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Battery and battery management for hybrid electric vehicles: a review

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According to the legal, social and economic requirements for improved road transportation hybrid electric vehicles (HEVs) are one of the most intensively investigated vehicle concepts of today. To exploit their potential for emission reduction and performance improvement the energy storage system has to be considered as one of the key components of HEVs. This paper reviews the present state of the art pointing out advantages and drawbacks for each battery technology relevant for HEV application. Moreover, it describes the main constrains and requirements from the battery management's point of view. The tools usually applied by battery system developers are covered as well as the processes for identification and design of the optimal battery pack and the appropriate battery management. Finally, the main adjustments that are necessary for customizing a basic battery management system for a given battery chemistry are discussed.

Keywords: energy storage; hybrid electric vehicle; battery; lithium; battery management

Batterie und Batteriemanagement für Hybridfahrzeuge: ein Review.

Aufgrund der vielfältigen legistischen, gesellschaftlichen, ökologischen und ökonomischen Anforderungen an die Fahrzeuge von morgen werden Hybridfahrzeuge als ein zukunftsträchtiges Fahrzeugkonzept intensiv analysiert und entwickelt. Um ihr Potenzial hinsichtlich Emissionsreduktion und Leistungssteigerung voll ausschöpfen zu können, müssen die einzelnen Komponenten und Antriebe optimal designed und aufeinander abgestimmt sein. Eine der Schlüsselkomponenten in diesem Zusammenhang stellt das Energiespeichersystem dar. Der vorliegende Beitrag befasst sich daher mit einem umfassenden Überblick über den aktuellen Stand der verfügbaren Technologien unter besonderer Berücksichtigung der jeweiligen Vor- und Nachteile für den Einsatz in Hybridfahrzeugen. Darüber hinaus werden die Anforderungen und Rahmenbedingungen aus Sicht des Batteriemanagements diskutiert. Um für eine spezifische Applikation die bestmögliche Technologie auswählen und ein optimales Batteriepack und Batteriemanagement designen zu können, sind neueste Simulationstools und Testeinrichtungen erforderlich. Darauf aufbauend werden ausgehend von einem allgemeinen Batteriemanagementsystem die erforderlichen Adaptierungen zur Realisierung kunden- bzw. fahrzeugspezifischer Batteriesysteme diskutiert.

Schlüsselwörter: Energiespeicherung; Hybridfahrzeug; Batterie; Lithium; Batteriemanagement

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1. Introduction

One of the key components of alternative vehicles, like hybrid electric vehicles (HEVs), is the energy storage device acting as energy buffer. For obtaining the highest possible emission and consumption reduction and at the same time an increase of the vehicle performance a sophisticated energy storage system and appropriate battery-powertrain management is essential. This is achieved by recovering the breaking energy as well as an additional degree of freedom for the combustion engine allowing the engine load-point shifting. For such ambitious goals the battery and the battery management have to fulfil very pressing requirements.

2. Requirements and specifications

The specification of the energy storage system is one of the main issues for vehicle application. Depending on the field of application different hybrid vehicle concepts are reasonably leading to different requirements for the battery system. For example in compact cars as well as in light duty vehicles a hybrid powertrain allows to switch off the engine during specific operation modes. This Start/Stop operation mode can significantly reduce the fuel consumption of the compact car especially in urban traffic. On the other hand a hybrid powertrain with an electric drive capability allows package delivery companies also to deliver in restricted areas of city centres.

These two hybrid powertrain concepts require two different types of electric function with two different energy storage devices.

According to the pressing compact car cost requirements the hybrid configuration in many cases is a simple Start/Stop feature without e-drive mode and in some cases even without regenerative braking *(Miller, Brost, 2001; Sebille, 2003).* In this case the energy storage device is relatively small and the design criteria is the cranking peak power demand. For this application the preferable solution is a 12 V or a 36 V lead acid battery, in case combined with an electric double layer capacitor bank.

On the other hand the light duty vehicle with e-drive mode requires energy storage with enough energy content (kWh) for providing the required e-drive mode range. Compared to the compact car example this battery is much larger and allows the implementation of further functionalities like power assistance, engine load-point shifting, regenerative braking and electric auxiliaries.

Due to the fact that lead acid batteries and electric double layer capacitors have a relative low energy density, the adoption of such

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batteries for light duty vehicles is limited. For that purpose lithium-ion batteries, which ensure an energy density over 100 Wh/kg, seem to meet the requirements of the light duty HEV much better.

These examples simply point out the variety and complexity of the battery issue for HEVs and the need for specific tools to identify and design the optimal battery system for a given powertrain configuration.

For specification of the HEV configurations and the battery systems, respectively, various parameters are taken into consideration. The *power to energy ratio* (P/E) is a useful parameter to single out the different hybrid powertrains and to select the optimal battery. The typical characteristic values of each HEV configuration are outlined in Table 1. It can be seen that there is an overlap regarding the power performance and the energy content for the different powertrains, but each HEV configuration is well separated by its P/E.

Table 1. Characteristic parameter overview for different HEV configurations

Configuration	P/E	Energy [kWh]	Power [kW]	Voltage [V]
ISG	>60	<0,6	<6	12
Mild HEV	30 – 80	<1	<13	12 – 42
Power HEV	20	<4	20 – 100	>150
Plug In HEV	7 – 12	5 – 20	<80	>200
BEV	2 – 3	>15	20 – 60	NA

The energy content and the power performance are the main specifications for the battery design. In addition to this the designer should take into account other important aspects like the safety of the energy storage system, the system performances over a wide temperature range, the performance stability over life in terms of durability (ageing) and calendar life, as well as production aspects like the long term availability of the raw material and, last but not least, the costs.

Intensive international investigations are performed to define the energy storage requirements and related test procedures. Among these the efforts of the U.S. Department of Energy (DOE) in collaboration with some car manufacturers have to be pointed out. They have defined the energy storage targets for different HEV configurations *(Barnes, 2006; Howell, 2006; AA.VV, 2003)*.

The Ragone Plot

The Ragone Plot is an important graphical tool covering a lot of useful information for understanding the different battery characteristics. It is well known that electric energy storages show different characteristics depending on the load profiles. These characteristics are strongly nonlinear. When the cells are high rate discharged or charged the losses are higher and consequently the cells show a more decreased capacity than the nominal ones. Peukert introduced a coefficient for empirically describing this phenomenon from an amperometric point of view *(Peukert, 1897)*. Ragone with his plot summarised the results of many measurements performed with different power rate, and correlated the results with the energy storage weight. The Ragone Plot therefore gives the specific energy and specific power relationship and by that means an overview of the cell behaviour for different discharge power rates *(Ragone, 1968; Christen, Carlen, 2000)*.

Therefore the Ragone Plot shows in an easy way the power limit of an energy storage system and helps to identify the optimal operative range for each energy storage.

Figure 1 shows a typical Ragone Plot of the energy storage devices relevant for HEV vehicles. It can be seen that each chemistry is localised in a well defined area of the Ragone Plot highlighting the specific operative range. For example the electric double layer capacitor (EDLC) is applicable for very high power needs, whereas lithium ion high energy batteries (Li-ion HE) are preferable for EVs.

3. Energy storage devices overview

Corresponding to the requirements for different HEV configurations discussed above the following will give an overview of the relevant energy storage devices for HEVs.

3.1 Lead acid battery

The lead acid battery is already commonly used in conventional vehicles, mostly in sealed configuration. This energy storage device is the oldest secondary battery and therefore its technology is well known and widely used.

This accumulator has lead (−) and lead oxide (+) as active material on the electrodes and sulphuric acid as electrolyte, which, in comparison to other secondary batteries, plays an active part in the reactions. For this reason one of the methods for determination of the battery state of charge is the electrolyte density measurement *(Kiehne, 2003)*.

Regarding the costs lead acid batteries are the best choice. But the weight limits its application to integrated starter generator (ISG) powertrains, due to the reduced energy content needs for this configuration. For that purpose the preferable battery type is a VRLA (valve regulated lead acid) one *(Karden et al., 2005)*, which is char-

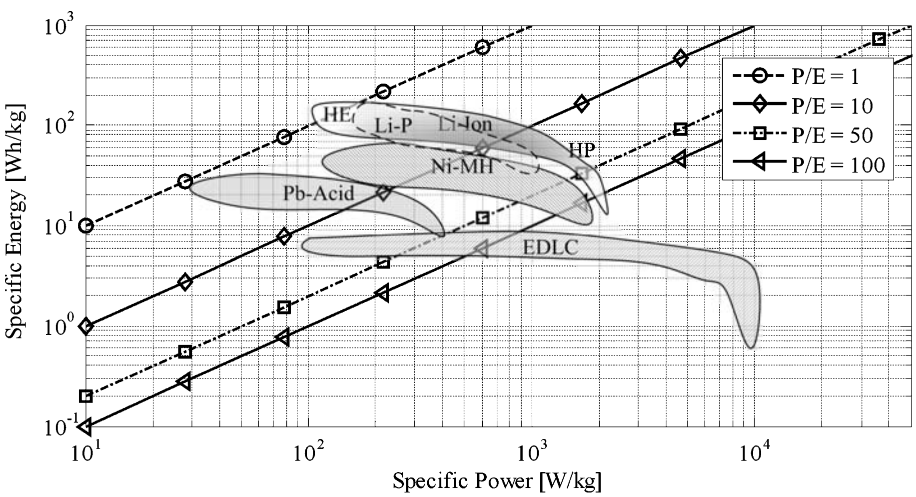

Fig. 1. Ragone Plot of different electrochemical energy storage devices relevant for HEVs and EVs

acterised by a higher Ampere-hour (Ah) turnover compared to the standard SLI (starting lighting and ignition) battery. In VRLA the application of an absorbent glass fibre mat (AGM) allows the oxygen transport via the gaseous phase with a consequent elimination of the oxygen reduction limit. The creation of this internal oxygen cycle permits to hermetically close the battery and therefore limits the drying up of the battery which leads to a consequent improvement of the life expectations*.

Though the VRLA has an increased life *(Spier, Gutmann, 2003)*, there are still some issues regarding the use under partial state of charge (PSOC). Shallow discharge cycles are inevitable for vehicles in city traffic where many stops are likely. The average engine speed as well as the generator speed is relatively low, only for short time periods the generator speed is high enough to enable the electric load supply and the contemporary battery recharging. Most of the time the battery is assisting the generator in supplying the loads. Therefore the battery is usually recharged at high rate, whereas it is discharged with an average low rate current. Based on this, the importance of the charge acceptance performance of the battery becomes obvious. Therefore the current rate and the voltage for the recharging process have to be determined accurately. They should permit the suitable recharge but at the same time they should avoid to exceed the charge acceptance limit of the battery. If the recharging is not aggressive enough the battery could undergo too deep shallow cycles with a consequent life shorting. This holds not only true for the VRLA chemistry but for almost any chemistry. On the other hand, if the recharging is too aggressive, the battery voltage as well as the average temperature could be too high, causing also a decrease of the battery life time. Hence, the battery strategy under PSOC must be well designed to avoid that these two factors will influence the battery life expectation negatively. For pointing out the optimal design the collected bunch of experiences for a mature technology like the lead acid one are definitely useful, but they are not completely sufficient.

Vehicle simulations and battery system simulations give an essential contribution to determine the optimal design solution in terms of battery sizing, strategy development, and system validation *(Gragger et al., 2006)*.

Concerning future market expectations for lead acid batteries in HEV application a big growth can only be expected if a technology breakthrough will occur. Research activities are trying to reduce the weight of the system by bipolar configuration *(Saakes et al., 2001)* or by modifying the lead electrodes using new lighter and more environmental friendly materials, in a way that lead is no longer used as support for the active material. Considering these new developments the system should not change strongly in its cell electrical characteristic but it will get lighter. Such a technology breakthrough would support the expansion of lead acid batteries also for other hybrid configurations.

3.2 Nickel metal hydride battery

The nickel metal hydride (NiMH) battery has been introduced few years ago as substitute of the nickel cadmium (NiCd) battery, which has a limited energy density, some severe environmental concerns and is affected by a pronounced memory effect. Nowadays, the NiMH alkaline battery is dominating the hybrid passenger cars market.

Comparing NiMH with other chemistries, NiMH batteries do not excel in any specific performance: lead acid is cheaper, lithium batteries generally offer higher energy density, as well as the NiCd has the highest cycle life and lower internal resistance which favours the application with high discharge current rates. The really big advantage of the NiMH is that it is a good compromise. Although there are no fields where it is outstanding, however, there are also no fields where it shows heavy weaknesses.

The specific density shown in the Ragone plot is not high, about 50 Wh/kg for HEV application, but it is compensated by a high power density, over 1000 kW/kg. The NiMH cell is similar to the NiCd cell, the positive electrode ($Ni(OH)_2/NiOOH$) as well as the electrolyte (KOH) are the same, whereas for the anode a metal hydride alloy (MH) replaces the cadmium electrode. During charging this alloy receives hydrogen ions and stores the hydrogen in a solid state. This capture of the hydrogen in solid state is weaker than in the cadmium electrode and this results in a higher self discharge rate of the cell, which is one of the NiMH cell weaknesses. However, compared to the Cadmium electrode the voltage depression, usually named ''memory effect'', under partial discharge usage is limited *(Conte, Pirker, 2005)*. This is very important because HEVs' load profiles are characterized by a narrow SOC bandwidth variation, usually around 50 – 60 %. Therefore the battery works mainly under partially discharged conditions where the memory effect can become significant, leading to a lowered power performance and a virtual lowered available capacity.

The NiMH thermal behaviour is more complicated than in NiCd batteries. An oxygen recombination mechanism between positive and negative electrode takes place when the positive electrode is fully charged. This oxygen reactions produce heat which is added to the heat of the exothermic charging process, whereas in NiCd this process is endothermic. All these factors lead to a higher temperature during charging than in NiCd cells. Therefore the NiMH battery shows a less pronounced voltage peak when fully charge. The detection of the end of charge is very tricky and an advanced charging battery management is mandatory. This battery management must be able to determine the optimal cut off voltage for any temperature condition and charging current *(Linden, Reddy, 2002)*.

Based on this overview the importance and challenges of the battery management for the NiMH becomes obvious. On the other hand a cell misuse usually only effects the life cycle, and only in case of a really strong misuse safety issues, like gassing or thermal runaway, occur. According to this intrinsic NiMH strength it is sufficiant to adopt module level monitoring systems, avoiding the installation of more complex and costly cell monitoring level systems.

NiMH batteries are nowadays the only batteries used in hybrid passenger cars because module level monitoring can be used, they have a good endurance against misuse, and the production is

Fig. 2. Nickel exchange price *(London Metal Exchange)*

* In any case a valve is present, that is sometimes opened for venting the hydrogen excess generated by the corrosion at the positive electrode and by the hydrogen evolution at the negative electrode.

rather uncomplicated. Due to these facts NiMH batteries are relatively inexpensive.

The future of this technology mainly depends on the development of the Li-ion technology and the future costs of nickel. The price of NiMH batteries has been reduced in the last years even when the row material price has strongly increased. But there are worries if battery manufacturers could maintain this trend. As shown in Fig. 2, the costs of nickel have been terribly increasing in the last years, moreover, since July 2001 the price has exploded by a factor of five – and this against any analysts market forecasts *(London Metal Exchange; US. Geological Survey Minerals Yearbook, 2005)*. For this reason it is hard to imagine that the NiMH battery costs will decrease in a remarkable way.

3.3 Lithium based batteries

The HEV's engineers are looking forward to an energy storage with very high energy density and specific energy. If such battery would be available the efficiency improvement in transportation would be substantial. Lithium based energy storages have the potential for such a breakthrough technology. This is based on the low equivalent weight of the metallic lithium combined with a very negative redox potential which makes it attractive as negative electrode for a high energy density cell. Moreover, the positive ion size of lithium is small, hence, it could easily diffuse into an appropriate compound cathode electrode which is able to store this lithium. This results in a cell with an adequate power density.

Although reactive lithium is not present in nature as lithium metal alone, nevertheless its compounds are abounding innature; therefore the lithium price is low. Based on the aspects mentioned above it becomes obvious why American, European and Japanese research programs heavily invest in the lithium chemistry development *(Barnes, 2006; Howell, 2006)*.

There are many different types of lithium batteries, however, it is out of the scope of this work to describe each chemical configuration in detail. An overview will be given focusing on the remaining open issues which prevent the lithium chemistry to be fully ready for HEV application.

Four main battery types can be distinguished: lithium metal, lithium metal polymer, lithium ion polymer and lithium ion.

The lithium metal cell has a lithium metal negative electrode, which is responsible for the very high energy density that can be achieved. On the other hand lithium is reactive against the organic electrolyte, which is mandatory for such high voltage cells. The reaction between the lithium metal and the electrolyte creates a solid electrolyte interface (SEI) and lithium passivation effects with consequent dendrites formation occur. These dendrites strongly reduce the battery life cycle and raise the likelihood of internal short circuit which results in safety risks. For reducing dendrites formation specific electrolytes are adopted as well as the charge current has to be limited. This recharge restriction together with the limited cycle life limits the adoption of this cell for HEV applications.

Another family of lithium based cells are using a polymeric electrolyte. Configurations with a lithium metal anode, so called lithium metal polymer cells, have been developed as well as configurations with intercalation compounds, so called lithium ion polymer batteries.

The adoption of a solid ion-conducting polymeric electrolyte can increase the energy density because the polymeric electrolyte contemporarily works as a separator. Hence, the cell is even more compact and more suitable for mass production. In addition a laminated configuration allows for realisation of cells with different capacities by changing the cell surface. Furthermore, a solid electrolyte increases the safety of the cell by preventing leakage.

On the other hand the solid state of the electrolyte is also the biggest disadvantage of these polymers because it leads to a reduced conductivity and therefore requires very thin membranes. For improving the conductivity liquid plasticisers could be adopted, however, to the detriment of the solid electrolyte safety improvements.

The most common lithium-based cell is the lithium ion one. In this case the lithium metal anode is replaced by a lithium insertion compound. The electrodes are intercalation electrodes, that means that the lithium ions can be intercalated or deintercalated in the host material depending on a charging or discharging process.

These intercalation processes are highly reversible and dimensional stable giving a good cycle life of the lithium ion cell. Furthermore, also safety increases compared to the lithium metal configuration.

On the negative electrode carbon-based materials are the state of the art. Alternatively, simple graphite or petroleum coke is applied. The first one is more commonly used because it shows a good specific capacity, it is highly cyclable and inexpensive.

A multitude of lithium metal oxides able to store lithium ions are proposed for the positive electrode. Cobalt which is a standard for consumer applications is too expensive for automotive application. Furthermore, Cobalt raises severe environmental concerns. Lithium manganese oxide suffers from a lower specific capacity but on the other hand it is less toxic and less expensive. Lithium nickel oxide is characterized by a good specific capacity and a good cycle life but it shows a lower thermal stability. For these reasons these materials do not meet all the requirements for HEV application *(Duong, 2000)*. In the last years investigations have been focused on developing and testing new ''doped'' compounds which are able to achieve the performance goals of HEV application with reasonable costs and without safety compromises *(Howell, 2006; Amine et al., 2002; Shim, Sierra, Striebel, o. J.)*. In particular lithium phosphate cathodes seem to provide interesting features especially concerning safety issues, because the oxygen bond is stronger compared to other proposed chemistries and it generates less heat during misuse *(Nguyen, 2004)*. Moreover, the phosphate is a widely used component and therefore rather inexpensive. However, there is also one main disadvantage with respect to other cathodes regarding the limited power rate capability. To overcome this, research activities focus on improving the power rate capability by using specific carbon coatings *(Geoffroy, Ravet, 2004)*.

Summarizing the lithium based chemistries the main barriers preventing the introduction of lithium technology in HEVs are:

- *Calendar Life*. The calendar life of energy storage is an important issue for any car application because the battery is only used for short time periods and most of the time it remains in stand-by modus. The high lithium voltage and the lithium reactivity against the electrolyte as well as the extreme environmental conditions the battery is exposed to in a vehicle raise major concerns on calendar life. For this reason the calendar life of new developed cells must be proven in relevant tests *(Howell, 2006; VV.AA., 1996, 2001)*.
- *Temperature range extension*. The cell conductivity decreases at low temperature, especially due to the electrolyte. This negatively influences the discharge power performance as well as it prevents the adoption of an aggressive regenerative braking strategy because it can lead to lithium plating. The operation of lithium batteries at high temperatures is also an issue that has to be further addressed. The electrolyte which is operated at high voltages – typical for a high SOC – and high temperatures can become instable and an exothermic electrolyte oxidation can occur resulting in a hazardous thermal runaway. Even without such critical operation conditions the charging at high rate and high temperature can accumulate gaseous electrolyte decomposition products, again raising safety concerns.

Table 2. Relevant energy storage performance overview

	Temperature [°C]	η_E [%]	Energy		Power [W/kg]	Voltage [V]	Self-discharge [%/Month]	Cyclelife @80 %DoD	Cost estimation	
			[Wh/l]	[Wh/kg]					[$/kWh]	[$/kW]
Lead Acid	−30 – 60	85	50 – 70	20 – 40	300	2,1	4 – 8	200	150	10
NiMH	−20 – 50	80	200	40 – 60	1300 – 500	1,2	20	>2500	500	20
Li-ion	−20 – 55	93	150 – 250	100 – 200	3000 – 800	~3,6	1 – 5	<2500	800	50 – 75
EDLC	−30 – 65	97	5	5 – 20	15000	~2,5	30	Not applicable	2000	50

- *Safety*. The lithium ion development provides continuously improved performance cells with better behaviour under misuse. However, there are still issues to be addressed. As obvious limitations of the lithium phosphate cells, for instance, overcharging and overdischarging, mechanical stress, as well as high temperature exposure can be named resulting in safety problems *(Kitoh, Remoto, 1999).* The lithium reactivity as well as the likelihood of the organic electrolyte decomposition could lead to hazardous conditions like cell venting, as best case, or flame and even explosion as worst cases. The current research is working on more stable and safer systems, like thermally more resistant ceramic separators. Furthermore, more environmental friendly components are investigated like alternatives for the popular hexafluorophosfate ($LiPF_6$) salt which up to now has to undergo a not inexpensive recycling process.
- *Costs*. The costs of the lithium batteries have to decrease. At the moment this chemistry is far away from the target costs, both in $/kWh and in $/kW, that have been determined by OEMs and independent research institutions as reasonable for allowing their introduction in HEVs *(Barnes, 2006)*. Theoretically, the lithium based cells for HEVs could be inexpensive, because the raw material is common in nature, but practically the costs are still high due to expensive development processes and production costs. For stable and life resistant systems high quality materials, e.g. for the separator have to be used. The production of such material with low impurities is expensive due to the needs of expensive production devices *(Andermann, 2003).* An actual cost estimation and performance overview for each relevant chemistry is given in Table 2 *(Conte, 2006).*

Lithium ion chemistry offers the highest performance potential and high design flexibility. It will be possible to realise high power (HP) as well as high energy (HE) cells by just making few design modifications. In this way, a wide area of the Ragone Plot will be covered, thus fitting to the requirements of a wide range of HEVs.

Therefore, it can be summarized that the lithium technology, most likely the lithium ion one, is the mid and long-term pathway for HEVs if the cost and safety issues will be properly addressed.

3.4 Electric double layer capacitor

A different energy storage system is the electric double layer capacitor (EDLC). This device stores the energy in a different way compared to classical electrochemical energy storages. In capacitors the energy is directly stored in the electric field.

The EDLCs, also named supercapacitors, have a high capacitance thanks to the adoption of active carbon electrodes characterised by a large active surface ($>2000\,m^2/kg$). When a voltage is applied to the EDLC a charge transfer takes place in the electrolyte. The ions in the electrolyte move to the boundary interfaces between electrolyte and electrodes. At this interface the energy is stored in the electric field of the two electrochemical double layers. Those layers are responsible for the high capacitance due to their extended surface and their extremely small thickness in the order of the molecular dimension of the ions *(Willer, 2003)*.

Without going into chemistry details, the big advantage of the ELDC is its surface phenomenon without faradic reactions. This implies very fast kinetics which ensures a high power performance. Moreover, the absence of faradic reactions results in an outstanding cycle life of the ELDC.

As a drawback, as clearly shown in Fig. 1 and Table 2, the modest available energy has to be named which limits the applicability of EDLCs to only power cache applications *(Wright, Jamison, 2003).*

The electrolytes developed for EDLCs show a good conductivity over a wide temperature range, especially when acetonitrile (CH_3CN) solvent is adopted. For this reason EDLCs show an outstanding cold cranking performance which allows their application in combination with other energy storage systems *(Burke, 2002)*.

The maximal admissible temperature is higher than in other energy storages, moreover, at high temperature the capacitance increases. However, a high average operating temperature encourages parasitic electrochemical reactions. Electrolyte oxidation caused by electrode structure modifications results in a consequent capacitance fade and accelerated ageing *(Brucchi et al., 1999*).

Concerning the safety issues of the EDLC a simple SOC detection, which is obviously depending on the cell voltage, helps to get reliable and safe systems. The only pressing requirement concerns the implementation of a cell level monitoring system. This monitoring is essential to prevent overcharging as well as overdischarging of each cell. While overdischarging, in case of cell reversing, this mainly influences the ageing, overcharging could cause hazardous conditions because the organic electrolyte decomposition increases the internal pressure. Hence, during overcharging cell venting could occur raising safety issues similar to those in lithium cells *(Barrade, 2001)*.

The optimisation of production processes has drastically cut down the costs Nowadays, a target cell price of 0.01 €/Farad is achieved. Of course the costs of the inevitable electronic cell monitoring board have to be added, however, the price has become competitive and the first series applications are appearing on the market *(Burke, Miller, 2003).* EDLCs have not been used as the main energy storage system up to now. However, they have been implemented as an assistant power supplier for heavy electric loads in HEVs like for the electric air condition, the electric braking pump or the electric steering system.

4. Battery management for HEVs

As described above each chemistry has its specific requirements and constrains which have to be taken into account for their operation to avoid accelerated ageing or safety issues. The battery management system (BMS) is the system monitoring the correct battery pack operation and performing the appropriate safety steps in case of hazardous situations.

Electrochemical energy storage devices are getting better, their performance increase as well as their life cycle. However, even if the energy density will further increase, they are still limited compared to fossil fuels. For example the energy content of the lithium ions HE battery is only about one fifteenth of the gasoline energy content *(Goodstein, 2004; Brooks, 2002)*. Hence, it is essential to optimise the electrochemical energy storage system to get the best performance achievable with the available chemistries. In particular, it is necessary to define the best battery for a given application, the appropriate configuration and the *optimal* operating strategy. In this design process the application of simulation tools and hardware-in-the-loop (HIL) test facilities are very useful.

For that purpose arsenal research has developed a simulation tool that takes into account all the complex and often nonlinear interactions that characterise the electrochemical energy storage systems *(Gragger et al., 2006; Ebner, Conte, Pirker, 2006)*. Using this tool and the HIL battery test infrastructure the configuration of a battery pack, its electrical design and cooling configuration can be defined.

For instance, laminated, prismatic or wounded cells require different thermal cooling concepts (Fig. 3). Their development process can be significantly improved by means of simulation tools. Laminated cells theoretically offer a high heat exchange surface and a small temperature gradient inside the cells. Therefore, an air cooling system can be adopted when the mechanical fastening system is properly designed. However, the mechanical construction for laminated cells is a rather challenging task. Arranging the cells in a pile drastically reduces the cooling surface which is not acceptable for HEV application. On the other hand the adoption of spacers between the cells reduces the mechanical strength of the pack.

Fig. 3. Samples of Li-ion cells

For wounded and some prismatic cells the handling is easier because the two poles are used for their mechanical fastening. However, the thermal model for the BMS is more critical because it has to take into account the thermal gradient between the internal and external layers of the cell.

4.1 The BMS from inside

It is evident how complex the development of a battery pack for an HEV is, and the BMS development is an integral part of this process. Therefore, a BMS for a HEV application is described in more detail.

The BMS, as shown in Fig. 4, needs an acquisition unit for monitoring the battery voltages, the currents, the temperatures, and in some cases other quantities like the pressure. These state quantities are necessary for estimating the state of the battery pack. Furthermore, the BMS has embedded electrochemical and thermal models. By means of these models the relevant parameters, like the SOC, the

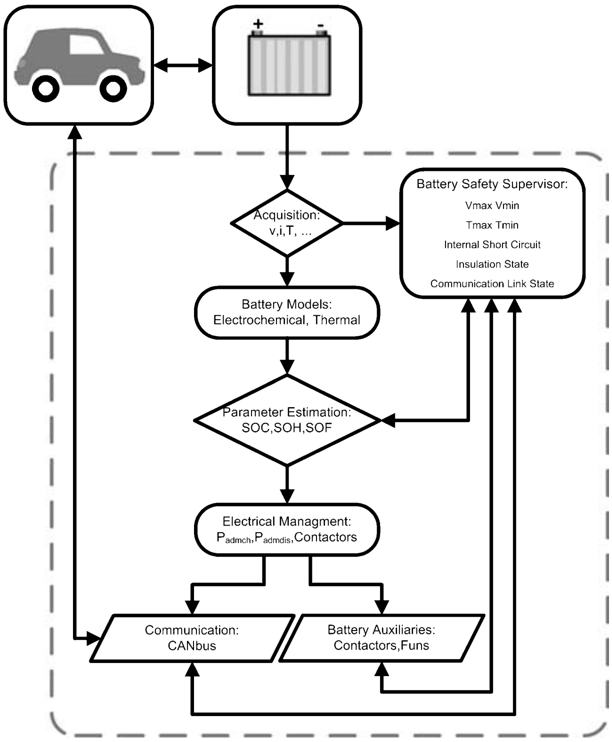

Fig. 4. Battery management system diagram

state of health (SOH), the state of function (SOF), the internal cell temperature, the internal resistance, etc. are determined. Based on these values the BMS is able to deduce the electrical management, in particular the admissible load limits for the near future. These results are communicated, usually via a CAN interface, to the powertrain management system that subsequently defines the *load flow* between the internal combustion engine, the electric drive and the hydraulic braking system.

In addition, the BMS operates the auxiliaries like the cooling fan speed, in case of an air cooling system, or the pump delivery, in case of a liquid cooling system. Besides that the BMS manages all the electrical and electromechanical circuitries for executing the precharge process or for coordinating the insulations like the shutdown in case of hazardous conditions.

Apart from all those tasks, one of the most important tasks of the BMS is the battery safety supervision. The battery safety supervisor ensures that the voltages, the currents, and the temperatures are within the admissible and forecasted ranges. Moreover, the battery safety supervisor monitors the insulation state and, if necessary, operates the contactors for disconnecting the battery pack from the powertrain. Furthermore, also the communication interface has to be supervised. It is essential that the connection between the vehicle management system and the BMS works correctly. Otherwise a precautionary battery pack disconnection from the powertrain can occur with subsequent unpredictable, and potentially hazardous vehicle behaviour.

4.2 BMS adaptations corresponding to the chemistry needs

In the previous paragraphs each chemistry and its specific needs in terms of voltage and current ranges, as well as charging strategies and temperature constrains has been given. Those differences between the cells naturally affect the BMS configuration and operation. Therefore, a description of the main BMS specific adoptions for each chemistry is given.

The lead acid management is already well known. For this chemistry the final charging voltage is an essential parameter. It is well-regulated by the device temperature for avoiding a drying out of the battery. The voltage monitoring could be performed at a module level. The thermal management is facilitated by the big thermal capacity of the lead acid battery and the limited influence of the temperature on the performance. The SOC and SOH estimation is intrinsically complicated. However, many years of experience with this chemistry facilitate the design of reliable models. Based on the big amounts of data also expert models can be adopted *(Salkind et al., 1999).*

The NiMH battery distinguishes from the lead acid due to its strong temperature dependence. Therefore, an accurate thermal management is necessary.

The SOC estimation is tricky due to the flatness of the voltage plateau. Besides that the NiMH battery shows a voltage depression under certain condition. This mandatorily requires a BMS able to detect and handle this memory effect. Hence, a voltage sensing is not satisfactory for estimating the SOC. In addition, at least a coulometric counter with a series of current rate adjustments should be added for the SOC estimation.

Microcontrollers usually require an adequate computational performance for executing a complex SOC model as well as for calculating the voltage depression growth. Nevertheless, the BMS for NiMH is less costly than for lithium-ion or EDLC because the voltage and temperature sensing could be done on a module level.

For lithium based or EDLC systems a cell level monitoring and balancing system is ineluctable to avoid overcharging. Since this complex balancing system has to be very reliable and precise, consequently also the costs increase. On the other hand for lithium based and EDLC systems the voltage is linked to the SOC simplifying its estimation.

The maximal currents are critical for lithium based cells and depend on the temperature and the cell typology. An incorrect current rate, especially for charging, accelerates the cell ageing.

The SOH estimation is usually based on precalculated look up tables and on the monitoring of the parameter variation like the internal resistance derivative or the capacity/capacitance derivative. More complex SOC-SOH estimators like those based on the electrochemical impedance spectroscopy (EIS), adaptive systems using fuzzy logic or neural networks can also be applied *(Hariprakash, Martha, Shukla, 2003; Hawkins, 1995).* In this case the BMS requires a high performing microprocessor for processing the big amount of data. Moreover, a tuning phase based on careful and time consuming laboratory analysis is mandatory for validating the strategy. Although these model approaches are more complex they are more accurate and reliable ensuring a higher safety level and the achievement of the maximal performance possible.

The importance of the BMS must not be underestimated. A good cell basis is mandatory for achieving a reliable and performing energy storage system. However, the cells have to be managed in the best possible way in order to utilize their full potential.

As an example the lithium ion chemistry can be given. The choice of the operating voltage range is a key issue, in particular the choice of the maximal charging voltage depends not only on the cell but also on the application. The BMS can decide to adopt a maximal charging voltage lower than the voltage suggested by the manufacturer, because for the given application that lowered voltage fulfils the same requirements but, the stress for the battery is reduced. In fact at high voltages the secondary reactions are facilitated unnecessarily shorting the battery life. Therefore, by lowering the voltage the BMS increases the battery life *(Bergveld, Kruijt, Notten, 2002).*

Control parameters like the ones mentioned above differentiate BMSs. This know-how, based on the manufacturers' inputs, the simulations and the laboratory results, allows the BMS developer to develop battery management strategies that maximise the cell performances by simultaneously minimizing the overall costs of the energy storage for HEVs.

5. Conclusions

A reliable, inexpensive energy storage system is ineluctable for realizing successful HEVs. The paper has summarized different options to solve this technical problem. Different scenarios offered by old, but still valid batteries like the lead acid, and by new developed energy storages like the lithium ion battery have been discussed. The presented advantages and disadvantages of each chemistry have shown that there is nothing like a *perfect* battery with high power, high capacity and eternal life. Even though lithium based cells seem to be the pathway for the HEVs' future.

The description of the BMS features and requirements have demonstrated that a general solution for a HEV battery pack is not possible. Only by combining advanced modelling techniques, HIL test facilities and comprehensive designer know-how the *optimal* energy storage system solution for any HEV application can be determined.

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