

Article

Directly Interconnected High-Energy and High-Power Battery Packs

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Abstract: Designing battery packs is a trade-off between power capability and capacity. Often, high power is only desired for short periods; otherwise, high capacities are preferred. To meet these requirements, hybrid packs comprising high-power and high-energy batteries can be used. However, a major drawback of these systems is the need for additional direct current to direct current converters, which increase the complexity, weight, and cost. By directly interconnecting high-power and high-energy battery strings in parallel, the current distribution is determined exclusively by Kirchhoff's laws, which can lead to the overloading of individual batteries and thus to damage or dangerous failures. To overcome these problems, we developed a layout and control algorithm for directly interconnected packs that keeps them in a safe state by solely controlling the external power, which is governed by two additional requirements. These keep the discharge current of the high-energy element below the maximum charge current of the high-power element and the charge current of the high-energy element below the maximum discharge current of the high-power element while the pack is discharging or charging, respectively. As a proof of concept, a directly interconnected lithium-ion battery pack was successfully designed using the electrochemical simulation software Battery Simulation Studio 2021, which was tested and integrated into a Audi A3 cabriolet.

Keywords: directly interconnected device; electromobility; hybrid battery packs; lithium-ion battery; power tools



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1. Introduction

Finding an appropriate battery for a certain application is often a challenging task. In principle, batteries can either deliver a high power or store a high amount of energy, but many applications require power sources with more complex properties. In power tools, electric vehicles, or certain grid applications, for example, high power capabilities are only required for short periods of time; at other times, a high energy density is desired. Electrochemical energy storage packs with a combination of high-power (HP) and high-energy (HE) elements can be used to meet those particular requirements, which, at the same time, promise a long lifespan and reliability [1–5]. A major drawback of these systems is the need for additional direct current to direct current (DC/DC) converters, which make them more expensive, more complex, and heavier. A direct parallel electrical interconnection can overcome these problems, but this is challenging, as compensating currents between components with different properties cannot be controlled. If the currents exceed the specifications of the electrochemical cells, heavy damages or even fatal failures may occur. In this paper, we present a layout for a directly interconnected battery pack that remains in a safe state by only controlling the external current with a special algorithm. The latter was mathematically validated independently from the operating condition, in order to ensure safe operation under any circumstances. As the distribution of current cannot be controlled from outside and the algorithm introduces certain restrictions for the operation, it is important to choose the right pack design in order to achieve the desired

capabilities in terms of power and capacity. For applications with short power peaks and long rest phases, a simple linear approach is sufficient. Otherwise, more sophisticated battery simulation tools, such as Battery Simulation Studio (BaSiS), are needed. For a manufacturer of sportive electric vehicles, a directly interconnected lithium-ion battery pack was successfully designed, built, tested, and integrated in a converted Audi A3 cabriolet [6]. For the given weight and power requirements, the nominal capacity of the hybrid pack is approximately 13% higher than the best non-hybrid pack. Furthermore, the results clearly show that directly interconnected battery packs are safe to operate if a proper design and control algorithm are chosen.

2. Methods

Designing an energy storage device with direct electrical interconnections between parallel electrochemical cells with significantly different properties is complex. Since there are no rectifiers or switches to influence the currents flowing through the electrical network, it is of crucial importance to carefully design and control the system in order to achieve the desired performance and to ensure safe and reliable operation. Therefore, we developed a special algorithm which safely keeps each individual unit within its specific limits under any circumstances by just controlling the external current, which is presented in this section. First, some fundamental theoretical considerations about directly interconnected batteries are presented, leading to the requirements for safe operation. In addition to Kirchhoff's laws, these requirements have an important impact on the design of such a system, which is discussed in Section 4. All symbols used in the following section (description and unit) can be found in Table A1 in Appendix A.

In directly interconnected electrochemical energy storage devices, only the total current can be controlled by external rectifiers, but there are no means to influence the distribution of currents between strings electrically connected in parallel. Therefore, for safe and reliable operation, a suitable control mechanism that keeps the individual loads of each string and battery within the respective safety limits is essential. In order to derive a general relation for the individual currents of each sub-unit of the circuit with respect to the total current, we start with the safe assumption that the derivative of the voltage U_j with respect to the current I_j for each battery j is as follows:

$$\frac{dU_j}{dI_j} \equiv U'_j > 0 ,$$

independently of the type and state in terms of state of charge (SOC), temperature, pre-treatment, aging, etc. Please note that a positive current value represents charging and a negative one represents discharging. First, we consider the simplest case of two batteries connected in series. Kirchhoff's laws apply to the total and individual currents and voltages as follows:

$$\begin{aligned} I_{\text{tot}} &= I_1 = I_2 , \\ U_{\text{tot}} &= U_1 + U_2 . \end{aligned}$$

Taking the derivative with respect to the total current I_{tot} , we obtain the following:

$$\begin{aligned} \frac{dI_{\text{tot}}}{dI_{\text{tot}}} &= \frac{dI_1}{dI_{\text{tot}}} = \frac{dI_2}{dI_{\text{tot}}} = 1 , \\ \frac{dU_{\text{tot}}}{dI_{\text{tot}}} &\equiv U'_{\text{tot}} = U'_1 \frac{dI_1}{dI_{\text{tot}}} + U'_2 \frac{dI_2}{dI_{\text{tot}}} = U'_1 + U'_2 \end{aligned}$$

which leads to the following:

$$\frac{dI_1}{dI_{\text{tot}}} > 0, \quad \frac{dI_2}{dI_{\text{tot}}} > 0, \quad U'_{\text{tot}} > 0 .$$

In a similar way, two batteries, which are connected in parallel, fulfill the below equations:

$$I_{\text{tot}} = I_1 + I_2 ,$$

$$U_{\text{tot}} = U_1 = U_2 .$$

The derivative with respect to the total current I_{tot} is as follows:

$$\begin{aligned} \frac{dI_{\text{tot}}}{dI_{\text{tot}}} &= \frac{dI_1}{dI_{\text{tot}}} + \frac{dI_2}{dI_{\text{tot}}} = 1 , \\ \frac{dU_{\text{tot}}}{dI_{\text{tot}}} &= U'_1 \frac{dI_1}{dI_{\text{tot}}} = U'_2 \frac{dI_2}{dI_{\text{tot}}} = U'_2 \left(1 - \frac{dI_1}{dI_{\text{tot}}} \right) \end{aligned}$$

which leads to the following:

$$\frac{dI_1}{dI_{\text{tot}}} = \frac{U'_2}{U'_1 + U'_2} > 0, \quad \frac{dI_2}{dI_{\text{tot}}} = \frac{U'_1}{U'_1 + U'_2} > 0, \quad U'_{\text{tot}} > 0 .$$

Therefore, we obtain the following:

$$\frac{dI_j}{dI_{\text{tot}}} > 0$$

which applies to any battery of such units. Furthermore, using $U'_{\text{tot}} > 0$, the basic assumption for the above derivations also applies to the total voltages. Hence, we can recursively add further batteries and sub-units in parallel and in series to any arbitrary network and still observe the same behavior, as follows:

$$\frac{dI_j}{dI_{\text{tot}}} > 0 \quad \forall j$$

and

$$\frac{dU_j}{dI_{\text{tot}}} = U'_j \frac{dI_j}{dI_{\text{tot}}} > 0 \quad \forall j . \quad (1)$$

The implications of (1) are crucial in terms of controlling the individual loads of each string and battery. To make this more clear, the simple case of a direct parallel connection of a high-energy and a high-power lithium-ion battery is considered. Such a system was simulated with BaSiS, the model specifications and details of which are provided in Section 3. At the beginning of each simulation, the system is at equilibrium with a SOC of 50% and a temperature of 25 °C. In the first set of simulations, the batteries are discharged at a rate of 6C for one minute before the total current is rapidly set to a new certain value I_{tot} , which leads to a different distribution of currents between the two batteries. In the second set, the system is charged at a rate of 3C for one minute, before the total current is again rapidly changed to a certain value. Figures 1 and 2 show the current distributions I_{HE} and I_{HP} for both cases with respect to I_{tot} .

Note that, although the processes in this particular case are predominantly governed by linear effects, the dependencies are generally non-linear. It can be clearly seen that I_{HE} and I_{HP} increase strictly monotonically with I_{tot} , as expected from the theoretical derivation. Furthermore, the individual currents at $I_{\text{tot}} = 0$ are $I_{\text{HE}} = -I_{\text{HP}} \neq 0$. Due to the different power capabilities, capacities, and open-circuit voltage profiles, compensating currents occur while the system experiences an external current. These are still present when the external current vanishes ($I_{\text{tot}} = 0$) and almost exponentially decrease on timescales of several seconds up to a few minutes. Since there is no way to control this process in a directly interconnected device, a suitable control mechanism of the total current must ensure that the inhomogeneities between the different batteries do not become too large. As the below is true:

$$\frac{dI_{HE}}{dI_{tot}} > 0 \quad \text{and} \quad \frac{dI_{HP}}{dI_{tot}} > 0,$$

both parts are always in a safe state when the following is correct:

$$\begin{aligned} I_{HE}^{\min} &\leq I_{HE}(t) \leq I_{HE}^{\max}, \\ I_{HP}^{\min} &\leq I_{HP}(t) \leq I_{HP}^{\max}, \\ -I_{HE}(t) &\leq I_{HP}^{\max} \end{aligned} \quad (2)$$

for $I_{tot}(t) \leq 0$ and for the following:

$$\begin{aligned} I_{HE}^{\min} &\leq I_{HE}(t) \leq I_{HE}^{\max}, \\ I_{HP}^{\min} &\leq I_{HP}(t) \leq I_{HP}^{\max}, \\ -I_{HE}(t) &\geq I_{HP}^{\min} \end{aligned} \quad (3)$$

for $I_{tot}(t) > 0$ at any time t , where $I_{HE/HP}^{\min}$ and $I_{HE/HP}^{\max}$ are the highest discharge and charge currents allowed for the respective batteries. Note that $I_{HE/HP}^{\min}$ has a negative value and $I_{HE/HP}^{\max}$ a positive one. Due to the strict monotonous behavior of the total pack current on each I_i , this can easily be controlled from an external DC/DC converter, which is required anyway. Compared to a non-hybrid pack, only one additional current sensor is needed. Additionally, each unit has to be kept within its particular voltage window. Like in every other pack, this is ensured by monitoring each individual voltage and reducing the absolute value of the total current if necessary.

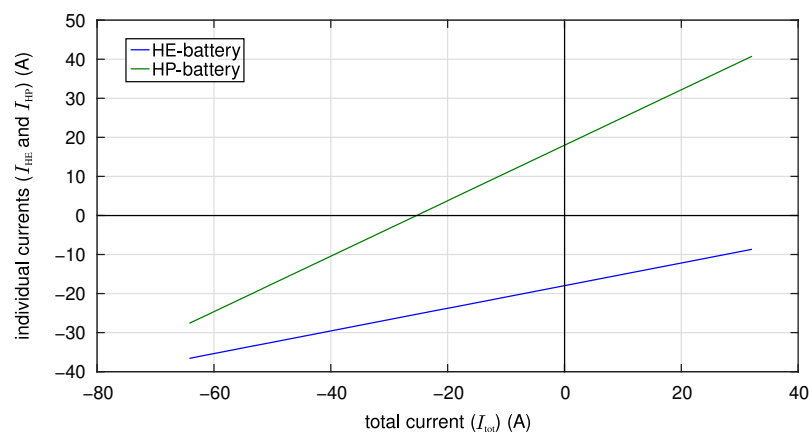


Figure 1. Simulated current distribution between a HE and a HP lithium-ion battery, which are directly interconnected in parallel at 50% SOC and 25 °C after 6C discharge for 1 min and a rapid change in the total current to a certain value of I_{tot} .

Depending on the pre-treatment, this might, in theory, still lead to a slight overcharge or overdischarge of certain parts if the compensating currents at $I_{tot}(t)$ continue charging or discharging a string that has already a SOC of 100% or 0%, respectively. As, in practical applications, the systems are never driven to their physical limits to avoid accelerated aging, this is effectively prevented. However, the parallel connection of batteries of different types or even chemistries with potentially different voltage windows might lead to additional restrictions in the operation. In packs with high voltages, this can be overcome by using strings with different numbers of batteries in series n_{HP} and n_{HE} , which are then connected in parallel. Figure 3 shows two examples for direct electrical interconnections of hybrid battery packs.

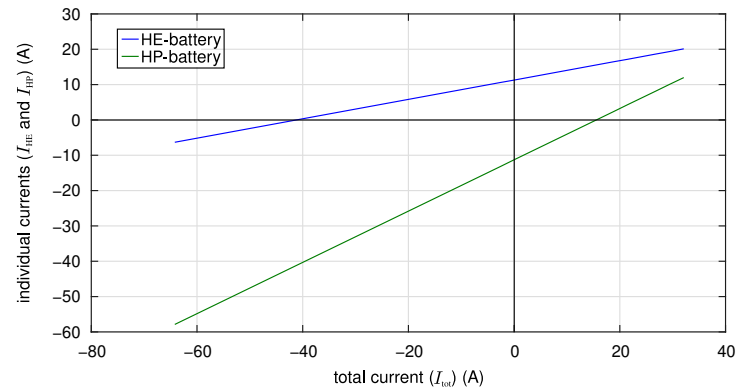


Figure 2. Simulated current distribution between a HE and a HP lithium-ion battery, which are directly interconnected in parallel at 50% SOC and 25 °C after 3C charge for 1 min and a rapid change in the total current to a certain value of I_{tot} .

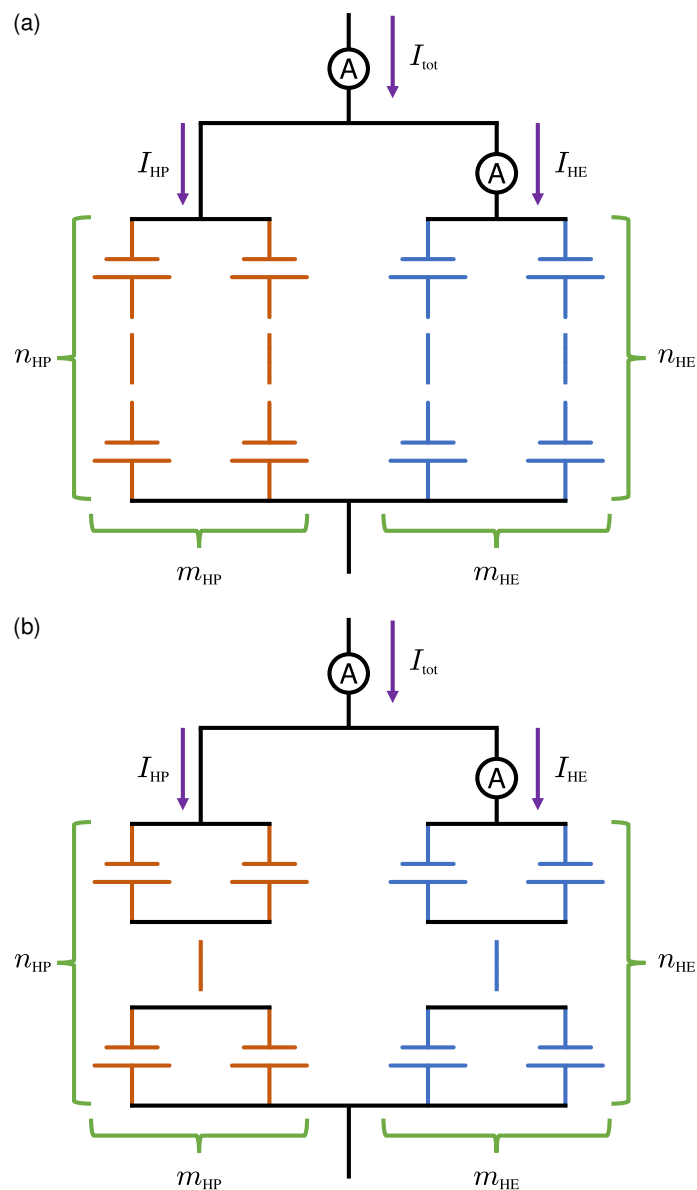


Figure 3. Examples of direct electrical interconnected hybrid battery packs: (a) parallel connection of serial strings, (b) serial connection of parallel batteries. In comparison to non-hybrid systems, an additional sensor is required in order to monitor the individual currents in the HP and HE strings.

The above derivation does not take the influence of temperature development over time into account. Strongly varying thermal behavior in different components of the pack may, in theory, still lead to states exceeding the limits of the individual batteries. Since, in the first order, the compensating currents decrease exponentially with time scales comparable or lower to the temperature development of batteries even without active heating or cooling, this is not a problem, as long as no strong external factors lead to rapid temperature changes.

3. Lithium-Ion Battery Model

The model implemented within BaSiS is based on Newman's approach to electrochemical systems [7,8] and its extensions [9,10], using a pseudo two-dimensional approach. In contrast to other approaches that use, for example, neural networks [11], equivalent circuits [12], and other data-driven models to determine the macroscopic battery properties (voltage, resistance, SOC, etc.), this approach is based on simulating the physical and electrochemical behavior of the (microscopic) state variables, which are then used to determine the macroscopic battery properties. For an overview of different modeling approaches for batteries, the reader is referred to, e.g., the review by Wang et al. [13].

The simulated batteries correspond to the macroscopic structure of a carbon/nickel manganese cobalt oxides (C/NMC) and a carbon/nickel cobalt aluminum oxides (C/NCA) lithium-ion battery, which is assumed to consist of five sheets: two solid conductors, two porous electrodes, and a porous separator. The influence of additives and binders (passive materials) is taken into account, albeit solely in an implicit way. The diffusion and migration of lithium ions are assumed to be homogeneous over the entire cross section of the battery cell; therefore, the model is reduced to a one-dimensional transport process along the x -axis. The pseudo-second dimension takes the diffusion into the active material of the electrodes (intercalation) into account. Both dimensions are connected by the conservation of mass and electric charge in the solid and the electrolyte phases. At pack level, BaSiS is able to simulate the current distribution as well as the heat exchange between individual batteries in arbitrary networks. The solution of the resulting system of partial differential equations is based on a simple Newton method or an advanced TRBDF2 solver for the first dimension, depending on the applied model complexity, combined with a tridiagonal solver for the pseudo-second dimension [14–17].

All symbols used in the following section (description and unit) can be found in Table A1 in Appendix A.

3.1. Reaction Kinetics

The charge transfer reaction during the charge/discharge process takes place at the electrochemical double layer between the active material and the electrolyte. The net current density is assumed to follow the Butler–Volmer Equation [7,18] (p. 212), as follows:

$$i_{\text{BV}} = i_0 \left(\exp \left(\frac{\alpha F}{RT} \eta \right) - \exp \left(-\frac{(1-\alpha)F}{RT} \eta \right) \right). \quad (4)$$

The exchange current density in the electrochemical equilibrium according to [7] (p. 206) is given by the following equation:

$$i_0 = i_{00} \left(\frac{c_e}{c_{e,00}} \right)^\alpha \left(\frac{c_s}{c_{s,00}} \right)^{1-\alpha} \exp \left(-\frac{E_A}{R} \left(\frac{1}{T} - \frac{1}{T_{00}} \right) \right), \quad (5)$$

where temperature dependence is calculated according to the Arrhenius equation.

The dynamics of the overpotential η are based on the conservation of the electric charge, as follows:

$$a_s c_{\text{DL}} \partial_t \eta = \partial_x i_e - a_s i_{\text{BV}}, \quad (6)$$

where the electric charge is the conserved quantity, the overpotential is the density, and the lithium-ion current density i_e is the current density of the conserved quantity. The

Butler–Volmer current density i_{BV} is considered to be the sink/source term in the continuity equation for the electric charge, since only a fraction of $\partial_x i_e$ is charging the double layer with its specific electrical capacity c_{DL} .

Due to the restriction of the charge transfer on the active material surface, the corresponding properties are scaled with the active material surface per electrode volume a_s , which is determined via the mass-related Braunauer-Emmett-Teller (BET) surface and the corresponding density of the active material.

3.2. Transport in the Electrolyte

The modeling of the lithium-ion transport within the binary electrolyte is based on Newman's concentrated solution theory. Based on the energy balance equation, the lithium-ion current density according to [7] (p. 302 and following) is given by the following equation:

$$i_e = \kappa \left(\frac{1 - t_+^0}{F} \partial_x \mu_e - \partial_x \phi + \partial_x \eta - \partial_x \phi_s \right). \quad (7)$$

Furthermore, the gradients of the chemical potential in the electrolyte μ_e and the cell potential ϕ can be replaced via the following:

$$\partial_x \mu_e \approx 2RT \frac{\partial_x c_e}{c_e} \quad \text{and} \quad \partial_x \phi = -\frac{i_s}{\sigma} = -\frac{i - i_e}{\sigma},$$

where the impact of porosity and tortuosity on the transport mechanisms are taken into account in the electrolyte conductivity κ and in the active material conductivity σ according to Bruggeman [19] and the temperature dependence according to Arrhenius. The active material dependent half-cell potential ϕ_s is passed as a measured parameter.

The transport of lithium ions within the electrolyte is governed by diffusion ($\propto \partial_x (D_e \partial_x c_e)$) and migration ($\propto \frac{t_+^0}{F} i_e$). According to the conservation of mass considering the exchange reaction at the solid–electrolyte interface ($\propto \frac{1}{F} \partial_x i_e$), the time derivative of the electrolyte concentration in the electrodes is given by the following [18]:

$$\epsilon_e \partial_t c_e = \partial_x (D_e \partial_x c_e) - \frac{t_+^0}{F} \partial_x i_e + \frac{1}{F} \partial_x i_e, \quad (8)$$

where the mass of the lithium ions is the conserved quantity, the lithium-ion concentration is the density, and the lithium-ion mass current density (due to diffusion and migration) is the current density of the conserved quantity. The last term on the right-hand side (change in the lithium-ion current density) is considered to be the sink/source term in the continuity equation. Due to the lack of a source/sink term and $i_e = i = \text{const}$, the equation simplifies within the separator to the following:

$$\epsilon_e \partial_t c_e = \partial_x (D_e \partial_x c_e). \quad (9)$$

Moreover, the partial differential equation is solved assuming the continuity of the diffusion current density at the boundaries between the electrodes and the separator and a vanishing diffusion current density at the boundaries between the electrodes and the conductors. Again, the diffusion coefficient includes the porosity and tortuosity as well as the temperature dependence according to Arrhenius.

3.3. Transport in the Active Material

Based on the properties of the active materials, the positive electrode is assumed to consist of spherical particles with isotropic diffusion, whereas the graphite material is considered to be transverse isotropic. The transport of lithium in the active material is solely driven by the concentration gradient. According to the conservation of mass, the

transport of the (uncharged) lithium within the electrodes is solely governed by diffusion, and the time derivative of the lithium concentration is given by the following [18]:

$$\partial_t c_s = \begin{cases} \partial_y (D_s \partial_y c_s), & \text{planar} \\ \frac{1}{r^2} \partial_r (r^2 D_s \partial_r c_s), & \text{spherical} \end{cases} \quad (10)$$

where the mass of lithium is the conserved quantity, the lithium concentration c_s is the density, and the lithium-ion mass current density (due to diffusion) is the current density of the conserved quantity.

The diffusion coefficient D_s includes the temperature dependence according to Arrhenius for both active material geometries, as well as the porosity and tortuosity of the planar graphite. In compliance with the conservation of mass at the boundary between active material and the electrolyte, the Butler–Volmer current density sink/source term is taken into account, according to the following:

$$\begin{aligned} \partial_y (D_s \partial_y c_s) \Big|_{y=l_s} &= -\frac{i_{BV}}{F} \quad (\text{planar}) \\ \frac{1}{r^2} \partial_r (r^2 D_s \partial_r c_s) \Big|_{r=r_s} &= -\frac{i_{BV}}{F} \quad (\text{spherical}). \end{aligned}$$

3.4. Thermal Behavior

The thermal behavior of the lithium-ion battery is calculated based on the conservation of energy. Temperature distribution within the battery is neglected and it is assumed that the entire heat production of the N_{cell} cells takes place in the center of the battery. In doing so, the driving force for the energy exchange with the environment can be reduced to the difference between battery temperature and ambient temperature, $T_{\text{amb},k}$, in all directions k , according to Fourier's law, as shown below:

$$\partial_t T = \frac{1}{C} \left(-\sum_k \frac{1}{R_{\text{th},k}} (T - T_{\text{amb},k}) + N_{\text{cell}} (P_{\text{th}}^{\text{irr}} + P_{\text{th}}^{\text{rev}}) \right), \quad (11)$$

where the heat is the conserved quantity, the temperature T is the density, and the heat flux density proportional to the temperature difference is the current density of the conserved quantity. The reversible heat production $P_{\text{th}}^{\text{rev}}$ and irreversible heat production $P_{\text{th}}^{\text{irr}}$ represent the source/sink term.

Irreversible heat production takes place due to the ohmic resistances of the conductors, the active materials, and the electrolyte, as well as the charge transfer reactions at the electric double layers. The electrochemical reaction and the corresponding change in entropy are represented by the reversible heat source. The thermal resistances R_{th} and the total heat capacity C include all battery cells and their composing sheets and materials, as well as the filing material and the battery casing.

3.5. Voltage and SOC

Based on the calculated state variables, the macroscopic battery quantity voltage can be derived as follows:

$$U = U_0 + R_{\text{ohm}} I, \quad (12)$$

where the current independent term is as follows:

$$U_0 = U_{\text{eq}} + \Delta U_{\text{DL}} + \Delta U_{\text{S}}^{\text{pos}} + \Delta U_{\text{S}}^{\text{neg}} \quad (13)$$

This takes into account the equilibrium potential U_{eq} and potential drops due to the double layer ΔU_{DL} (overpotential) and due to the active material ΔU_s (lithium current density $i_s = i - i_e$). The resistance is as follows:

$$R_{ohm} = R_{agg}^{pos} + R_c^{pos} + R_s^{pos} + R_e + R_s^{neg} + R_c^{neg} + R_{agg}^{neg} + R_{ind} \quad (14)$$

This takes into account the resistances due to the aggregate R_{agg} , the current collector R_c , the active material R_s , the electrolyte R_e , and the inductivity R_{ind} .

The SOC is derived from the active material concentration, according to the following:

$$SOC = 1 - \max \left\{ \left(\overline{c_s^{pos}} - \epsilon_s c_{s,00}^{min,pos} - \overline{c_{s,DL}^{pos}} \right) d_e^{pos}, \left(\epsilon_s c_{s,00}^{max,neg} - \overline{c_s^{neg}} + \overline{c_{s,DL}^{neg}} \right) d_e^{neg} \right\} \frac{N_{cell} F A}{C_R} \quad (15)$$

considering the volume fraction of the active material ϵ_s , the average active material concentration, and its respective maximum and minimum values within the electrode, as well as the double layer $c_{s,DL}$ for both electrodes, where d_e is the electrode width and C_R the rated capacity.

4. Results and Discussion

Classical hybrid battery packs, which include additional power electronics to control the currents flowing through the different parts of the system are fairly flexible in design on the expense of higher costs, complexity, and weight. As already discussed above, these drawback can be overcome by a direct electrical interconnection of batteries with different properties to form a hybrid pack. However, the findings in Section 2 have to be taken into account, in addition to Kirchhoff's laws, in order to determine an appropriate layout. For example, a good layout for an application that primarily consumes power from the pack is achieved when the following relation for the maximum discharge current I_{tot}^{min} holds:

$$I_{tot}^{min} \approx m_{HE} \cdot I_{HE}^{min} + m_{HP} \cdot I_{HP}^{min},$$

where $m_{HE/HP}$ is the number of parallel connected HE and HP strings, respectively. As the current distribution strongly depends on their properties, the correct choice of the applied batteries and the layout of the interconnection is of crucial importance in order to achieve the desired performance. Furthermore, the requirements for a safe operation, given in (2) to (3), additionally imply that $-m_{HE} \cdot I_{HE}^{min} \leq m_{HP} \cdot I_{HP}^{max}$, which can again limit the power capability. For maximum positive total currents, i.e., if the pack experiences peak charging due to recuperation, for example, the condition $-m_{HE} \cdot I_{HE}^{max} \geq m_{HP} \cdot I_{HP}^{min}$ applies, which is usually easily fulfilled. These implications limit the degrees of freedom for the design of directly interconnected packs, so the availability of appropriate batteries for the HE and HP elements determines whether such a system can provide a benefit for a certain application. At first, the current distribution between HP and HE strings is determined by the ohmic resistances of the batteries and the busbars, as well as the respective equilibrium voltages. If current peaks for more than just a few seconds are expected or insufficient rest phases occur, it is recommended to simulate the current distribution with a comprehensive simulation model such as BaSiS, in order to take all relevant effects within the batteries, such as diffusion processes, reaction kinetics, and the change in SOC and temperature, into account.

Various techniques for increasing the power and the range of electric vehicles were developed and tested in an Audi A3 cabriolet equipped with a novel electrical drive train serving as a demonstrator. The battery pack for this application had to meet the following requirements:

- Technology: lithium-ion;
- Battery format: 18650;
- Peak discharge power: > 150 kW;
- Nominal capacity: > 25 kWh;

- Pack voltage: 300 V–400 V;
- Weight of batteries: < 120 kg;
- Constant charging power: > 22 kW.

This is only possible using a hybrid solution with HP and HE strings. According to the findings above, a directly interconnected hybrid pack consisting of 14 HP and 9 HE strings, each containing 104 batteries in series, as shown in Figure 3a with $n_{HP} = n_{HE} = 104$, $m_{HP} = 14$, and $m_{HE} = 9$, was designed. The series connections within the strings were created by spot welding contact strips to the battery terminals. Each string was then directly screwed to common busbars at the positive and the negative ends, respectively. Both techniques ensure low additional impedances due to the interconnections. Two batteries, Sony US18650VTC5A (Tokio, Japan) and LG INR 18650MJ1 (Seoul, South Korea), were chosen for the HP and the HE elements, respectively. The technical data can be found in Table 1.

Table 1. Technical data of the batteries used for the hybrid battery pack in the Audi A3.

Manufacturer	Sony	LG
Name	US18650VTC5A	INR 18650MJ1
Type	Lithium-ion HP	Lithium-ion HE
Chemistry	NMC	NCA
Format	18650	18650
Weight	0.049 kg	0.0471 kg
Nominal voltage	3.6 V	3.6 V
Rated capacity	2.5 Ah	3.5 Ah
Max. continuous discharge current	35.0 A	10.0 A
Max. continuous charge current	6.0 A	3.4 A

This forms a hybrid pack of 2392 individual batteries with a total battery mass of 114 kg that delivers 168 kW peak discharge power with a nominal capacity of 25.4 kWh. Its dimensions are 505 mm in length, 610 mm in width, and 340 mm in height. The best non-hybrid system for this application would consist of 2392 Sony US18650VTC5 batteries with a total mass of 106 kg and a peak discharge power of 160 kW, but a capacity of only 22.4 kWh. Hence, due to the chosen appropriate layout, the pack is capable of delivering the demanded high transient currents with a capacity approximately 13% higher than the best non-hybrid system. Compared to a non-hybrid pack, only one additional current sensor is required in order to determine the currents in the HP and HE strings individually as a necessary input for the control algorithm. Current, voltage, and temperature control are directly implemented in the battery management system (BMS). In principle, only slight modifications to existing systems are required to build a BMS for a directly interconnected hybrid battery pack. This comprises a further current sensor, according to Figure 3, and individual programming for the HP and HE strings due to the different properties and limits of the batteries, as well as the implementation of current monitoring, according to (2) and (3). For this demonstrator, however, two interconnected classical BMS were applied for the HP and HE elements, in order to save time and money during the development process. In addition to voltage, current, and temperature monitoring for all batteries, the following features, for ensuring safe and reliable operation, were integrated:

- Passive balancing of the batteries in the HP and HE strings;
- SOC calculations from current integration;
- Temperature- and current-dependent derating;
- Insulation monitoring;
- Interlock detection;
- Leakage monitoring for coolant;
- Pre-charge unit;
- High-voltage fuses for both terminals;
- Safety contactors for both terminals.

The different heat generation rates can be addressed by an appropriate heating and cooling system or by distributing the strings in a way that each HP battery is surrounded by HE batteries and vice versa. This leads to a homogeneous temperature distribution as a prerequisite of a uniform aging. As the software BaSiS is also capable of simulating heat distributions in packs as well as degradation on a cell level, these factors can also be taken into account during the design process. In the demonstrator, the HP and HE batteries were assembled side-by-side in an upright position. Four of these modules were stacked with cooling plates in between them, as well as on the top and at the bottom, using water as the coolant. The pack was thoroughly tested over a wide range of temperatures and SOC, utilizing constant current and real-drive cycle power profiles before being installed in the car. For each experiment, the pack was connected to a test bench in a climate chamber, preconditioned in terms of SOC and temperature, and subsequently operated under different current and ambient temperature conditions. All individual voltages and temperatures, measured by the two BMSs, as well as the currents in the HP and HE elements, were recorded. Figures 4 and 5 show the resulting HP and HE currents for one of these tests, as well as the results of a corresponding simulation with BaSiS. The minimum and maximum voltages of the HE and HP batteries are depicted in Figures 6 and 7, respectively.

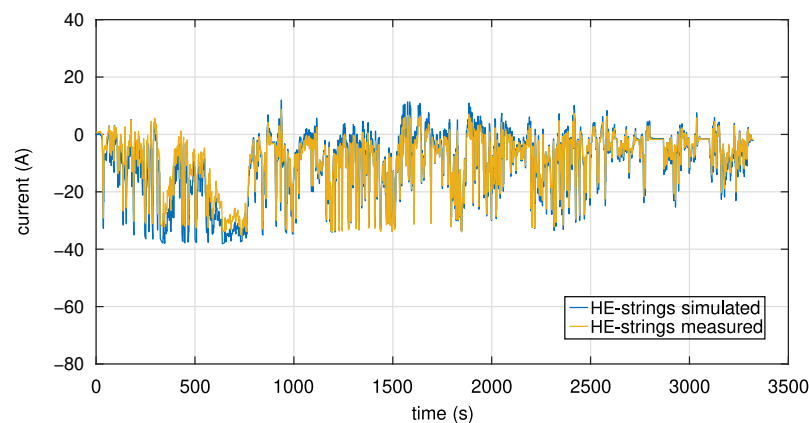


Figure 4. Test of the battery pack for the Audi A3 cabriolet with a real drive cycle on a test bench: measured and simulated currents in the HE strings. The batteries were kept within safe limits.

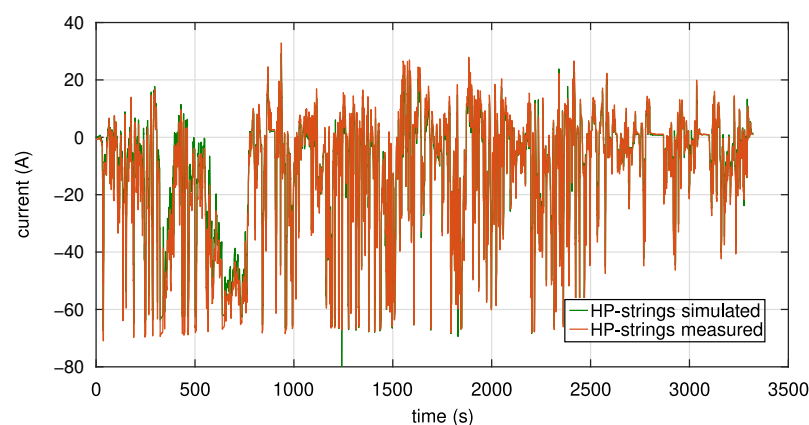


Figure 5. Test of the battery pack for the Audi A3 cabriolet with a real drive cycle on a test bench: measured and simulated currents in the HP strings. The batteries were kept within safe limits.

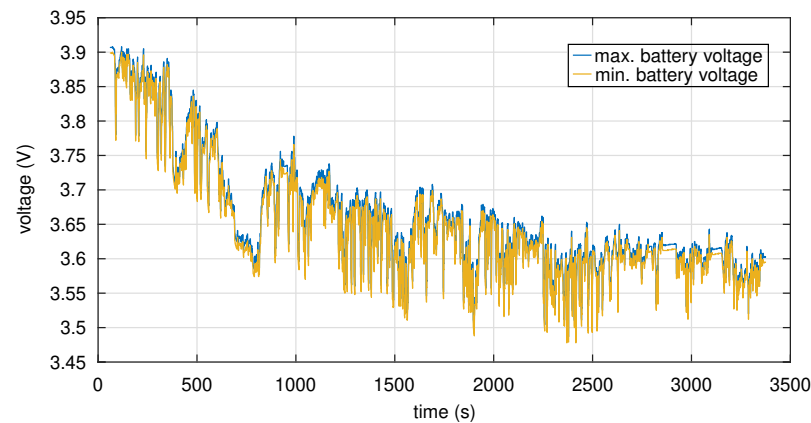


Figure 6. Test of the battery pack for the Audi A3 cabriolet with a real drive cycle on a test bench: measured minimum and maximum voltages of the HE batteries.

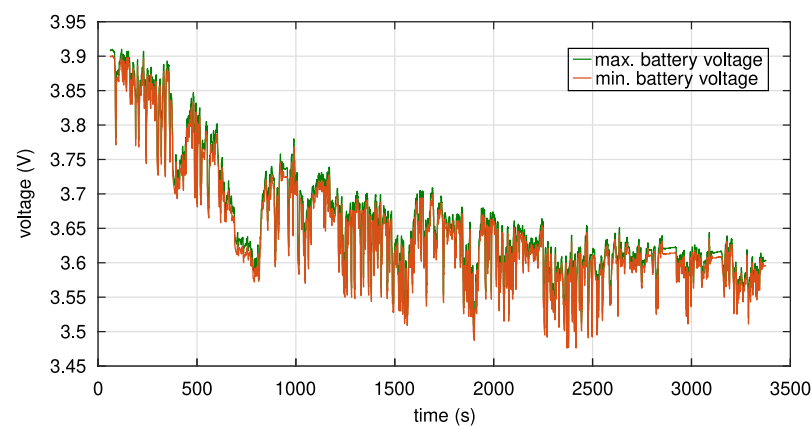


Figure 7. Test of the battery pack for the Audi A3 cabriolet with a real drive cycle on a test bench: measured minimum and maximum voltages of the HP batteries.

The experiment started at a total SOC of 70% with a temperature of 20 °C. Throughout the whole test, the cooling system was active and the ambient air was kept at 20 °C, leading to battery temperatures between 21 °C and 23 °C, with a spread of 2 °C across the pack. As can be seen in the figures, the pack was able to reliably deliver the demanded power while all batteries were kept within their individual safety limits at all times by only controlling the total current, as specified in Section 2. Furthermore, there was a very good agreement between the simulated and experimental results, showing that a comprehensive electrochemical model is the right tool for designing a hybrid system. In the next step, the pack was fitted to the car serving as a demonstrator. For this, the bottom of the trunk was removed and a rigid housing made of aluminum was placed there instead, providing good mechanical stability as well as insulation for thermal management and heat protection against fire in the case of an accident. The subsequent drive tests were also successful and confirmed all the preceding tests and simulations. In comparison to classical hybrid packs, no additional power electronics were required, which reduced cost, complexity, and weight. In summary, it has been shown that directly interconnected hybrid batteries are safe, powerful, and reliable energy storage systems, if the layout and the control algorithm are properly chosen, in particular for applications that require high peak currents in combination with the highest possible capacities.

5. Conclusions and Outlook

Directly interconnected hybrid battery packs offer many advantages for developing energy storage systems for certain applications. Compared to classical hybrid systems, where parts with different properties are connected via DC/DC converters, they provide lower complexity, weight, and cost. The theoretical background for the safe operation of

packs with direct electrical interconnections was derived and comprehensively discussed. This showed that only the integration of an additional current sensor and software changes in the BMS are required in order to ensure safe and reliable operation. Approaches and tools for the design of such devices were presented, such as the Newman-based model BaSiS for electrochemical energy storage systems. A directly interconnected hybrid battery pack consisting of 2392 individual 18650 lithium-ion batteries was designed, built, comprehensively tested, and subsequently installed in a converted Audi A3 cabriolet for further investigations of the overall system. In this way, a very high electrical peak discharge power of 168 kW was achieved, with a nominal capacity of 25.4 kWh and a total battery mass of only 114 kg, which would not have been possible with a non-hybrid approach. Safe and reliable operation was demonstrated under a broad variety of scenarios with a very good agreement between measurements and the corresponding simulations with BaSiS, showing that such models are the right tool for designing hybrid devices. Nevertheless, the lack of control of the current distribution between parallel connected strings with different properties requires the correct choice of batteries and the layout of the pack. Furthermore, the required control algorithm for safe operation implies further restrictions. These limits the degrees of freedom for the design of directly interconnected packs, so the availability of appropriate batteries for the HE and HP part determines whether this approach can provide a benefit for a certain application. We have made our findings available to our industrial and academic partners in the field of automotive and battery technology so they can use this technology for future devices.

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Abbreviations

The following abbreviations are used in this article:

DC/DC	direct current to direct current
BaSiS	Battery Simulation Studio
C/NMC	carbon/nickel manganese cobalt oxides
C/NCA	carbon/nickel cobalt aluminum oxides
BET	Braunauer-Emmett-Teller
BMS	Battery management system
HE	High-energy
HP	High-power
IEE	Institute for Energy Economics and Energy System Technology
SOC	State of charge

Appendix A

Table A1. Symbols and units.

Symbol	Description	Unit
A	Cross section	m^2
a_s	Active material surface per electrode volume	m^{-1}
C	Total heat capacity	J K^{-1}
C_R	Rated capacity	As
c_{DL}	Specific double-layer capacitance	F m^{-2}
c_e	Lithium-ion concentration (electrolyte)	mol m^{-3}
$c_{e,00}$	Lithium-ion concentration at reference state	mol m^{-3}
c_s	Lithium concentration (active material)	mol m^{-3}
$c_{s,00}$	Lithium concentration at reference state	mol m^{-3}
$c_{s,00}^{\max}$	Maximum lithium concentration at reference state	mol m^{-3}
$c_{s,00}^{\min}$	Minimum lithium concentration at reference state	mol m^{-3}
$c_{s,DL}$	Lithium concentration in the double layer	mol m^{-3}
D_e	Lithium-ion diffusion coefficient (electrolyte)	$\text{m}^2 \text{s}^{-1}$
D_s	Lithium diffusion coefficient (active material)	$\text{m}^2 \text{s}^{-1}$
d_e	Electrode width	m
E_A	Arrhenius activation energy for exchange current density	J mol^{-1}
F	Faraday constant	As mol^{-1}
I	Current	A
$I_{HE/HP}$	Current of HE/HP string	A
$I_{HE/HP}^{\max}$	Maximum charge current allowed for HE/HP string	A
$I_{HE/HP}^{\min}$	Minimum discharge current allowed for HE/HP string	A
I_j	Current of individual battery j	A
I_{tot}	Total current of interconnection	A
i	Total current density	A m^{-2}
i_0	Exchange current density	A m^{-2}
i_{00}	Exchange current density at reference state	A m^{-2}
i_{BV}	Butler–Volmer current density	A m^{-2}
i_e	Current density (electrolyte)	A m^{-2}
i_s	Current density (active material)	A m^{-2}
l_s	Half-width of planar active material	m
N_{cell}	Number of cells per battery	-
$n_{HE/HP}$	Number of batteries in series in HE/HP string	-
$m_{HE/HP}$	Number of strings in parallel in HE/HP string	-
P_{th}^{irr}	Irreversible heat power	W
P_{th}^{rev}	Reversible heat power	W
R	Gas constant	$\text{J K}^{-1} \text{mol}^{-1}$
R_{agg}	Aggregate resistance	Ω

Table A1. Cont.

Symbol	Description	Unit
R_c	Current collector resistance	Ω
R_e	Electrolyte resistance	Ω
R_{ind}	Inductivity resistance	Ω
R_{ohm}	Ohmic resistance	Ω
R_s	Active material resistance	Ω
R_{th}	Thermal resistivity	$K W^{-1}$
r	Intercalation direction for spherical active material (pseudo-second dimension)	m
r_s	Radius of spherical active material	m
T	Temperature	K
T_{00}	Reference temperature	K
T_{amb}	Ambient temperature	K
t_+^0	Transference number	-
U	Voltage	V
U_0	Current independent voltage term	V
U_{eq}	Equilibrium voltage	V
U_j	Voltage of individual battery j	V
U_j'	Derivative of voltage with respect to individual current of battery j	V
U_{tot}	Total voltage of interconnection	V
x	Spatial current direction (first dimension)	m
y	Intercalation direction for planar active material (pseudo-second dimension)	m
α	Charge transfer coefficient	-
ΔU_{DL}	Double layer voltage drop	V
ΔU_s	Active material voltage drop	V
ϵ_e	Porosity	-
ϵ_s	Active material volume fraction	-
η	Overpotential	V
κ	Conductivity (electrolyte)	$S m^{-1}$
μ_e	Lithium-ion chemical potential (electrolyte)	$J mol^{-1}$
σ	Conductivity (active material)	$S m^{-1}$
ϕ	Cell potential	V
ϕ_s	Half-cell potential	V

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