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Dimensioning and Optimisation of Hybrid Li-Ion Batteries for EVs

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Summary

Commercial electric vehicles (EVs) are powered by one homogenous battery system with one kind of Li-ion battery cells. Typically an OEM (Original Equipment Manufacturer) or battery system manufacturer has access to a limited portfolio of different Li-ion cells. Due to the fixed ratio of the cells' maximum power to nominal energy ratio, the possibilities in designing power and energy of the battery independently are limited. The battery system can only be scaled by adapting the number of cells and modules.

If additional power electronics in form of one or more dc/dc converters is included in the system, different cell types may be used to form a hybrid battery system comprised of more than one pack. This allows individually designing each battery pack and thus well suit the overall battery specification. In the public funded research project "HV-ModAL" modular approaches for drive train solutions in order to increase the vehicle performance while showing advantages when being used cross-carline are analysed. The requirements for the different vehicle classes are defined by the OEMs and Tier1 suppliers in the consortium.

This work focuses on the energy storage part of the drive-train and presents a battery dimensioning and optimisation approach for single pack and hybrid battery systems. It is based on an evolutionary optimisation algorithm and a detailed, modular Matlab-Simulink vehicle model which has been developed in the project. The vehicle model, as well as the battery optimisation tool box, are presented in the paper. Results and comparisons to common battery systems are then shown for representative vehicle classes. A demonstrator setup is introduced to evaluate the hybrid battery approach. Recent findings indicate that an optimised hybrid battery systems can lead to weight and volume savings and further advantages in TCO (total cost of ownership) by e.g. enhanced battery life time or less invest costs.

Keywords: BEV (battery electric vehicle), optimisation, lithium battery, powertrain

1 Introduction

Electric vehicles (EVs) still suffer from slow market penetration in Germany [1] and worldwide although German politics have sought for a quick ramp up since 2011 [2] and are currently supporting purchases of new EVs with a monetary reward. Main hurdles still are the lower mobility flexibility when using EVs due to their limited range compared to combustion driven vehicles as well as their higher invest costs - at least if not significantly funded. One of the main cost drivers of EVs is the battery system although cell prices have decreased over the last years [3]. A sophisticated dimensioning and design of the battery system is thus essential for a successful electrification of vehicles. Otherwise battery systems may be dimensioned conservatively and thus lead to systems outside the economical and ecological optimum.

This work presents an approach to address the above mentioned challenges. The key idea is to equip electric vehicles with a hybrid battery system consisting of different battery cell types instead of using only one type of cell. A typical battery cell used in current EVs is neither a cell designed towards very high energy (apart from Panasonic cells used by Tesla), nor is the cell designed for high power as it is the case in hybrid electric vehicles. Instead it is designed as a trade-off between driving agility through power of the battery and range of the vehicle, influenced by the battery's energy content. This leads to an overdimensioning of the battery system if the available cell types do not fulfil the desired power to energy ratio which is schematically shown in Figure 1, left. In contrast to this single-pack approach, a hybrid battery system using two different cell types enables an exact dimensioning of both power and energy as shown in Figure 1 right. In many cases this leads to less mass, volume and costs of the complete system.

Figure 1: Dimensioning of a battery system.
Left: using just one type of cells, right: using a hybrid approach with two kinds of cells

Current battery systems in EVs are well suited for one type of EV but it is difficult to scale them to different vehicle classes and models like it is done with sizing of combustion engines for more powerful models. Hybrid battery systems on the other hand can be dimensioned rather free in terms of energy and power. An OEM might therefore use modules of a high-energy (HE) pack across his models portfolio and add further high-power (HP) modules for more powerful vehicle models and classes. Such an approach supports the economy of scales effect and thus may contribute to decreasing EV investment costs.

Hybrid battery systems require additional power electronics to adapt the different cell characteristics. In the easiest case, this can be one dc/dc converter attached to the clamps of one pack as shown in Figure 2, left.

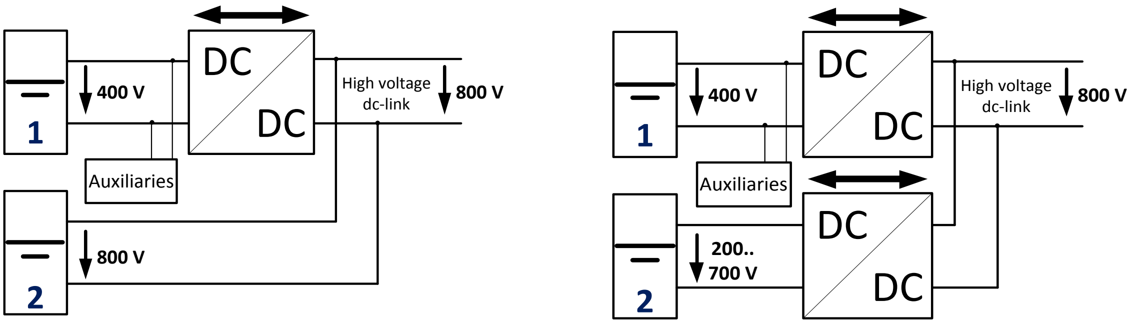

Figure 2: Hybrid battery system topologies using dc/dc converters

Such a system topology simultaneously enables to use different voltage levels in the drive-train, e.g. using 800 V inverters for high power drives and one battery pack at 400 V nominal voltage and a second one at either 800 V dc-link voltage (Figure 2 – left) or a completely different voltage (Figure 2 – right). A dc-link voltage of 800 V has the advantage, that the charging power can be fed into the car with lower current than with 400 V system voltage and thus allows higher power with the same cable diameter [4].

Hybrid battery systems have been analysed in literature for many applications from consumer electronics [5] to stationary and mobile applications, using many different types of energy storage technologies. Most of the combinations use super capacitors to increase the system's maximum electrical power [6], [7], [8]. This work though focuses on the combination of different types of Lithium-ion batteries in one EV. Lithium-ion batteries cover a wide field of energy to power ratios. One distinguishes between high-power cells (today typically using Lithium-Titanate anodes – LTO or Lithium-Iron-Phosphate cathodes – LFP) and high-energy cells (today consisting of silicon doped graphite anodes and transition metal cathodes like in Tesla's battery packs).

The dimensioning process for hybrid battery systems is even more difficult than it is for single pack battery systems, as shown in chapter 2.3. Due to the complex solution space the optimisation process cannot be performed manually. Optimization goals can be chosen amongst or be a combination of cost minimisation, weight and volume reduction or minimisation of environmental impact. The optimisation methodology and results for specific vehicle types are presented in the next chapters.

2 Description of the Battery Optimisation Methodology

One of the goals of the research project "HV-ModAL" is to analyse the modularisation approach for every drivetrain component in EVs enabling the usage of components for different vehicle classes and supporting the development of high-power drivetrains with flexible number of battery packs and machines (Figure 3).

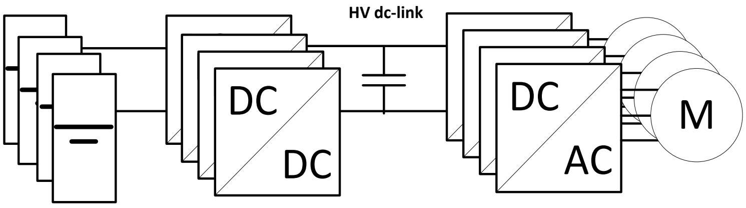

Figure 3: Modular drive-train with flexible number of batteries and machines

To analyse and compare different topologies quantitatively, a detailed vehicle model has been created in Matlab-Simulink. The modularisation of the battery is enabled by an external scaling possibility and the choice amongst a certain cell portfolio. The optimisation tool itself makes use of an evolutionary optimisation algorithm and is implemented in Matlab. It uses the vehicle model to analyse different battery combinations. Both parts of the tool chain are described in the following sections.

2.1 Vehicle and battery model

The vehicle model contains sub-models of all relevant drive-train components (batteries, dc/dc converters, inverters and machines), as well as a chassis and a driver model. The chassis model calculates the vehicle speed, resulting from the applied torque of the machine(s). The quantity and type of each component is not static but can be chosen prior to every simulation start in certain boundaries. The whole model is fed with speed and slope over time profiles, representing logged and standard driving profiles, like WLTP (Worldwide Harmonized Light-Duty Vehicles Test Procedure) [10]. The requirements for each vehicle type have been determined by the OEMs and Tier1 suppliers in the consortium and are motivated by current and future electric vehicles perspectives. The chosen battery cells for this exemplary portfolio were characterized on the test benches of the institute for Power Electronics and Electrical Drives (ISEA) of RWTH Aachen University. Their characteristics are summarized in Table 1. There are no explicit favours towards any of the cell manufacturers or products. Amongst the cells there are all three major cell formats: Prismatic cells (like in BMW i3 [11]), pouch bag cells (like in Smart electric drive [12]) and cylindrical cells (like in Tesla Model S [13]). The portfolio contains very high-energy cells as well as very high-power cells as can be seen from the gravimetric energy and power densities. This also motivates the differing anode and cathode combinations ranging from common NMC (Nickel Manganese Cobalt Oxide) cathodes to NCA (Nickel Cobalt Aluminium Oxide) and LFP (Lithium Iron Phosphate) on cathode side and common Graphite to silicon doped Graphite and LTO (Lithium Titanate Oxide) on anode side. The different cell characteristics significantly influence the cell costs relative to their nominal energy content. These were determined using a bottom-up cost model, similar to the “BatPac” approach by Argonne National Laboratory [14, 15, 16, 17]. The material amounts were extracted from measured data from post-mortem analysis carried out at the institute as well as adapted assumptions from “BatPac” tool.

Table 1: Battery cell types of the used cell portfolio

	SB LiMotive	**Kokam**	**Panasonic NCR18650B**	**A123 26650 M1B**	**Toshiba**
Cell format	prismatic	pouch bag	cylindrical	cylindrical	prismatic
HE / HP[1]	HE/HP	HE	HE	HP	HP
Electrode composition (Cathode vs. Anode)	NMC/LMO-Blend vs. Graphite	NMC vs. Graphite	NCA vs. (silicon doped) Graphite	LFP vs. Graphite	LMO vs. LTO
Nom. capacity	60 Ah	46 Ah	3.25 Ah	2.5 Ah	2.9 Ah
Nom. voltage	3.75 V	3.7 V	3.6 V	3.3 V	2.4 V
Grav. energy density	123 Wh/kg	144 Wh/kg	241 Wh/kg	109 Wh/kg	46 Wh/kg
Grav. power density[2]	860 W/kg	433 W/kg	362 W/kg	2170 W/kg	3200 W/kg
Relative costs	304 $/kWh	264 $/kWh	153 $/kWh	360 $/kWh	899 $/kWh
Cyclic aging rate relative to reference	1	1.4	1.6	1.33	0.2

The invest costs for the dc/dc converters in the near future are assumed to be 6 $/kW in this work. The total costs of ownership (TCO) of an EV are significantly influenced by the aging of the battery system. If the aging effect exceeds a certain limit, the battery system has to be overdimensioned initially to compensate the decrease in capacity and power capability. Key figures in this context often are 70 % remaining capacity after 8 years or 100 thousand kilometres [18],[12],[19],[20]. To evaluate the aging effect of dedicated battery packs in each vehicle, a straight forward battery aging model was included. The used data is adapted from a battery aging study and model by Ecker et al. [21] and Schmalstieg et al. [22] and transferred to the cells in this portfolio. The relative aging factors shown in Table 1 are not all reflecting measured data as battery aging characterisation is very time consuming. An aging rate of 1.4 (Kokam) means that the capacity decrease of one cycle is 1.4 times the capacity decrease of the reference (SB LiMotive cell in this cell portfolio). LTO anodes are assumed to have a very good cyclic stability since the volumetric work seen in Graphite anodes does not occur in this material. Thus, the Toshiba cell’s aging rate is assumed to be 20 % of the automotive grade SB LiMotive cell. The aging model itself analyses the cyclic-aging stress on the batteries through the car usage in the specified aging driving cycles (micro and macro cycles) as well as the stress through calendric-aging. The latter mainly depends on the average voltage and temperature of the battery system. Note, that due to performance reasons of the tool chain not the complete vehicle life of 8 years is simulated. Instead, the aging driving cycles are simulated once for each battery system under investigation to determine the above mentioned stress factors. It is then assumed

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[1] HE: High-Energy, HP: High-Power

[2] In discharge direction at high State of Charge (SoC)

that both aging factors (cyclic and calendric) can be expressed with a linear behaviour in the relevant time frame (8 years and ca. 100 thousand kilometres). Using that approach the capacity decrease and resistance increase can be approximated for the cycle life so that the battery system can also be evaluated at this aged point in time. The complete aging model is implemented in Matlab with an interface to the Simulink vehicle and battery model to feed in the “aged” battery parameters.

The generic battery model as part of the vehicle model internally consists of an electrical model interacting with a thermal model and a battery management model. The electrical model consists of an open circuit voltage part, a serial resistor and an RC-element and is parameterized by electrical cell tests at different temperatures. It calculates the voltage response to a certain power which is fed into the battery pack or vice versa. It further computes the thermal loss power according to the electrical power which is then fed into the thermal model. The thermal model can represent a battery pack with pure passive cooling, with active air cooling or with active liquid cooling. The type of cooling system is chosen before the simulation is started. Each component of the battery system is assumed to have a homogenous temperature distribution. Temperature gradients inside the system model can thus only exist between components, e.g. between cell and cooling channel or surrounding air. The temperature of the individual components is calculated based on the heat transfers into ($\dot{Q}_{\mathrm{in}}$) and out of the component ($\dot{Q}_{\mathrm{out}}$), the component’s initial temperature ($T_{\mathrm{component\ initial}}$), its mass ($m_{\mathrm{component}}$) and thermal capacity ($c_{\mathrm{p,component}}$), according to eq. 2-1. This leads to an efficient simulation with limited computational errors.

$$T_{\mathrm{component}} = T_{\mathrm{component\ initial}} + \int \frac{\dot{Q}_{\mathrm{in}} - \dot{Q}_{\mathrm{out}}}{m_{\mathrm{component}} \cdot c_{\mathrm{p,component}}} dt \qquad \text{2-1}$$

The battery management model outputs the battery’s state dependent maximum available power and also controls the cooling system of the pack depending on the actual temperature.

At least one instance of the above described combination of electrical-thermal and battery management model has to be available and active in the vehicle model. In case of hybrid battery systems there can be up to five instances of battery models each parameterized individually prior to simulation. This approach enables the user of the tool chain to specify five different cell types which generates one battery configuration and which is then evaluated by the dimensioning optimisation tool chain, described below.

2.2 Power distribution in hybrid battery systems

In case of just one battery pack the complete power for the drivetrain and auxiliaries is extracted from this pack. Hybrid battery systems on the other hand require a sophisticated power distribution logic continuously determining which portion of traction power is taken out of which pack respectively fed into which pack during recuperation. In the model this task is done by a central control software called the energy management, as shown in Figure 4.

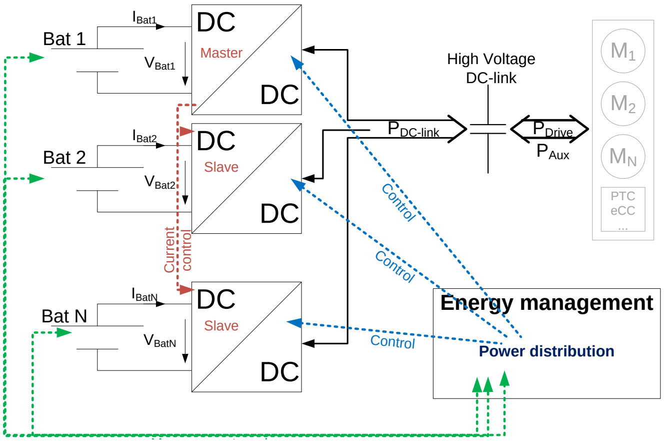

Figure 4: Energy management controlling the power distribution to the individual battery packs

The energy management has a communication link to the batteries to determine each battery pack's state as well as a communication link to each dc/dc converter to actually control the power flow. In literature one can find many solutions for distributing power amongst different energy sources, ranging from rule based ([23],[24],[25]), over stochastically methods [26] up to complex methods trying to predict future traction power profiles based on navigational data [27]. However, none of them describes the here required distribution for 5 batteries which are only distinguished and characterized based on the communication link between battery and energy management. Thus, a straight forward power distribution algorithm has been implemented in this work: It seeks to equalize the state of charge (SoC) of all packs and simultaneously maintain each pack's individual power limitations. Figure 5 shows an exemplary result from using the implemented power distribution logic for 5 different battery packs in a driving scenario.

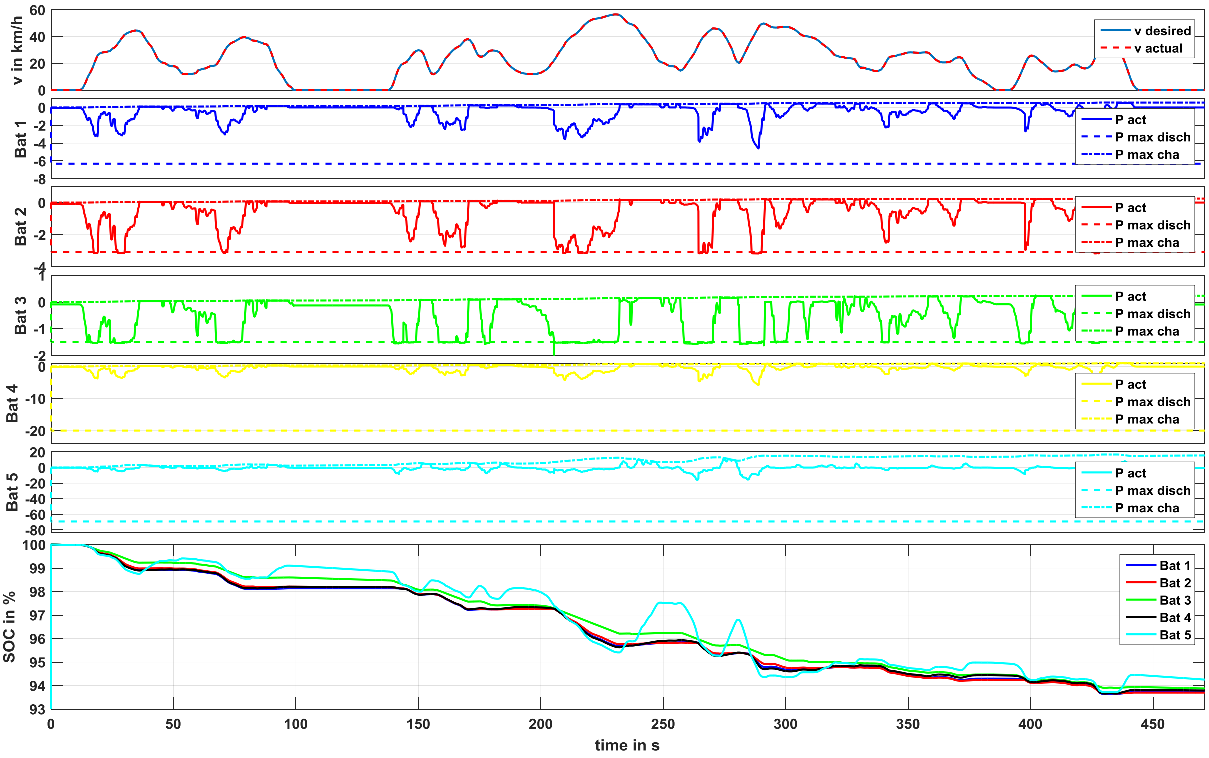

Figure 5: Example of power distribution for five different battery packs, each with 1 kWh of different cells

The upper most graph in Figure 5 shows the reference speed and the actual vehicle speed controlled by the driver. This speed results in a certain drivetrain power, depending on the vehicle's properties (i.e. front area, chassis mass, tire friction etc.) and the actual mass of the drivetrain – in many cases dominated by the battery system. The latter is the reason why in this tool chain every new battery system has to be evaluated in the vehicle model as the battery mass directly influences the vehicle's traction power requirements. The example in Figure 5 makes use of 5 equally dimensioned battery packs, each containing cells with a nominal pack energy of 1 kWh. The first pack contains SB LiMotive cells, the second pack contains Kokam cells, the third Panasonic cells, the fourth A123 cells and the fifth contains Toshiba cells – all described in Table 1. The different cell characteristics can be clearly seen by the output maximum discharge and charge power limits, indicated by the dashed lines in plots 2 to 6 (Figure 5). The power distribution algorithm works in a way that these limits are never exceeded while distributing the power to each battery so that the states of charge of all batteries are equalized as much as possible. This strategy can be recognized in the instances of long and powerful recuperation, e.g. at t=250 s in Figure 5. Battery 5 containing the Toshiba cells with a very high charging capability is charged with a higher current rate than the other packs in this instance. Thus, the SoC of this pack rises more than the SoC of the other packs. To compensate this mismatch, the power distribution strategy tries to assign relatively more power to this pack in the next acceleration phases. One can see in the bottom plot in Figure 5 that this strategy works well in this scenario although the packs have such different characteristics – the states of charge can diverge temporarily but are levelled out afterwards. The power distribution algorithm is implemented in Simulink

Stateflow and is part of the energy management. It is used for the tool chain, described in this paper. The algorithm is fully generic in a way that up to five batteries can be handled. If fewer batteries are available the algorithm adapts itself automatically based on missing availability-signal of the not available packs. Only in case that just one pack is in the vehicle, the complete power distribution algorithm is bypassed to save computational effort.

2.3 Battery Optimisation Framework

The design process of a battery system is complex because the dependencies of characteristics spread across the complete development chain: The choice of cell type influences the necessary amount of cells for given requirements which influences weight and volume for the pack. The resulting weight and loss power of the cells directly influence acceleration and range characteristics of the vehicle. The cooling system has to be well adapted to the chosen cells and application requirements. Thus, the design process is circular dependent. Assumed, that an OEM may choose amongst five different cell technologies and also combines them to hybrid systems, the solution space is huge. An evolutionary optimisation approach ("Covariance-Matrix-Adaption-Evolution-Strategy" CMAES, developed by Hansen et al. [28]) has been chosen to solve this multi-dimensional and non-linear problem. A major advantage compared to e.g. genetic algorithms is the significantly reduced number of parameters that have to be set in order to use the optimisation algorithm for a specific problem. The migration towards the optimum solution is reached by mathematical methods, i.e. adapting the covariance matrix.

In the following, one specific hybrid battery configuration can be e.g. the combination of 20 kWh of Panasonic cells and 3 kWh auf Toshiba cells. Such a battery configuration is called an *individual* in the context of optimisation. In this work the *individual* is coded by its energy of each cell type in the five packs:

$[E_{\mathrm{SB\ LiMotive}}, E_{\mathrm{Kokam}}, E_{\mathrm{Panasonic}}, E_{\mathrm{A123}}, E_{\mathrm{Toshiba}}]$ – each given in Wh.

The above mentioned individual would thus be coded as [0, 0, 20000, 0, 3000]. The optimizer evaluates a certain number of such individuals in the very first step, called the first generation. The best individuals are then chosen for the next generation of individuals, i.e. the covariance matrix is adapted. Similar to evolutionary theory the new generations contain individuals which are closer to the problem's optimum. The key in this process is the individuals' evaluation. This is done inside the *cost function*. Other than the name suggest it not only calculates the direct costs of the particular individual but also assigns penalty points or "costs" if certain requirements of the vehicle are not fulfilled with the chosen battery configuration. Inside the cost function the vehicle model is used to determine the vehicle's acceleration, maximum speed and range for the specified individual under different conditions (warm, cold, begin of life, after eight years). Simulinks *Rapid-Accelerator* mode is used in order to maximize simulation speed. In this mode an executable is built which contains all components of the model itself as well as the equation solver. Thus, the model is not interpreted as it is the case in the Simulink *Normal Mode*. In order to use the executable without modification, the particular settings for each individual are fed into the model using the concept of *tunable parameters.* This enables very fast simulations and furthermore parallelisation of evaluations on multicore CPUs using the same executable. If the determined performance requirements cannot be reached with the particular battery configuration (e.g. vehicle acceleration too low due to insufficient battery power) then penalty "costs" are assigned (e.g. X $ for every second acceleration time from standstill to 100 km/h which is higher than the required time).

Weight, volume and invest "costs" can be directly calculated in the cost function without simulation in the vehicle model. While invest costs are calculated in a currency, weight and volume are also converted using a linear penalty "cost" approach. All penalty "cost" factors can be parameterized in accordance to their particular relevance. If for certain applications the weight is of higher importance than the volume than the weight penalty "cost" factor can be increased relative to the volume "cost" factor.

The components of the cost function which sum up to the total costs are visualized in Figure 6 for an example of a single pack battery system which is iteratively increased in its nominal energy size by 1 kWh steps (x-axis). Note, that the y-axis is logarithmic. Very small battery systems generate very high penalty points, since they cannot fulfil the performance requirements in the vehicle. One can see that from 35 kWh upwards the penalty points for acceleration vanish, meaning that these battery configuration enable the vehicle to accelerate fast enough. From 45 kWh onwards also the penalty points for range are zero. The total costs thus have a minimum in this range of energy. For even higher energy capacity the mass and volume increase which generates higher penalty points again.

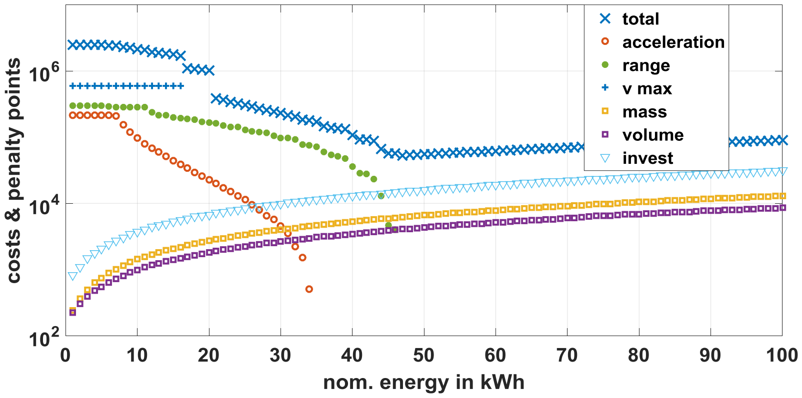

Figure 6: Costs and penalty pointss evaluated in the cost function of the optimisation tool box

Figure 7 shows the result of the cost evaluation for the five different cell types with different sizing of the packs. The particular cost components are not visualized but only the total costs. Similar to Figure 6, one can see a global cost minimum in the range of 50 kWh for packs with SB LiMotive, Kokam and A123 cells. Due to the limited power of the Panasonic cell, significantly higher energy content is required with this cell type in order to fulfil the acceleration requirements. Battery systems with only the Toshiba cell show comparatively high mass and volume figures which leads to high costs over the complete energy range. Such visualisation, as shown in Figure 7, is only possible for single pack battery systems since a combination of cell types leads to a more dimensional solution space. Furthermore, the computational effort to analyse all cell combinations with all sizes (brute force optimisation) increases significantly in a hybrid battery approach. This is why a systematic optimisation approach was developed in this work.

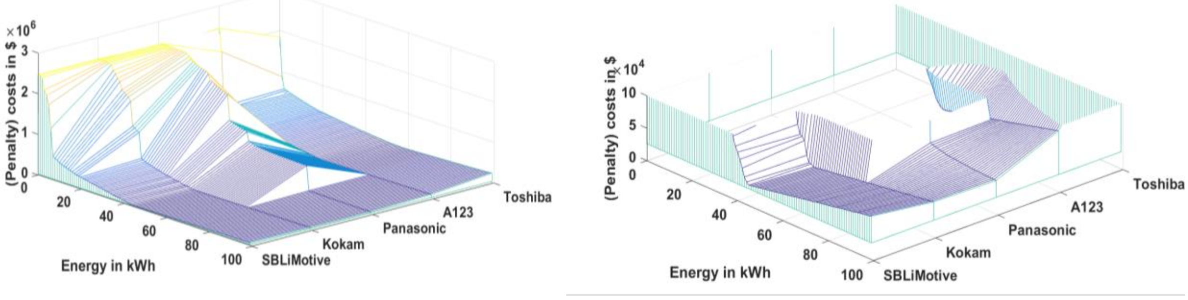

Figure 7: Costs for different single pack battery systems with different cell types and different energy content left: full cost range, right: only relevant cost range – irrelevant configurations are not shown

3 Dimensioning Results and Discussion

To evaluate the concept of hybrid battery systems the developed tool chain was used for 4 different EVs:

- a reference vehicle of the current generation with 150 km range, called “ref. EV 150 km”,
- a reference vehicle with 300 km range, called “ref. EV 300 km”,
- a sportive compact vehicle with 350 km range and 3.9 s accel. time, called “compact EV 350 km”,
- and an upper class vehicle with 400 km range and 5.1 s acceleration time, called “High class EV 400 km.

For each of these vehicles a reference battery system was optimised using the full cell portfolio from Table 1. This reference battery has a certain mass, volume and invest costs, each value indicated as 100 % reference in Figure 8. Note, that all three values are stacked in the figure so that the reference vehicle’s mass, volume and costs indications sum up to 300 %. One can observe that in case of the vehicles with a rather high power to energy requirement the SB LiMotive cell turns out to be the best choice for a single cell battery system (“ref. EV 150 km” and “compact EV 350 km”). In case of the other two vehicles with higher range and thus higher energy requirements the Kokam cell with slightly higher energy density is more suitable. Furthermore, for each vehicle the best battery system is obtained using the developed hybrid battery dimensioning tool chain. The resulting battery configurations and dimensions are indicated in the middle column in Figure 8 for each vehicle and called global optimum. It becomes clear that in all cases the mass, volume and invest costs of the hybrid batteries are lower compared to the best single pack system (reference), although these solutions require an additional dc/dc converter. Furthermore, it is obvious that the combination of a high-energy Panasonic cell and high-power cell lead to the best combinations for all vehicles In case of the vehicles with moderate acceleration performance the A123 cell is the better option in combination with the Panasonic cell. In case of the vehicles with more mass or higher acceleration power the Toshiba cell is more suitable. The highest reduction potential in mass through hybridisation can be obtained in case of the compact class EV (17.8 %). The same applies for the volume reduction compared to the reference (more than 28 %). The highest cost reduction potential is gained in case of the High class vehicle (16.8 %). The lowest mass reduction effects through battery hybridisation are obtained with the two reference EVs, both in the range of 11 to 13 %, the lowest volume reduction with the “ref. EV 300 km” (5 %) and the lowest cost reduction with the “ref. EV 150 km” (5 %).

A third configuration for each vehicle is evaluated: a hybrid battery system with specifically Pansonic and Toshiba cells. This is the combination with the highest difference in energy to power ratio as well as a very high recuperation possibility due to the excellent charging power capability of the LTO technology. By comparing the absolute height of the columns one can see that this combination is also significantly better than the best single pack battery system (reference) but in case of the reference EVs worse or at least not better than the global optimimum i.e. the combintaion of Panasonic and A123 cells for these EVs. This is due to the fact that the gain in power density switching from A123 cell to Toshiba cell is not that useful for these vehicle types that it would compensate the loss in energy density and increase in cost when switching between these two cell types.

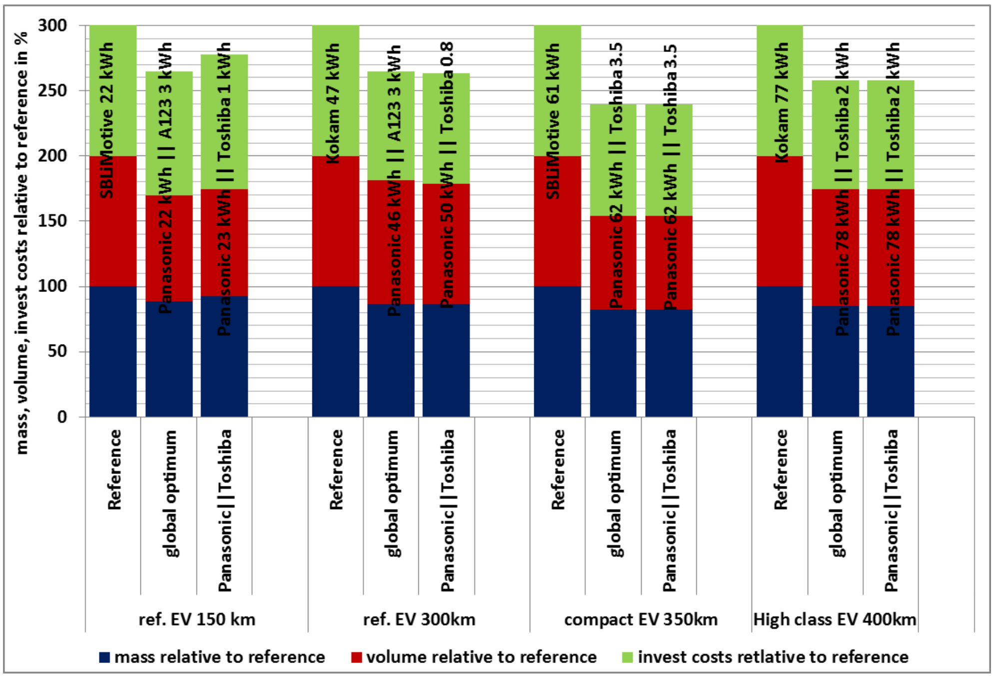

Figure 8: Battery optimisation results for different vehicle types

4 Hybrid Battery Demonstrator

For a detailed analysis of the operation of a hybrid battery system, a demonstrator is currently under development. It will be built up and characterized on the test bench of the Institute for Power Electronics and Electrical Drives within the project “HV-ModAL”. The system consists of a high-energy (HE) and a high-power (HP) battery pack, each connected to the dc-link via a bi-directional silicon carbide based dc/dc converter. The converters are also developed by the institute. While the two battery packs have a nominal voltage of 360 V and 400 V, the dc-link voltage can be set independently between 500 V and 800 V (topology in Figure 2 – right). The power supply, connected to the dc-link, is able to deliver up to 240 kW continuous charge or discharge power. One or multiple inverters and electric machines will be simulated by the Matlab-Simulink model, which is capable to emulate various vehicle classes and topologies.

An original battery system of a BMW i3 series electric vehicle is used as HE unit in the setup. It consists of 96 battery cells (Table 1 – SB LiMotive) connected in series and has a total energy of 21.6 kWh. It is capable to deliver continuous power of 40 kW in discharge mode and will be used in the system as long term energy storage unit. The HP battery pack uses 168 battery cells (Table 1 – Toshiba) with LTO anode material, all connected in series. A long cyclic lifetime and a high pulse power density during charging and discharging mode make the cells a suitable choice for an operation as peak power unit, which supports the HE pack in acceleration and recuperation phases, where power demands cannot be fulfilled by the HE pack alone. The HP pack will be cooled through a bottom cooling plate which is one of the investigated aspects during the test bench operation. The hybrid battery system will be used to investigate multiple subjects e.g. the influence of the dc-link voltage on the overall system efficiency or the optimal power split strategy, which determines the power distribution to the two battery packs in each driving condition. Measurements already started and will be completed end of 2017.

5 Conclusion and Outlook

In this work a methodology was developed and described to optimize hybrid battery systems for automotive applications. These battery systems can consist of different battery cell technologies which are connected by dc/dc converters on pack level.

After setting the requirements for a certain vehicle (e.g. acceleration, maximum speed and range) as well as defining a cell portfolio, the developed tool automatically searches for the battery solution which generates the least penalty points for weight, volume and the least invest costs. The search algorithm makes use of the optimisation approach “Covariance-Matrix-Adaption-Evolution-Strategy” (CMAES).

The obtained and presented results show that the hybrid battery approach generates significant advantages concerning weight, volume and invest for the investigated vehicle classes. The concept allows exact dimensioning of both energy and power simultaneously while using the best properties of two battery technologies. The hybrid approach was analysed by optimizing battery systems for each vehicle with the developed tool in three configurations: the best single pack approach considered as the reference, the best hybrid battery approach and a dedicated hybrid battery system using the cells with the highest energy density in combination with the cells with highest power density. It was shown that the weight advantage of the best hybrid battery system was at least 11 % for the smaller cars but up to 18 % for the compact class vehicle. Similar results were obtained for the volume reduction potential (5 % for the reference EV with 300 km range and up to 28 % for the compact class EV). The cost saving potential using hybrid battery systems ranges from negligible 5 % for the small vehicle to 17 % for the high class vehicle. The results show that in the investigated cases the weight, volume and cost advantages by far compensate the additional weight, volume and costs of additional power electronics which are included in the given numbers. The analysis also shows that for the investigated vehicles the cells and the energy content of each battery pack have to be carefully chosen and dimensioned.

Future extensions of the analysis will cover the best modularisation for multi-vehicle usage of battery types. Furthermore, the analysis will be extended to other vehicle classes like electric busses and light trucks. A hardware demonstrator with a hybrid battery system is currently constructed. It consists of an off-the-shelf BMW i3 battery pack assisted by a newly developed Toshiba LTO pack and two dc/dc converters which are also developed and constructed at the Institute for Power Electronics and Electrical Drives at RWTH Aachen University. The developed battery power distribution algorithm and hybrid battery management will be evaluated in this real setup of a hybrid battery system.

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