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Thermal Management of Hybrid Vehicle Battery Systems

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Abstract

Complete system design, including mechanical, electrical and thermal control, is critical to realize the benefits of Li-Ion technology in automotive batteries. In order to meet the technical requirements in a demanding automotive environment efficient thermal and electric control strategies have to be developed and implemented. These strategies must deliver on two opposing goals: a wide operation window to support optimal vehicle performance and protection of the battery from states which could negatively influence reliability, safety and long term endurance. This is true for all applications ranging from small batteries in Mild Hybrid Vehicles to large batteries for Full Electric Vehicles. Due to the wide variety of performance requirements in these vehicle applications the control strategies must be flexible and adaptable. The special requirements of these applications and the applied technologies will be discussed.

Keywords: Battery Management // Efficiency // Heat Exchange // Lithium Batteries // Thermal Management

1 Introduction

Li-Ion-Batteries play an increasing role in the electrification of vehicles to improve fuel efficiecy and reduce emissions. These batteries are required to provide a broad spectrum of power and energy capability.

The general challenge is to package sufficient energy and power capability in given space of the target vehicle. In many cases these are existing vehicle platforms in which the high voltage battery must be mechanically and electrically integrated with consideration for weight limitations, the climate control system and other vehicle interfaces. Even with new vehicle platforms the goal is maximum energy density, with the result being minimized weight and volume impact of the battery system.

During the operation of the vehicle the battery system is subjected to a wide range of thermal and electrical load conditions. In order to support optimal energy efficiency the power capability of the battery must be maintained during these conditions. Since batteries are electrochemical systems, lower temperatures lead to decreasing power capability and elevated temperatures can lead to premature aging of the device.

This paper discusses techniques for how the high demands for available energy and power can be fulfilled using suitable battery designs and management strategies to maximize the utilization of the battery. The focus of the discussion is on the design and management of the thermal system to keep the cell temperatures in the optimum range. A short overview on the control strategy to maximize the utilization of the battery in real world conditions will close the presentation.

2 Requirements for a Li-Ion Battery System

2.1 Performance

A battery system typically includes the following main requirements:

- Power levels for charge and discharge at ambient temperature as well as at low temperatures, especially if a crank function needs to be supported by the battery system.
- Range of energy in which the specified power levels should be provided
- Calendar lifetime over which the battery must be fully capable
- Cycle lifetime that indicates the energy throughput roughly corresponding to the expected life and usage of the battery.
- Power and temperature profile to be considered to calculate aging effects of the battery.
- Targeted mass and volume
- Specific mechanical packaging envelope and location in the vehicle.

This key specification defines the required system-level specific energy and power. The following figure shows typical ranges for the spectrum from mild hybrid to full EV:

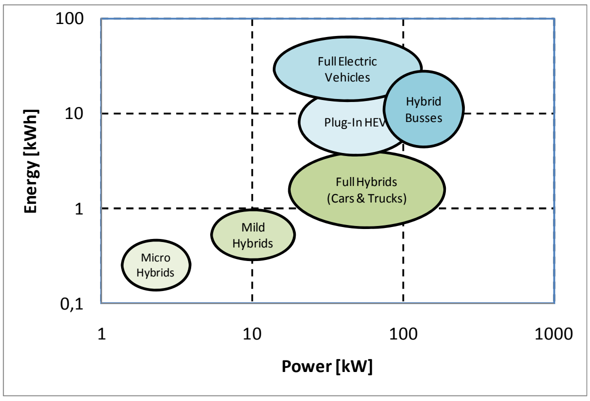

Figure 1 Energy and power ranges for battery systems for different vehicle applications.

As these specific power and energy requirements push to the limits of existing battery technology – in many cases a good step beyond – almost all battery system requests explicitly state to use Li-Ion technology.

In Figure 1 the ranges for power and energy of the whole spectrum of high voltage vehicle batteries is shown. It should be mentioned that there is no established standard voltage range for any of these applications. While the most applications operate in the range at or below 400 V, many commercial vehicle applications require nominal voltages greater than 700 V.

2.1.1 Vehicle Integration

In most cases the targeted hybrid or electric vehicle is based on an existing car platform. Therefore, rather than designing the car around the battery, the battery needs to be packaged into the car while infringing on the functionality of the car as little as possible. This leads to a required package volume which may or may not correspond well to existing system architectures or components. The challenge is to find the best combination which provides the required functionality with the least amount of compromise.

For the definition of safety features it is important to know where the battery is to be located in the vehicle. Possible locations can be in the passenger compartment, including the trunk, or outside in the engine compartment or under floor. A seal is provided to both prevent moisture and other contaminants from entering the battery as well as ensuring that vented gasses are managed appropriately during an in abuse situations like a crash. The location of the battery in the vehicle can influence the sealing strategy for both of these functions.

In regard to thermal management, care needs to be taken for potential hot components placed close to the battery.

3 Performance Characteristics of a Li-Ion Battery System

3.1 Design characteristics

Given the primary customer requirements, the battery system can be designed as follows:

- The required power-to-energy density balance leads to the choice of a cell type that is optimized for power delivery, energy storage or a combination of both.
- The voltage range defines the number of cells in series.
- The required energy and/or power level defines the capacity of the cell.

Typically, electric vehicle applications are driven by a certain range requirement which defines the usable energy content of the battery. To meet this requirement the energy content of the battery can be extended by connecting two or more cells, modules or full strings in parallel. The maximum number of parallel cells or strings may be limited by the complexity and cost impact of the system.

3.2 Power dependence on State of Charge and Temperature

The available power depends largely on the temperature and state of charge (SOC) of the battery. At lower temperatures the power capability decreases but the battery is still capable providing power down to -40°C and below. At higher temperatures the power capability of Li-Ion cells is increasing, but must be limited at a certain point – between 50°C and 60°C – to prevent accelerated aging and to maintain the cell in the safe temperature range. The preferred temperature range – providing a close to maximum power capability and providing acceptable thermal ageing rates – is between 20°C and 40°C.

Discharge power decreases towards lower states of charge and the charge power decreases while approaching the fully charged state.

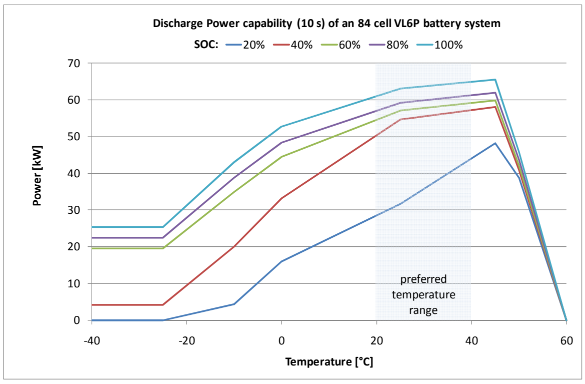

Figure 2: Discharge power capability based on temperature and state of charge

The power limitation is based on two factors, cell voltage and maximum current. For the NCA/graphite technology used by JCS the voltage limits are 2.5 V for discharge and 4.1 V for charge. The current limit is dependent on the cell type, temperature, and may be different for discharge and charge direction. It can be further limited by components of the battery or vehicle system.

3.3 Utilization of the available energy

The utilization of available energy is different for power and energy systems. The operation strategy for a full or mild hybrid vehicle utilizes relatively small swings in SOC, typically below 10%, superimposed on macro swings utilizing a bigger range of the available SOC spectrum. A typical target operation range is a 20 % SOC window which lies somewhere between 40% SOC and 80% SOC.

For high energy applications such as PHEV or EV a much larger SOC window is essential to achieve the electric range targets of the vehicle. For a Plug-In-Hybrid application three operational modes are considered:

The **charge depletion mode** of the battery is linked to the electric drive mode of the vehicle. The battery is discharged by propulsion, acceleration, and supply of other electrical loads of the vehicle, with some amount of recharge by regenerative braking pulses. No regular recharge is provided in this mode, since the combustion engine is turned of. The acceleration pulses (discharge direction) and regenerative braking pulses (charge direction) define the required power level and therefore the SOC operating range of the battery. Since the charge balance is negative for this mode, the achievable mileage for pure electric driving is defined by the total energy content of the battery and the provided minimum full power SOC. A typical charge depletion SOC window covers 70%.

In the **charge sustaining mode** the vehicle is operated like a hybrid vehicle. The purpose is to optimize the energy efficiency of the power train. The combustion engine is running and can provide regular charging to the battery. A charge neutral operation is possible.

The third mode is the plugged-in **recharge mode**. Normal charging in the range up to 10 A as well as quick charging with much higher rates is considered. Since during the recharge phase the combustion engine is not operable, this phase is typically run without active cooling.

An EV application also comprises the charge depletion mode and the external charge mode, while no charge sustaining mode is available.

3.4 Effect of aging

A Li-Ion battery is subjected to two different kinds of aging. One is driven by thermal effects the other is by cycling.

The thermal aging defines the calendar life of the battery. The rate depends on the temperatures of the cells as well as the on the state of charge. Looking at a certain state of charge – fully charged is more severe than partially charged – the temperature dependence could be well approximated by an Arrhenius type law:

$$k_{aging} = exp(-E_a/RT) \qquad (1)$$

This means, for instance in the case of Li-Ion cells, that increasing the temperature by ca. 10 – 15 K would lead to 30% - 50 % reduction in life endurance.

The thermal aging increases the internal resistance and decreases the total capacity of the battery cells over time. The same effects can also be caused by cycling of the battery, where larger cycling depths as well as higher current levels result in faster aging rates.

Since the required performance data typically apply to end of life status, which is normally given by a certain number of calendar years and / or by a number of operating hours/cycles, the design of the battery needs to anticipate these aging effects and define the ‘size’ of the battery based on the evaluation of the specified temperature histograms and electrical load cycles.

To estimate the thermal aging effects correctly and support a suitable operation time temperature level, a thorough design and analysis of the thermal management systems is necessary, as will be explained in the following chapters.

4 Thermal Management

4.1 Heat generation in cells

The basic ‘work’ of a hybrid or EV battery is the transfer of electrochemically stored energy into electrical energy, and the reverse. Every battery has an internal resistance which depends on several factors as previously discussed. Therefore, based on equation (1) below, the application of an electrical load profile always generates heat in the cells with the rate P_{loss}.

$$P_{loss} = I^2 * \mathrm{R} \qquad (2)$$

The internal resistance R is related to ohmic as well as polarization losses in the cell and the electrical collector system.

This heat either needs to be dissipated (heat dissipation rate $P_{dissipate}$ or increases the temperature of the cell.

Looking at a time period Δt, the temperature is increased by

$$\Delta T = (P_{loss} - P_{dissipate}) * \Delta t / c_{bat} \qquad (3)$$

In Figure 3 a typical hybrid load cycles is shown as well as temperature curves with and without heat.

4.2 Heat buffering capability of the battery system

As indicated in Figure 2, the ideal temperature range of the cells is between 20°C and 40°C, while higher temperatures could be tolerated temporarily. The power capability is degraded as temperature is increase to prevent from overheating.

If the battery is at a certain temperature in the ideal range, it can absorb waste heat that cannot be dissipated by the cooling system immediately. The heat buffering capability is given primarily by the heat capacity of the cells, with some additional contribution from the tray or module housings.

As an example, the heat capacity of a 9.5 kWh PHEV is 84 kJ / K, of which more than 90 % is given by the cells. If the average cell temperature is 30°C and the cooling system is able to dissipate 10 W/cell, but the heat loss is 13 W / cell for a period of 30 min, the cells will heat up by 5.6 K, according to (2).

In the case of a PHEV, cell temperatures in many applications will not reach elevated steady state temperatures before the end of the charge depletion cycle is reached. So it may be that the thermal management system's heat rejection capacity is determined by the lower RMS current of the longer charge sustaining cycle, where steady state temperatures can easily be reached.

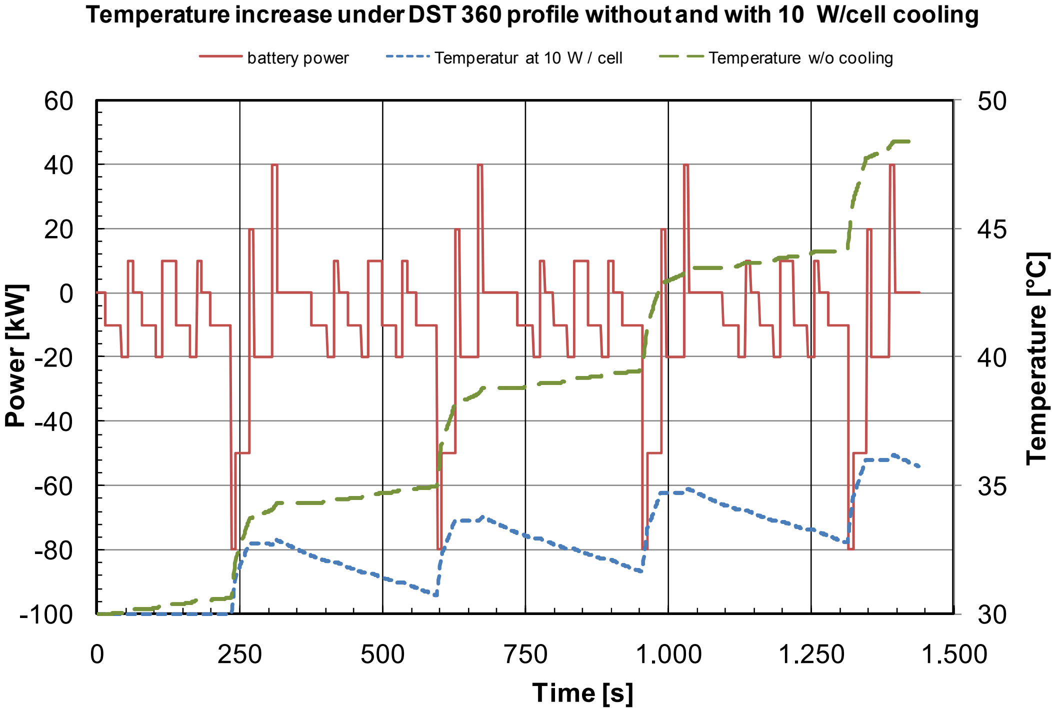

Figure 3: Temperature increase under DST 360 profile with and without cooling (10W/cell).

4.3 Uniformity of cells

An HEV or EV battery requires a thermal management system that is able to keep the cell temperatures uniform. The target is to maintain the maximum and minimum cell temperatures within a 3 - 5 K range.

At lower temperatures the coolest cell determines the power capability; at elevated temperature the hottest cell sets the rate of power limiting. A cell spread of 5 K can lead to a variance in power capability up to 10 % relative to the maximum peak power. In the range of the high temperature power degradation the effect is even much higher, could be up to 50%.

Another effect of temperature imbalance among cells is that thermally induced aging will be more rapid for cells which are consistently hotter than the others. A 5 K difference would result in an approximate 25 % acceleration of the aging kinetics.

If, over a longer period of time, the cell temperatures have significant variation, the self discharge rates will also be different. This leads to SOC deviations among the cells. Since the cell with the lowest SOC determines the discharge capability and the lower end of the usable energy range, and the cell with the highest SOC determines the upper end of this range, non-uniform self discharge rates will lead to reduction in the effective operational SOC window.

5 Cooling systems

The heat capacity of the battery can buffer only a certain amount of waste heat. Further on continued operation at elevated temperatures contributes to the thermal aging of the cells. Therefore in most cases an effective active cooling system may need to be installed in the battery. There may be cases where an active cooling system is not necessary, assuming the heat capacity of the battery is great enough to maintain the maximum and variation in cell temperatures within critical limits.

Depending on the operational profile, the size of the battery system and the vehicle environment, a suitable cooling system can be chosen from the available alternatives. There are three general types that can be implemented, distinguished by the cooling medium:

- Air
- Water / glycol mixtures
- Refrigerant

All of these types have advantages, disadvantages and require a different level of integration into the vehicle.

5.1 Air cooling

The essential idea of an air cooled battery system is to utilize the conditioned air from the passenger compartment to maintain the battery in desired temperature range in warm ambient temperatures. As previously noted, the ideal temperature range for the battery to achieve the best balance between performance and life is between 20°C and 40°C. The typical temperature of conditioned cabin air is consistent with these targets. In case of colder ambient where no cabin AC is used, it is an option to use air taken from the outside with control by a actuated damper.

In the case where air is taken from the passenger compartment, the maximum flow rate is typically limited, depending on the type of car, between 100 m^3/ h and 250 m^3/h. For passenger cars these limits are driven by both cabin comfort and noise considerations. Conditioned air taken from the cabin is not available to cool occupants and this must not compromise their comfort level. Noise caused by airflow or the fan must be kept below the ambient threshold as much as possible to avoid customer dissatisfaction. This can be compensated somewhat by adapting the fan speed to the noise level of the car given by the engine noise level as well as wheel rolling noise.

Filters for the incoming air may be necessary to prevent dust and other particle contamination inside of the battery system. This is especially true if the air is taken directly from outside the vehicle rather than pre-filtered air from the passenger compartment.

The case of cell venting during an abuse situation, and the potential emission of toxic gases like carbon monoxide, must be considered in an air cooled system. These gasses cannot enter the passenger compartment even in an extreme abuse cases like a crash situation. They must be routed outside of the vehicle separate from the air circuit. Therefore adequate sealing must be implemented to ensure segregation between the cooling air circuit and the vent plenum.

As stated earlier, the cooling system must be able to keep the cell temperatures as uniform as possible. Air flow simulations are executed in the course of the battery development to ensure this goal will be met. Examples are shown in Figure 4: CFD simulation of the air flow and cell temperature uniformity for a 44 cell stack of cross flow type. for a cross flow cooling system and in Figure 5 for an axial cooling system. Simulations as well as measurements on real battery systems show that up to four cells in series can be cooled sufficiently in most applications.

The cross flow cooling strategy, where air passes over the cells in a transverse direction, can be the preferred solution if the height of the battery is limited by vehicle packaging constraints. On the other hand, if the footprint is limited, an axial air cooling design can be implemented. In this case the air is provided below the cells and ducted through a tray in a uniform way along the skin of the (cylindrical) cells and is collected in the head space of the battery.

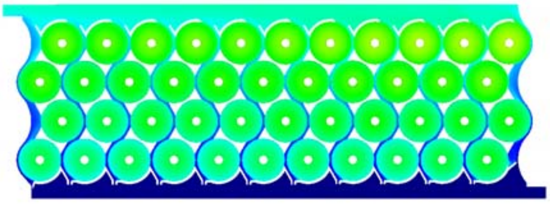

Figure 4: CFD simulation of the air flow and cell temperature uniformity for a 44 cell stack of cross flow type.

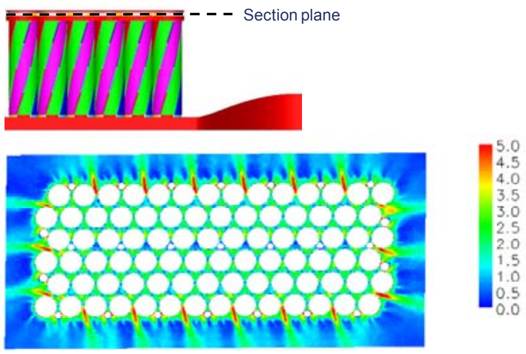

Figure 5: CFD simulation of the air flow for a 96 cell stack of axial cooling type.

Designs have been developed and tested providing similar cooling efficiencies for both design approaches. Heat dissipation rates of up to 10 W / cell have been demonstrated. Based on the design of the air channels even higher cooling rates seem possible, with the penalty of decreased packaging efficiency due to larger spacing between cells.

5.2 Low pressure liquid cooling

In some applications it is difficult to package a fan and air ducts in the vehicle or there is not enough space for a proper cell arrangement to provide sufficiently uniform air cooling. In these cases liquid cooling, where water/glycol mixtures are pumped through the battery, can be an option. One advantage of this type of system is that the pump, coolant reservoir and heat exchanger are typically arranged outside the battery and have more package flexibility than a fan with ducts.

This type of system can be implemented in large blocks (whole or partial systems) but are best used in smaller modules which maximize packaging flexibility and reuse in multiple systems. In a module the cells are arranged (e.g. in a 2 x 6 matrix) inside the housing with a cooling element placed between with sufficient contact to the cells. To setup a battery these modules can be mounted either horizontally or vertically and are hydraulically linked by cooling tubes and manifolds. Arrangements of modules in parallel, series or a combination are possible in order to optimize the packaging and cooling performance are possible. A schematic for a parallel arrangement is shown in Figure 6.

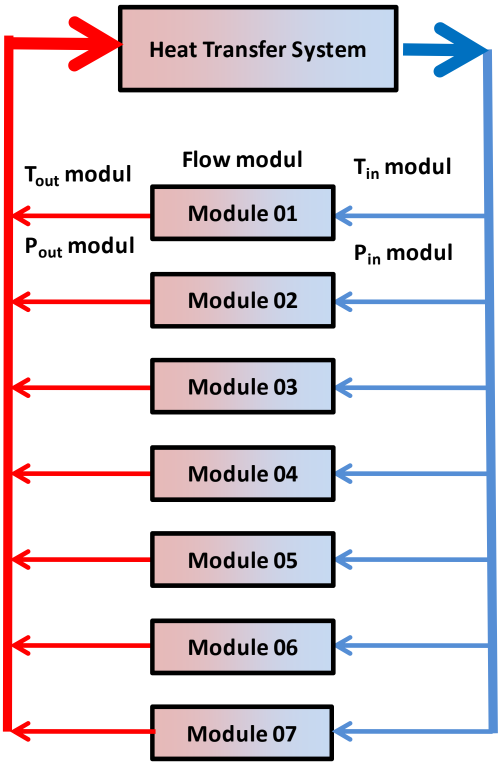

Figure 6: Schematic of the heat transfer system of a liquid cooled battery

In selecting the cell count for a module there are considerations in addition to the thermal management strategy. The modules also contain the electronics and electrical connections, so the selected size should provide the best combination of cost (cell count higher) and package flexibility (cell count lower). A size of 12 cells per module has been identified as providing a reasonable compromise between packaging flexibility and component cost.

The cooling capability $P_{dissipate}$, expressed in W/cell, depends on the following factors:

- Coolant temperature $T_{coolant}$ near the cell
- Thermal resistance $R_{thermal}$ of the path from the cell internals to the coolant medium

$$P_{dissipate} = (T_{cell} - T_{coolant}) / R_{thermal} \qquad (3)$$

where T_{cell} is the inner cell temperature.

The average coolant temperature at the cell depends on the inlet temperature and the coolant flow rate. The higher the flow rate, the lower the outlet temperature and the average temperature near the cells. Since a low thermal resistance is the key to sufficient cooling rates, it is essential to establish a close contact between the cell surface and the heat exchanger.

The heat dissipation is driven by the temperature difference between the cells and the cooling liquid. To keep the cell temperatures sufficiently uniform the difference between inlet and outlet coolant temperature needs to be kept in small limit (e.g less than 3 K) by using a sufficient flow rate.

Given the statements above, under quasi steady state conditions (i.e. constant RMS current load profile) the inlet temperature determines the temperature level of the cells. The thermal resistance determines the necessary temperature difference to dissipate the generated waste heat. Ultimately, this sets the requirements for the cooling of the cooling liquid, the total volume of the liquid and the type of heat exchanger outside the battery.

One possibility is a liquid-to-air heat exchanger, either with ambient air or with a forced air flow using the cabin air. Since the air temperature is often in the range of 25°C or above, coolant inlet temperatures of approximately 30°C can be achieved with this method. This reaches cell temperature levels in the range of ca. 35°C to 45°C, depending on the load profile. For passenger vehicle applications with average daily operation times of 1-2 hours this may be acceptable. However, for commercial vehicle applications with much longer daily utilization of the vehicle this would lead to accelerated thermal aging, as previously discussed.

Another option where duty cycles are particularly aggressive is heat exchange with refrigerant from the climate control system. The refrigerant temperature is typically in the range of 0°C-10°C, which enables much lower cell temperature levels, even under even more severe load conditions. However, this creates greater complexity with respect to vehicle integration.

5.3 Refrigerant cooling

A third type of cooling system utilizes refrigerant directly in the battery system, in close contact with the cells. In this case the battery acts as a second cooling path parallel to the cabin cooling loop, as showing in figure 7. The requirement is that the passenger comfort must not be compromised by the battery cooling. The balance of both loops is controlled with use of expansion valves.

The refrigerant material, typically R134a but moving to CO_2 in the near future, enters the battery with a high percentage of liquid, which subsequently evaporates as it passes among the cells, exiting with a low liquid percentage. With this type of system cooling rates in excess of 20 W / cell are possible.

This type of system also provides the best packaging densities as the cooling tube cross-sections are small compared to water/glycol heat exchangers. Modular or individually customized packages are possible.

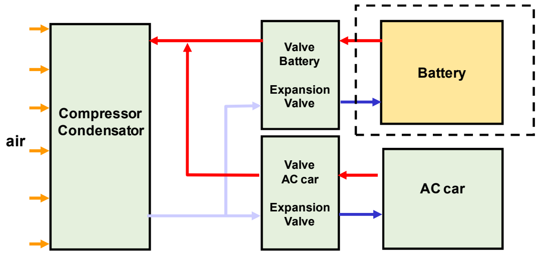

Figure 7: Schematic of the climatic system of a vehicle with refrigerant cooled battery parallel to the AC loop for passenger cabin cooling.

5.4 Selection of cooling medium

The choice of battery cooling system depends on the constraints and requirements of the vehicle application. The total cost impact to the vehicle must also be considered. Heat exchanger possibilities, available space for fans and air ducts, as well as safety constraints must be taken into account. Where the operating environment is particular harsh or the duty cycle is extreme, closed loop systems like water/glycol or refrigerant may provide better cooling efficiency.

6 Control Strategy

Based on the chosen type of cooling system a strategy must be defined which takes account of all the measured inputs and defines control outputs. Typically the cell temperatures are measured at representative locations in the battery. Thermal cell models allow for the estimation of the inner cell temperature based on the measured values which determines the internal resistance and the thermal aging rate. Coolant inlet and outlet temperatures are also measured to control the coolant flow. For systems using ambient air or cabin air, the corresponding air temperatures can be transmitted to the battery by CAN bus.

Since active cooling requires energy – to operate fans or coolant pumps, to control valves or to put additional load onto the drive train for more AC power – the cooling intensity should be controlled to maintain the temperature level of the battery cells but also minimize the total energy usage of the system. This control may be done continuously with PWM controlled fans or pumps, or in a binary way by switching on and off the coolant flow. A hysteresis must be implemented for the binary option, to avoid excessive switching and early wear out of cooling components.

A proper thermal management strategy needs to be accompanied by equally effective electrical management of the cells and system. Based on measurements of current, cell voltages and cell temperatures, the SOC is estimated, tracked and corrected. For cobalt oxide based lithium ion technologies SOC accuracies better than 5% are feasible, allowing a precise management of the usable energy range.

Single cell voltage measurement allows control of the cell voltage limits and precise SOC determination. The knowledge of the state of charge of each cell, as well as of a representative number of cell temperatures is the base for power capability forecasts that will be communicated to the vehicle hybrid controller. This allows the vehicle to utilize the power capability of the battery system with maximum efficiency, while keeping the cells in the safe operational range. This also allows detecting voltage variations between the cells, which can be balanced by dedicated discharge of single cells.

7 Summary

To support the high demand on specific energy and power in HEV, PHEV and EV applications, the utilization of a battery must be maximized. This must be done by design, including the right choice and size of the battery cooling system, and by implementation of appropriate thermal and electrical management strategies.

Different types of active cooling systems have been presented. The choice for either air cooling, low pressure liquid cooling or refrigerant cooling depends on the heat dissipation demand imposed by the application profile, any vehicle integration constraints, and with consideration of the total vehicle cost impact.

An active thermal management strategy keeps the cell temperatures in the appropriate range, to provide sufficient power capability as well as to avoid aging rates higher than anticipated. The electrical management controls the SOC range to maintain the necessary charge and discharge power availability.

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