMS and the VCU to communicate with the external ECUs (see Fig. 2).

3.1 Calculation of the maximum propulsion power

Li-ion batteries require a strict compliance with the voltage limitations. This applies for the upper voltage limit,

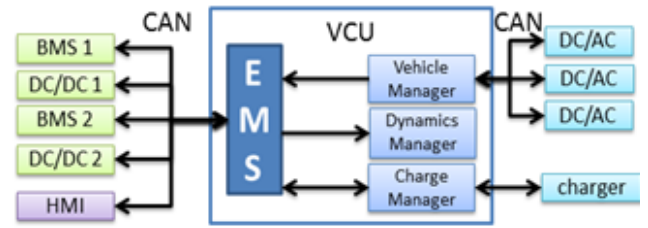


Fig. 2. ECU communication structure

which must not be exceeded while charging the battery, as well as for the lower voltage limit in case of discharging. Exceeding these boundaries will lead to physical degradation and can cause severe damages up to fire or explosion [8]. Mainly due to these voltage limitations, both batteries are subject to certain power limitations. In the chosen HV topology it is crucial to avoid voltage breakdowns in the HV-DC link, which might happen in case the inverters require more power than the batteries can provide. To avoid such a failure, the EMS limits the maximum power that can be used for acceleration or regenerative braking by the vehicle dynamics manager (VDM). To guarantee the maximum possible power in each time step, the EMS continuously receives information from the two battery management systems (Fig. 2). The BMS in each battery pack calculates the maximum power of the corresponding storage unit ($P_{MaxDisch}$) that can be delivered to the HV-DC link as well as the maximum power, the battery can absorb from the DC link ($P_{MaxCharge}$). These calculations follow the maximum current rating of the converter and the above mentioned limits of the battery cells and are based on self-adapting onboard diagnostic algorithms, as described in [9] in order to determine the state of the battery for further power estimation [10]. A complex thermal battery model was developed in the project to support the algorithms with accurate temperature data [11]. Additionally, the EMS provides a maximum duration for which the currently requested power may be supplied by the battery system, considering a time prediction of available power from each BMS ($t_{MaxCurrentPower}$). This is based on algorithms as described in [12]. The time prediction allows the VDM to prevent the drivetrain from sudden power drops which may result in decreasing acceleration and could therefore lead to safety concerns, e.g. during an overtaking maneuver. The maximum power ($P_{maxProp}$), which is available for acceleration is calculated using the maximum discharge power of the batteries ($P_{MaxDischRear}$, $P_{MaxDischTunnel}$) and the power of the auxiliaries connected to the DC link (electric air-conditioning, heater P_{Aux}) as

$$P_{maxProp} = (P_{MaxDischRear} + P_{MaxDischTunnel}) - P_{Aux}. \quad (1)$$

This information is then transferred to the VDM. The maximum power, that can be used for recuperation is

calculated following the sum of the maximum charging powers of each battery unit plus the auxiliary power consumption.

3.2 Power distribution to the batteries

In normal operation mode there are two battery units that may provide the propulsion power. For most situations the maximum power of one single pack would be sufficient for feeding the traction inverters with power. Nevertheless, using only one pack at a time is not the optimum way by means of system lifetime and reliability. When accelerating very fast, the driver may demand more power, than one pack can deliver. The chosen strategy and the implementation of the power distribution are described in this chapter.

First the function collects all power demands of the three inverters and the auxiliaries to determine the effective total power demand for the two storage units. The EMS uses this information to distribute the requested power to the battery packs by controlling the two dc-dc converters. The control of the power distribution is implemented by regulating the battery currents through one CAN message ($p_{PowerDistrib}$) which specifies the proportional power distribution in percent between the two packs (see Fig. 3). Besides the actual distribution, the EMS determines which of the two dc-dc converters operates as master and therefore regulates the DC-link voltage. The master feeds as much power into the DC link, as the EMS requests and simultaneously sends a current demand (I_{Slave}) to the second converter to set its percentage of the total power. This results in an effective power provided by the first converter assigned as master P_{Master} and respectively the power of the second converter P_{Slave} . Equations (2) and (3) show, how the propulsion power P_{Prop} is distributed to the two batteries.

$$P_{Master} = P_{Prop} \times p_{PowerDistrib} \quad (2)$$

$$P_{Slave} = P_{Prop} - P_{Master} \quad (3)$$

The master / slave assignment of the dc-dc converters can stay unchanged during driving but in case of a battery failure or operation with only one battery pack the EMS assigns the master task to the remaining battery unit and

converter. A change during operation requires the demanded propulsion power to be very low (e.g. vehicle is not driving). Otherwise a voltage breakdown in the DC link might occur. As the total power demand may be subject to high dynamic variation and the EMS' adaption of the power distribution is only updated with 1 kHz frequency, the actual power at the converters varies slightly from the demanded values when the controllers regulate the DC link voltage. The power distribution stays constant until the dc-dc converters receive the next distribution values from the EMS.

As mentioned above, the two battery packs consist of the same type of battery cells. Thus, the developed power distribution algorithm primarily aims at equalizing the states of charge (SoC) and available power for the following time period in both battery units. This strategy guarantees a maximum power capability of the system even at the lowest SoCs which is desired in the developed sports vehicle. Furthermore the two battery units suffer from approximately the same rate of degradation using this distribution algorithm. A reason for having uneven states of charge in the two packs might be due to unequal self-discharge rates based on cell production distribution or different compartment temperatures. The calculation of the power distribution is based on three independent summands (s_1, s_2, s_3) adding up to the power distribution.

$$p_{PowerDistrib} = x_1 \times s_1 + x_2 \times s_2 + x_3 \times s_3 \quad (4)$$

Considered individually, the summand s_1 would lead to a balanced current distribution in both packs so that the states of charge (SoCs) change likewise. The unequal terminal voltages of the two battery units are taken into account in the calculating of this component. The task of the variable s_2 is to balance the SoCs in both packs. It shifts the power distribution more or less to the battery unit with the lower SoC, depending on the power direction (accelerating or recuperating). The component's absolute value increases with a rising difference between the SoCs of the batteries so that the pack with the higher state of charge feeds a greater portion of the propulsion power. Its value is also depending on the absolute value of the SoC in order to accelerate the equalization when the battery approaches its end of discharge. The third component s_3 is similar to the second one but aims to equalize the predicted maximum power times $t_{MaxCurrentPower}$ of the two battery packs. Thus it changes the power distribution in a way that the pack with the lower $t_{MaxCurrentPower}$ prediction is loaded with less power. Such a situation may occur if one unit has a significantly higher temperature than the other one which would lead to an earlier temperature affected power reduction of this pack. In principle it is possible, that s_2 and s_3 have opposite signs, which means that they would influence the power distribution in opposite directions. The component s_3 is more critical and much more dynamic than s_2 (equalization of the SoC). Thus s_3 is prioritized

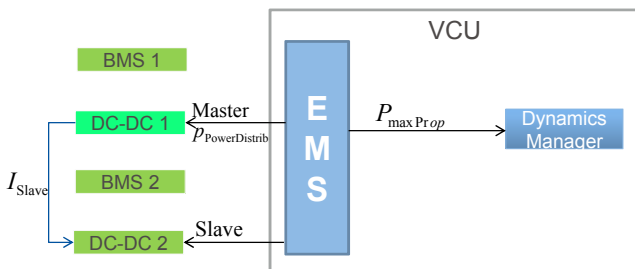


Fig. 3. Control principle of the dc-dc converters

by the algorithm, meaning that the ability to get power out of both battery units is privileged over having an even state of charge in both packs, if it is necessary.

After calculating the three components, they are weighted with variable factors (x_1, x_2, x_3 in (4)) before being added up to the final power distribution. The weighting factors were tuned using the vehicle model and many representative driving cycles so that they generate an appropriate distribution which supports the driver's requirements and simultaneously is beneficial for the battery-lifetime.

To minimize switching losses in the converters, the EMS disables one of them in times of low power operation by assigning the complete power to one of the two converters. This enables the inactive converter to switch into a power saving standby-mode. Nevertheless this mode is only activated if the drivetrain power has been below a certain threshold for at least 0.5 seconds so that the control of the DC link voltage is not overstressed when driving the vehicle in the margin around the threshold. The occurring imbalance of SoCs in the battery packs which results from using only one dc-dc converter is leveled later on. To further support the SoC equalization strategy, the EMS disables the converter of the battery having the lower SoC.

3.3 Charge control

Two charging modes were implemented in the system. The driver can either instantaneously charge the batteries when connected to the power grid ("normal charging") or define a certain point in time, when he expects the batteries to be fully charged. This may be the time he wants to continue his journey (e.g. the next morning). The latter method is called "time controlled charging" and can extend the batteries' lifetime since the EMS initializes the charging as lately as possible. Thus, unnecessary time periods at high SoCs are minimized which lead to accelerated degradation of Li-Ion batteries [13]. The time controlled charging is a requirement for vehicle to grid concepts (V2G) in the future as explained in [14] and in [15].

In time controlled charging mode, the EMS determines the charge start time by establishing a bidirectional communication with the battery management systems (see Fig. 4). The EMS requests an individual time prediction, how long the full charging would take with a particular percentage of the available charging power from each battery. If the two predictions differ significantly, the EMS redistributes the charging power and starts another inquiry (State "Pre-Charge preparations" in Fig. 4). The aim of this process is to iteratively find an identical charging duration for both battery packs, even if they have unequal states of charge and charging power capabilities. This method finally leads to the shortest possible charging time.

In contrast to the driving mode, the EMS does not calculate a power distribution for the charging power. The

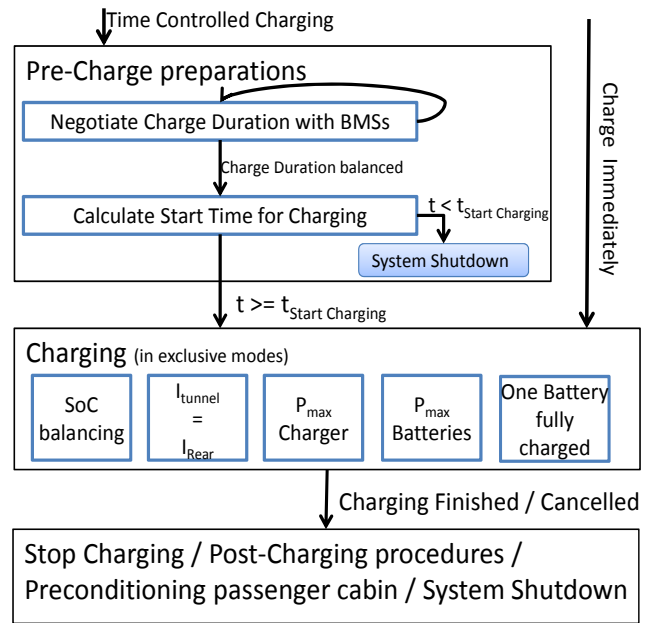


Fig. 4. Flow Chart of Charging Process

on-board charger operates in constant voltage mode so the charging power being fed into each batter pack has to be actively drawn from the DC link. That is why the EMS computes a battery charging current for each pack. The algorithm simultaneously aims at maximizing the total charging power and to equalize the state of charge in both packs. This leads to a minimum overall charging time. Differing from the other EMS functions, the charging algorithm is implemented in Matlab / Stateflow. This reflects the fact, that in charging mode the EMS passes through several different states which influence the charging currents of the batteries. For example, in case of imbalanced SoCs, the EMS tries to feed all the available charging power into the pack with the lower SoC. If the battery cannot use the complete charging power, the remaining part is consequently fed into the other pack to maximize the used charging power and therefore minimize the charging duration. Further states during the charging process are, that the charging power is limited by the batteries (most likely, when they are both in constant voltage phase), that one of the packs is completely charged and finally that both units have reached full charge state (i.e. at the end of charging process). A further reason for using Stateflow is, that the interaction between the battery management systems and the VCU prior to the actual charging process is complex (Fig. 4 - state "Pre-charge preparations") and thus easier to implement in a state machine than in Simulink.

It is not unlikely that in time controlled charging mode the vehicle rests for several hours before the batteries are charged (e.g. over night). This implies that some conditions can change significantly between the first calculation of the charging start time and the actual start of charging. For example, a drop of ambient temperature requires a

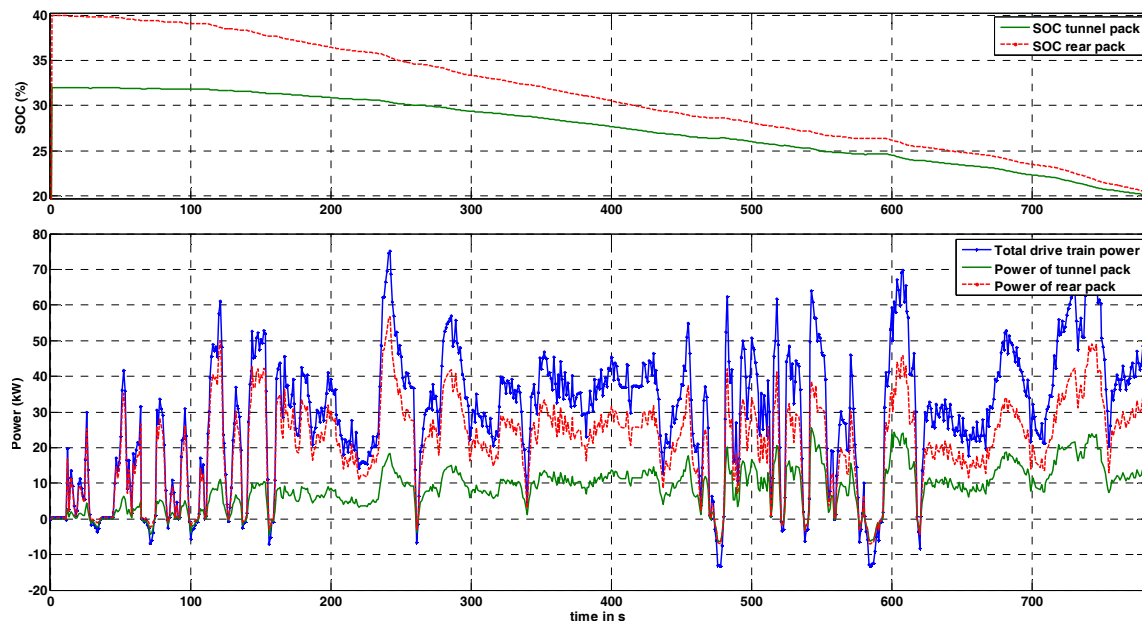


Fig. 5. Equalization of States of Charge during a driving scenario (simulation)

preheating of the batteries before electrically charging them. To take account of changing conditions, the system wakes up in regular time intervals to recalculate the charging start time with the current conditions. If the time of charging is not reached yet, the system shuts down again to save energy after each recalculation.

4. Software Validation in a Vehicle Model

Besides the advantage, that software failures do not lead to hardware damages when run in a model, a model based testing environment ensures equal accuracy of input conditions every time, the test is conducted. This is usually not the case when executing software in the target system. Especially for debugging and tuning this possibility proved to be of great importance. In the following, test results from the simulations are presented correlating to the above presented EMS functions.

4.1 Validation of EMS functions in driving mode

Several driving cycles were used for testing driving related functions of the EMS software. Most important were the “ARTEMIS” driving cycles which are more dynamic than NEDC (New European Driving Cycle) and are therefore said to deliver the more realistic consumption values [16].

During the tests it was of particular interest, whether the EMS meets its demands for an optimum power distribution under all circumstances. As an example Fig. 5 shows, how imbalanced SoCs in the packs (upper plot) are equalized in relatively short time to assure continuous power supply from both packs even at low states of charge. Nevertheless

the driving power (blue curve in bottom plot) is distributed in a way (red and green curve in bottom plot) that none of the battery packs is stressed to its maximum which may lead to unnecessary heating of a battery and therefore increase the ageing effects of the battery cells. What can be observed from the lower plot in Fig. 5 is, that at the beginning of the shown driving cycle the requested propulsion power is small enough so that it can be almost completely delivered by the pack with the higher SoC (in this case the rear pack). When the vehicle is in recuperation mode ($P < 0$) the EMS attempts to feed all the kinetic energy into the tunnel pack. If the recuperation power exceeds the beneficial charging power of the pack, the remaining power is fed into the other pack to avoid unnecessary battery stress. The more the two SoCs are balanced, the more the power is distributed equally to both packs. Note that the two packs have the same Ah-capacity but unequal nominal terminal voltages so that the power is not distributed 50 / 50 in case of balanced SoCs - only the battery currents are identical then (not shown in this figure).

As mentioned in the beginning, the redundancy in the battery system is a great advantage of the vehicle concept, compared to conventional EV battery systems. While offering a higher availability, a discontinuation of one pack must be handled correctly by the EMS and the VCU. Fig. 7 shows a test scenario for this functionality in which one of the battery packs fails due to an internal hardware error. In the simulated scenario the car accelerates with maximum power (upper plot) to top speed when suddenly a cell voltage sensor in the rear pack fails. The BMS immediately measures zero volts on this sensor (2nd plot from top). In the simulation, the BMS is forced to set the maximum power allowed for this battery to zero (red dashed line in 3rd plot). Such an error is handled differently by the BMS

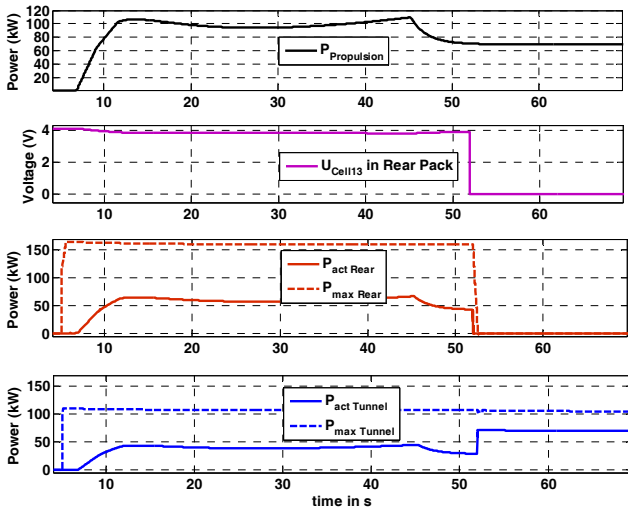


Fig. 6. Simulated reaction to a hardware failure in one battery pack while driving

in the vehicle since the battery voltage is measured redundantly and can be extrapolated for a short time. The curves in Fig. 6 show that the EMS can handle such a dynamic process by assigning the complete power to the still available tunnel pack. In this scenario the driver would not even notice the outage of the rear pack as the full propulsion power can be delivered by the remaining pack. This may be different if the power of the packs is more limited (e.g. in case of lower SoC or significantly higher cell temperatures).

4.1 Validation of EMS charging function

Related to the charging functions, the simulations had to prove that the EMS distributes the power as intended during the actual charging process. On the other hand the negotiation processes for the time controlled charging,

described in chapter 0 had to be validated.

Fig. 7 shows the actual charging part of a time controlled charging scenario. The charging was programmed to be completed at 6:30 am. As described above, the latest start of charging is negotiated by the EMS and the two battery management systems to complete charging just in time. The tunnel pack has a higher state of charge than the rear pack (upper plot) before the charging is initiated. Thus, the EMS starts charging the pack with the lower SoC at its maximum power (4:46 am until 4:54 am). The figure also shows that the maximum power which can be delivered by the charger is completely fed into the rear pack (3rd plot from top) - there is no power left for charging the tunnel pack in this case. Note that the voltage of the HV-DC link differs from the battery voltages so that

$$I_{\text{Charger}} \neq I_{\text{RearPack}} + I_{\text{TunnelPack}} \quad (5)$$

As soon as the SoCs are balanced (4:54 am), the EMS switches into the charging mode in which both packs are charged with the exact same current (2nd and 3rd plot). Thus, the packs approach their individual upper voltage limit at the same time. At 6:02 am the charging mode changes again because both batteries have to be charged with constant voltage from then on. That is why the charger current decreases (lower plot). As soon as both batteries have approached the upper SoC limit set by the software, the EMS stops the charging process (6:10 am).

Fig. 8 shows the result of a scenario with driving periods, normal and also time controlled charging. It starts with a 35 km long trip which discharges the previously fully charged battery system down to 80 % SoC. The upper plot shows the combined state of charge of both battery packs which is calculated by the EMS and presented to the driver in the dashboard. After the drive, the vehicle is connected to the grid and the driver chooses the “normal” charging mode. Thus, the EMS immediately initializes the charging

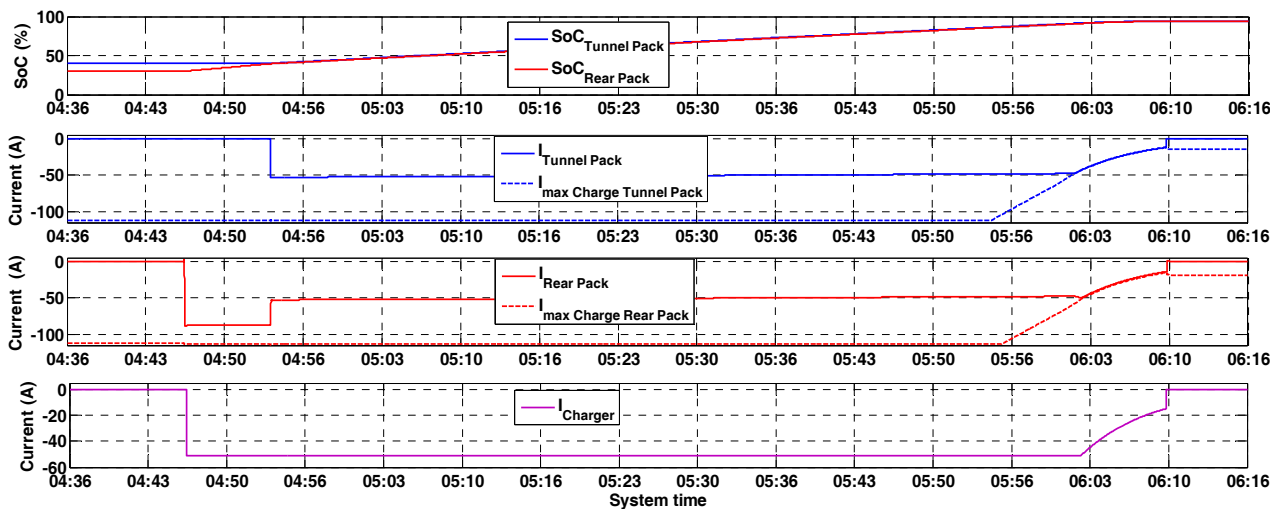


Fig. 7. Charging of the batteries with initially imbalanced states of charge (simulation)

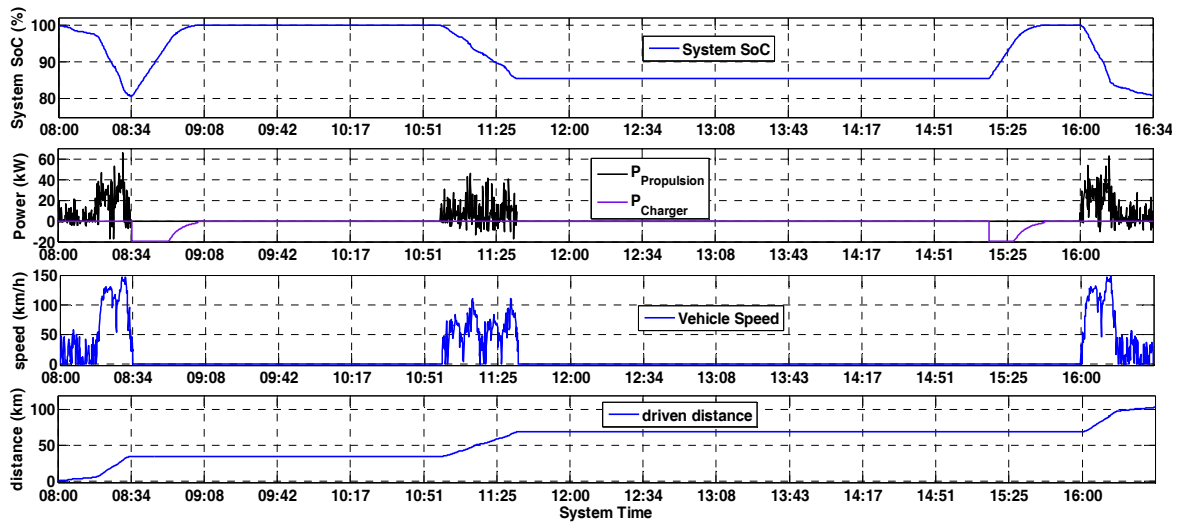


Fig. 8. Simulation of a complete day with driving and charging

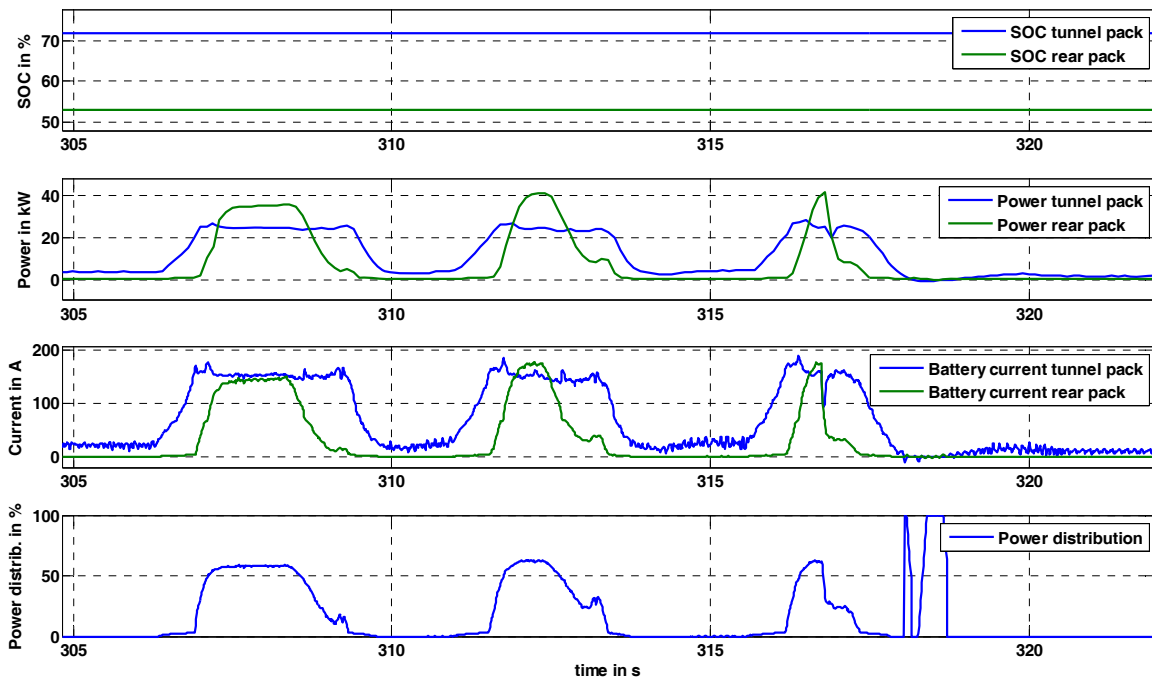


Fig. 9. Test drive on a roller dynamometer with different SoCs in the two battery packs

process. Thirty minutes later the batteries are fully charged again and the EMS requests the VCU to shut the system down. At 11:00 am the vehicle is used for an overland journey. Afterwards connected back to the grid, the driver chooses the time controlled charging mode and sets the desired end of charge time to 4 pm. As can be seen from the second plot in Fig. 8 the EMS initiates the charging process at 3:15 pm which was negotiated with the two BMS in the time before. The batteries are then fully charged at 3:40 pm to leave a certain safety margin in case the charging time prediction is not accurate or the driver wants to leave earlier. Finally at 4 pm the journey is

continued with a fully charged battery system.

5. Results and Experiences from the Vehicle

At this juncture a few measurements from the real vehicle are available for comparison with the simulation and further analyzing. Fig. 9 shows a short excerpt from a measurement of the vehicle on a roller dynamometer to validate the power distribution in the real system. The dc converter connected to the rear pack is acting as master in this situation. A power distribution (bottom plot) of 0 %

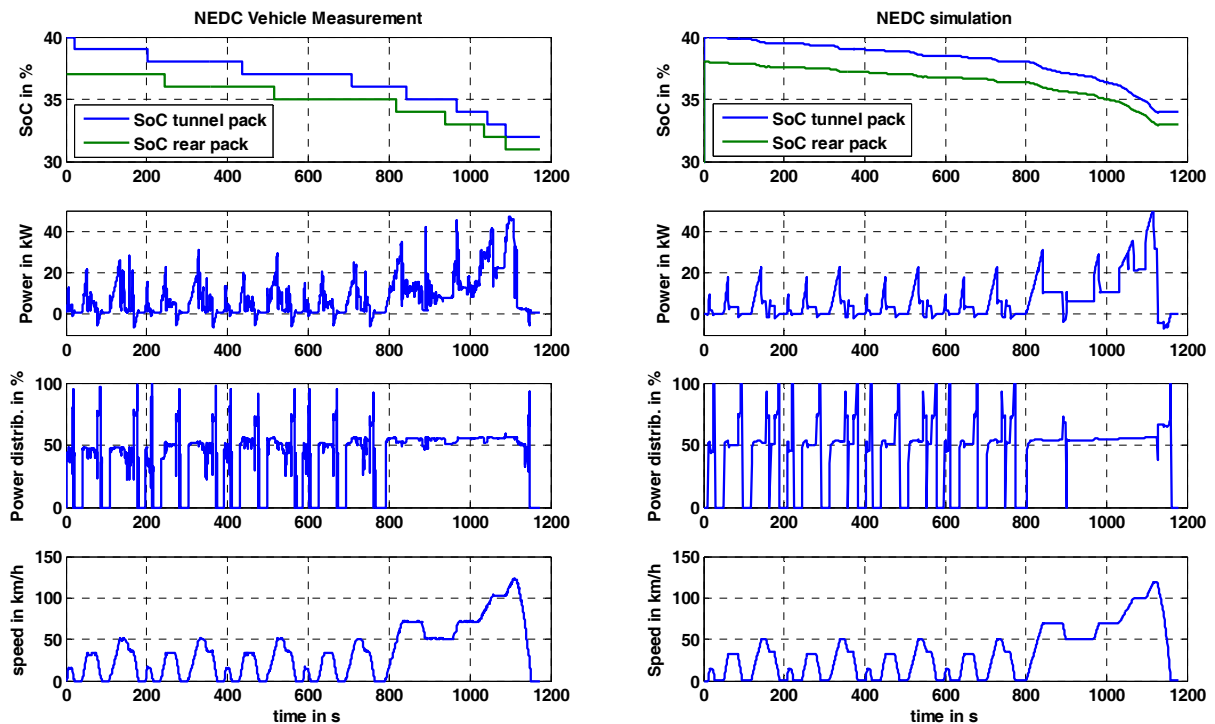


Fig. 10. Comparison of simulation result (right) to real vehicle measurement (left) in NEDC driving cycle

therefore means that the rear pack is not used, whereas 100 % means that the complete power is drawn (or loaded) from (into) the rear pack. Due to the testing procedures in advance on this day, the states of charge in the two battery packs differ significantly - the SoC of the tunnel pack is about 10 % higher than the SoC of the rear pack (uppermost plot). One can observe how the driver accelerates three times using a peak power of about 65 kW in the rear axle machines (sum of battery powers is 2nd plot from top). In these moments of high power consumption, the EMS tries to equalize the stress for the batteries by setting the power distribution (bottom plot) in such a way, that the battery currents are almost identical in both packs (3rd plot from top). During the remaining time periods of less power consumption, the EMS follows the SoC-equalizing strategy. As the tunnel pack has the higher state of charge, it is preferentially used, whenever the power is not too high to be provided by only one single pack (first and last section of the measurement). In those instances, when the power distribution is set to 100 %, a slightly negative propulsion power occurred meaning that the inverters feed power back into the batteries. Like explained above, the EMS tries to charge this recuperation energy completely into the pack with the lower state of charge (the rear pack in this situation). The noticeable high frequent current ripple (3rd plot) is caused by noise of the current sensor.

A comparison between the simulation results and a measurement from the real vehicle, driving the same cycle is shown in Fig. 10. The left column of the figure shows

the results from the vehicle on the roller dynamometer (SoC of the battery packs, total drivetrain power, EMS power distribution value and vehicle speed). The right column displays the according signals from the simulation. The battery starting conditions of the simulation (state of charge and temperature) were chosen according to the real world test to validate the simulation. The similarity between the simulation results and the measurement shows the accuracy of the simulation. An energy of 2.2 kWh is needed for the NEDC driving cycle in the simulation, whereas the real vehicle uses a total energy of 2.6 kWh. Nevertheless, in the simulation a higher peak power is needed for the driving cycle. This difference may be explained with a slightly different parameterized model, compared to the roller dynamometer (friction, front area, drag coefficient). Note that the SoC in the vehicle is output in 1 % resolution.

6. Conclusion and Outlook

The implemented EMS described in this paper has been extensively validated in a vehicle model in many different scenarios. The power distribution in driving mode fulfills the requirements under all test conditions (different driving cycles, initial SoC difference, and battery cooling performance and temperatures). The requested propulsion power is always delivered and distributed in a way that the driver does not notice the allotted battery architecture and simultaneously the batteries are cycled in the gentlest way.

This function has also been validated in the real vehicle. The first tests showed that the parameterization of the control parameters, which had been fine-tuned for the simulation model also fit well for the system in the real vehicle.

In the simulations the charging algorithm has been proven to fulfill all the requirements. The batteries are charged as fast as possible with the deliverable power from the on-board charger. In time controlled charging the start of the charging process is postponed as long as possible, to preserve the cells from unnecessary aging at high states of charge.

The obtained results are very promising and already show the advantages of the distributed battery architecture (e.g. lower risk of car breakdown because of complete redundancy). Through the control of the EMS, the two packs act as one integrated battery system that guarantees maximum power even down to the lowest state of charge but gives a significant higher redundancy in case of a battery or converter failure. They also prove that the challenges have been mastered: The driver is not stressed with any technical details about the individual battery packs and the distribution of the power.

Future implementations may include features like vehicle-to-grid functions. By providing an interface to the user to set the time of the next journey, most constraints on vehicle side are already met by the current system and EMS. Another interesting research possibility is the usage of different battery cell types in the two battery packs. One unit equipped with high energy cells, whereas the other pack consists of high power cells may lead to a more powerful system.

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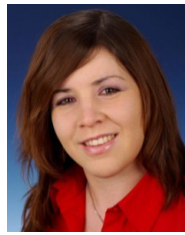
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