32nd Electric Vehicle Symposium (EVS32)
Lyon, France, May 19-22, 2019

48 V High-power Battery Pack for Mild-hybrid Electric Powertrains

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Executive Summary

Mild hybridisation, using a 48 V system architecture offers fuel consumption benefits approaching those achieved using high-voltage systems, at a much lower cost. To maximise the benefits from a 48 V mild-hybrid system, it is desirable to recuperate during deceleration events at as high a power level as possible, whilst at the same time having a relatively compact and low cost unit.

This paper examines the particular requirements of the battery pack for such a mild-hybrid application and discusses the trade-offs between battery power capabilities and possible fuel consumption benefits. The technical challenges and solutions to design a 48 V mild-hybrid battery pack are presented with special attention to cell selection and the thermal management of the whole pack. The resulting battery solution features a continuous-power capability of more than 10 kW and a peak-power rating of up to 20 kW. The paper will present the results from testing of the pack.

Keywords: Battery, HEV (hybrid electric vehicle), regenerative braking, vehicle performance

1 Introduction

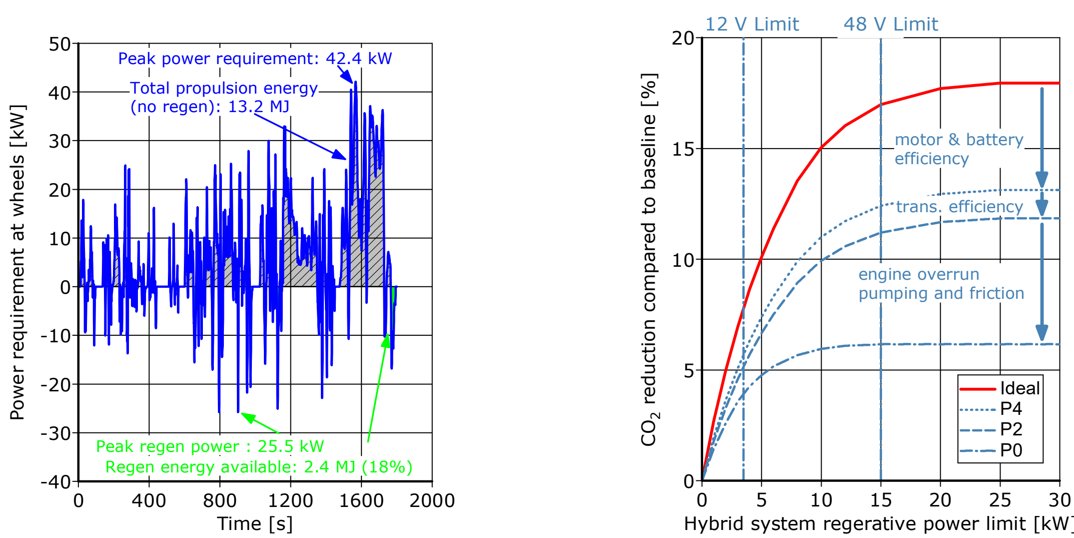
Mild-hybridisation, using a 48 V system architecture, is currently receiving significant interest, as it can offer fuel consumption benefits close to those achievable with high-voltage systems, at a price similar to a conventional 12 V architecture. To maximize the benefits achievable through a 48 V mild hybrid system, it is desirable to be able to recuperate during deceleration events at as high a power level as possible. At the same time, to minimize the cost and installation package required by such a 48 V hybrid system, it is also desirable to be able to minimize the storage capacity of the battery. These conflicting requirements lead to the desire to have a small battery pack capable of repeated high power charge and discharge events.

The investigation of 48 V battery pack requirements in this paper is based on a C-segment mild-hybrid vehicle, which has been fitted with a highly downsized 1.2 litre, 3-cylinder, engine equipped with a belt-integrated starter generator (BSG) and a 48 V electric supercharger (eSupercharger), in addition to a conventional turbocharger [1]. This demonstrator vehicle achieves performance levels that are equivalent to the non-hybrid production 2.0 litre TGDi vehicle that it is based on, whilst achieving a CO_2 reduction of

15 % over the new European Driving Cycle (NEDC) and 12 % based on the World-harmonised light-duty test procedure (WLTP).

2 Hybrid System Power Requirements

It has been shown in previous studies [2] that the peak recuperative requirement for the target vehicle over the WLTP cycle is 25.5kW, with potential recuperative energy of 2.4 MJ available under idealised circumstances, as shown in figure 1a. This means that up to 18% of the energy deployed for propulsion could be regenerated for use, offsetting the fuel consumption of the vehicle. This 18% ideal saving is degraded through component and system inefficiencies and sources of friction, as shown in figure 1b, but with a very high power system and minimised losses through the use of a P4 hybrid layout, it is possible to realise up to 13% CO_2 and fuel consumption reduction.



a) b)

Figure 1: Hybrid system power requirement: a) Power required at the wheels to propel a C-segment car across the WLTP; b) Influence of recuperation power capability and electric machine installation location on CO_2 reduction potential during WLTP

This level of performance is achievable using a 48V P4 Mild Hybrid Electric vehicle (MHEV) electrical system with charging and discharging capability of at least 20 kW. This was taken as the performance target for the battery pack designed during this investigation.

3 Battery Pack

The maximum charging and discharging performance of the pack is already defined. In terms of the pack storage requirements, analysis revealed that after a regeneration event, deployment at the next acceleration event is as effective as any other control strategy. Furthermore, events demanding high power are generally shorter than 10 s. Therefore quite a modest electrical storage capability is required. The targeted capacity enables a maximum discharging or charging event for a duration of at least 15 seconds beginning at a state of charge (SOC) of 50 % and not exceeding the safe operating window of 10 to 90 % SOC.

Table 1 summarises the targets set for the pack developed during this study. The minimum and maximum system voltages have been set to comply with the limits defined in LV148 [3] for 48 V automotive systems.

Table 1: Battery pack high-level targets

Parameter	Value
Nominal voltage	48 V
Minimum voltage	36 V
Maximum voltage	52 V
Discharge Current	>= 650 A
Charge Current	>= 500 A
Capacity	>= 0.3 kWh
Power	>= 25 kW

3.2. Cell Selection

The high-level performance targets enabled the selection of cells most suited for use in this battery pack. Using information from different cell manufacturers, pack layouts were configured for each solution. This was achieved by calculating the number of cells that would be required in series to achieve the voltage targets set out in Table 1 and then by also looking at the number of parallel strings required to achieve the charging and discharging targets given in Table 1. It should be noted that the selection of the final number of cells in series was not just based on meeting the nominal voltage target but also to achieve a well-balanced discharging and charging capability within the lower and upper voltage boundaries. Once this exercise was complete, it was possible to compare the total mass of the cells and total package volume of cells required to meet the pack level performance targets, for all of the cells considered. This enabled the identification of a high-specific output cell, with a relatively low specific energy capacity, as being the cell most suited to this application.

The cells selected for this application were based on Lithium Titanium Oxide (LTO) technology. Furthermore, it was the sub-variant of high power (but low energy) cells which were considered to be the most appropriate for this application. The expected duty cycle, results in a high frequency of very high current charge and discharge cycles, with more extreme state of charge swings being experienced during more aggressive driving cycles, as can be seen in Fig 2. In this study then discharge current was limited to 250A to maximise the efficiency of the energy used for propulsion, but the maximum charge current was unlimited to enable maximum recuperation in order to maximise the stored energy available. The LTO cells used have a very high specific power capability, with 20-50C being, theoretically, reliably available with adequate cell cooling with little effect on cell lifetime.

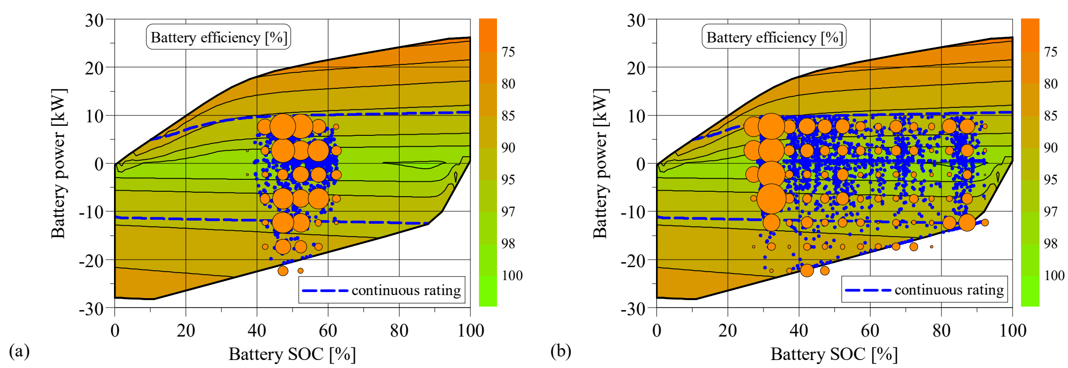


Figure 2: Operating points in efficiency map during different drive cycles: (a) WLTP, (b) RDE.

LTO cells have additional benefits, one of which is better low temperature performance relative to more traditional Lithium ion technologies. The traditional layered carbon anode is replaced with a titanium oxide anode, which inhibits lithium plating. Lithium plating is common at low temperatures in traditional carbon anode cells and can also occur when charging currents are too high for the chemical reaction that allows the lithium ions to collect between the intercalation layers of the carbon anode to occur, at which point they collect on the outer surface of the anode. Additionally, lithium plating can be encouraged by high cell voltages, around 4.2V [4]. The lower characteristic voltage of LTO means that voltages this high cannot be reached without excessive over-charging. The lack of lithium plating with LTO cells has two positive effects, it prevents the loss of capacity seen when the plated lithium prevents lithium storage within the layers of the carbon cathode, resulting in less degradation in energy capacity under these usage conditions. Secondly, there is no risk of dendrite formation which can be a result of lithium plating. Lithium dendrites can cause ruptures of the separator material and short circuiting of the cell, which has the potential to lead to thermal runaway.

Additional safety benefits are realised by the ability of the LTO chemistry to withstand external trauma such as penetration and crush by forming a protective layer of low conductivity LTO around the site of the damage. This protective layer inhibits the high current discharging between layers in the cell normally caused by these type of events. This results in a much slower discharge event, which is much less likely to lead to critical overheating of the cell chemistry and is therefore more likely to avoid cell fire or explosion.

The negative characteristic of LTO technology is the low characteristic cell voltage. LTO has a linear voltage range between 2.3 and 2.6 volts, with a nominal mid-point voltage of 2.45V, as shown in Fig 3. This compares to a nominal mid-point voltage of around 3.2V for other lithium Ion chemistries, such as Lithium Iron Phosphate (LiFePO4). This means that to get to the desired pack voltage, a higher number of cells are required in series, which can lead to higher costs, weight and package size. However, in this application, the very high specific power capability of the cells used means that no parallel strings are required to achieve the desired power levels, resulting in a small package considering the performance targets.

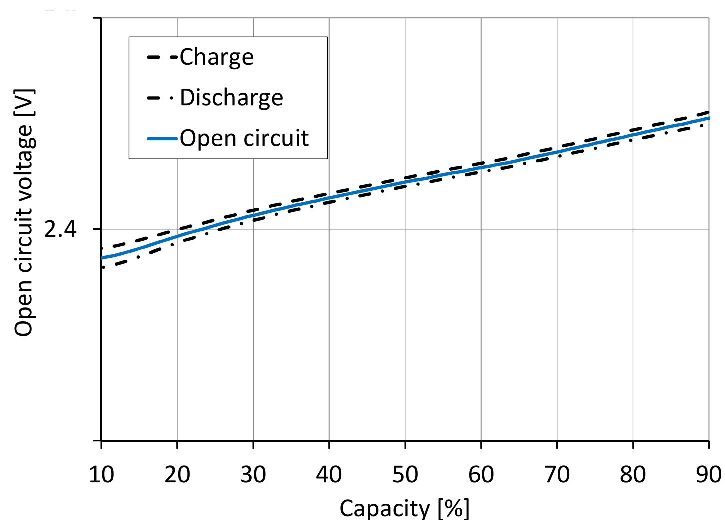


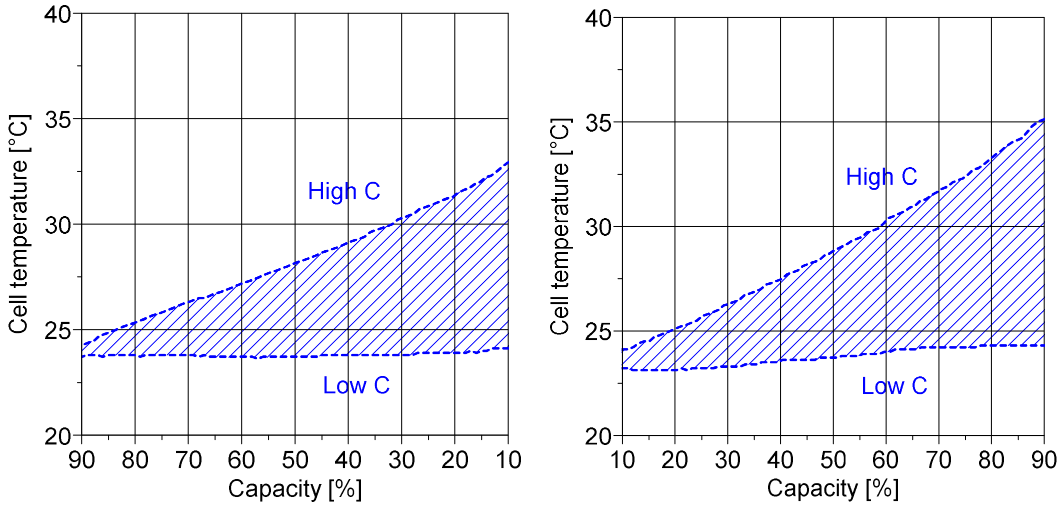
Figure 3: Open circuit voltage of the LTO cell used in this investigation, tested at 23 °C

3.2. Cell Characterisation

Individual cells were subjected to a series of tests using a climatic test chamber. The purpose of these tests were to validate the overall energy capacity of the cells, the open circuit voltage profile and also the effect of increasing discharge rates on the temperature and the voltage of the cells. This data was used to inform the likely performance of the overall battery pack and to assess the degree of cell cooling that would be required.

The cells were tested at soaked temperatures of 10, 23 and 40 ºC, where they were charged and discharged at increasing rates from low to high C ratings. Tests were not performed at very high levels because the cell was tested in an uncooled state.

Fig 4 shows an example of the measured cell temperature test results at an ambient temperature of 23 ºC and a starting cell temperature of 24 ºC, under both charging and discharging conditions which correspond to relatively low C-rates.



a) b)

Figure 4: Temperature of the cell; (a) discharging at various C ratings; (b) charging at various C ratings

It can be seen that under the most extreme condition, a temperature rise of 11 ºC is measured following a full charge or discharge event. The temperature rise in both cases is similar but the charging temperatures are generally higher, indicating a small increase in the internal resistance of the cell under charging conditions. In a battery pack of large capacity where this type of charge or discharge cycle may be experienced over a long length of time and normally at a lower rate, it could be questioned whether cell cooling is required. The maximum allowed cell temperature far exceeds the levels seen above and headroom still exists when the tests are performed at a 40 ºC ambient temperature. However, the highly cyclic nature of this small capacity MHEV battery pack leads to repeated charge and discharge cycles over a significant range of state of charge with only short cooling periods between events. Fig 2a shows the battery operation points expected during a WLTP cycle. As previously illustrated in Fig 2b, the SOC variation during the more aggressive and transient RDE-compliant test cycle are quite severe and will lead to a higher thermal load on the cells. Without cooling, it is expected that the maximum cell temperature would be exceeded quickly. For this reason active cooling using a water-glycol coolant was incorporated into the design of the pack.

It is also necessary to maintain stable system voltages during high current charge and discharge cycles. With some cell chemistries, severe changes in system voltage are experienced during high current events. This can lead to de-rating of the performance of the system, restricting the amount of energy that is able to be recovered and deployed during driving. The cell characterisation tests showed small changes to the voltage of the cells, even during the high discharge events. Figure 5 shows the cell voltage variation with SOC for high charging and discharging rates at an ambient temperature of 10 ºC (the lowest temperature tested).

At low cell temperatures and very high discharge rates, the voltages will droop further, which may require some de-rating of the pack performance at very low SOC levels. For example, at 10 ºC, the voltage droop at the pack level would be in excess of 2 Volts, but the natural cell warming resulting from increased resistive losses will heat the pack to the medium temperatures quickly, after which it will be maintained by the cooling system.

Further characterisation tests will be carried out at lower temperatures and using transient loading cycles to represent aggressive in vehicle use, to establish the transient behaviour of the cells under cooled and uncooled conditions.

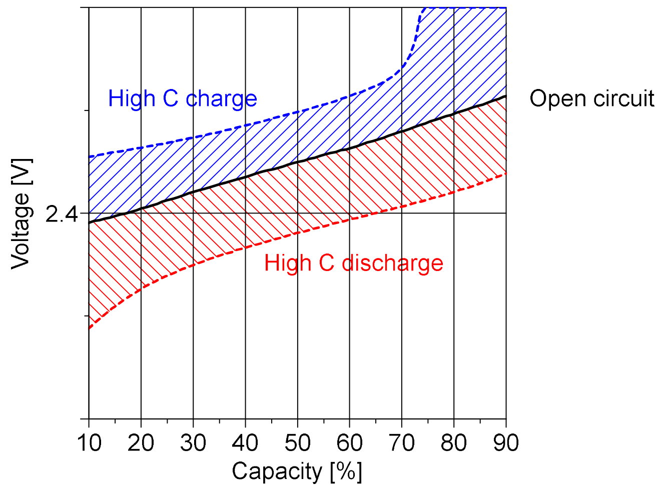


Figure 5: Terminal voltage curves at 10 °C for high C discharging and high C charging

It was possible to calculate the theoretical useful lifetime of the cells, using data provided by the cell supplier. The useful lifetime was defined as the point at which only 80% of the original capacity of the cell is available for use. The capacity against charge/discharge cycles data was measured at a rate of 3C and using the different drivecycles described earlier in this paper to inform the number of full charge and discharge cycles expected per unit distance (km). It was therefore possible to estimate the lifetime of the pack under these conditions to be approximately 250,000 km using the WLTP test profile and even higher lifetime over the RDE test profile.

3.3 Battery Pack Performance and optimisation

Once the cells had been selected, the battery pack was designed and analysed and a detailed investigation of the peak pack performance was carried out, as described in an earlier paper [3]. An image of the resulting pack is shown in Figure 6. Using an equivalent circuit for the battery cells to model open-circuit voltage and internal resistance correctly and adding parasitic resistances and power consumption on the pack level, a performance map could be derived.

Figure 6: Main module of the battery pack

The result is shown in Figure 7. The pack can provide up to 26 kW electric power while discharging and for recuperation in the vehicle an electric charging power of up to 28 kW is theoretically available at the extremes of state of charge. With the thermally stable continuous rating of ±250 A, a discharge power of 10 kW, and a charging power of 12 kW is achievable.

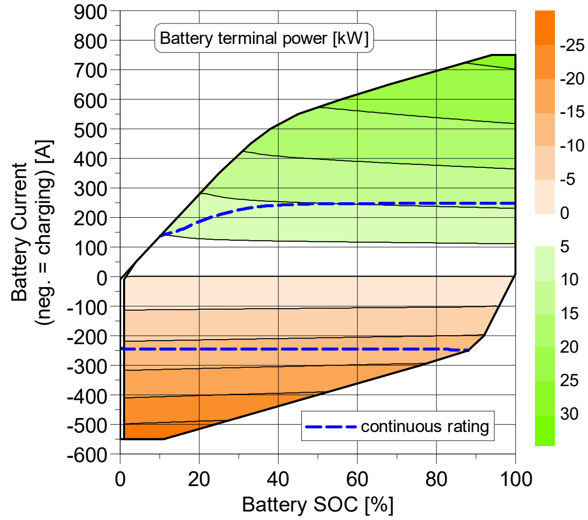


Figure 7: Possible operating conditions of proposed battery pack

To achieve this level of performance, the detailed design of the components was of key importance, including the minimisation of resistive losses of the components themselves and also of the connections. This was achieved through the careful optimisation of each component in the system from the initial design concept, through simulation of the resistive losses and component heating to identify high resistance hot-spots and final re-optimisation of the design based on the conclusions drawn. The accuracy of this process was improved through bench testing of reference samples to correlate the initial assumptions and hypotheses. In addition, the more complicated Battery Management System (BMS) components, which could not be accurately modelled, were characterised using resistance measurements and thermal survey techniques. The results of some of these tests are illustrated in Fig 8.

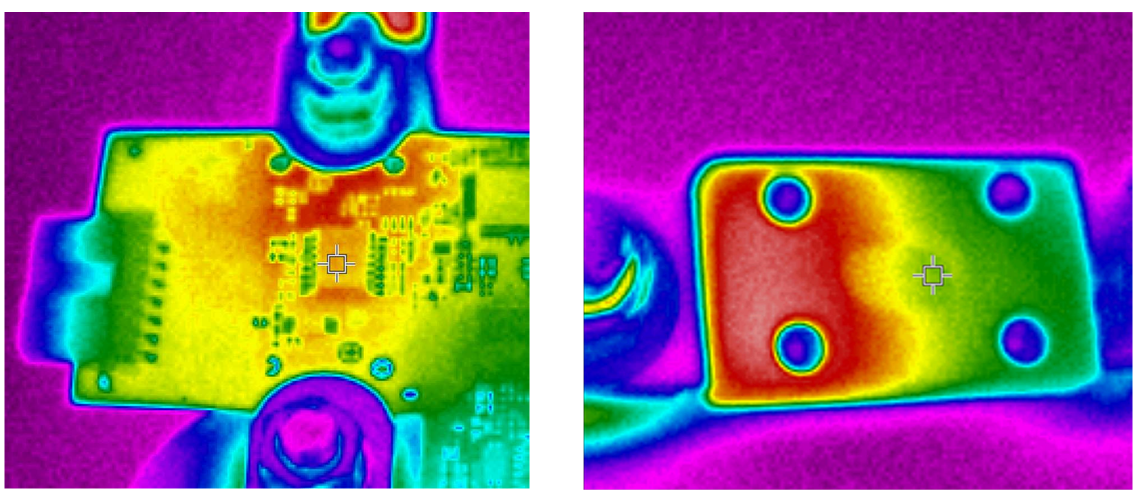


Figure 8: Thermal images of system components during constant current testing

The resistance of the electrical connection point was also considered, starting with the busbar welding pattern. Different welding patterns were trialled and the resistance measured to establish the minimum required weld path and the trade-off between weld complexity and resistance, as can be seen in Fig. 9. This enabled a cost effective and mechanically robust solution to be selected, with low resistance. The final designed components were also checked against the calculated values to close the loop on the model correlation process. Finally, the relationship between contact pressure and resistance at the bolted joints within the pack was also quantified to enable robust instructions to be written to provide consistent low loss connections to be achieved and also to minimise losses and subsequent busbar heating. Minimisation of the heating of the busbars is important to prevent additional load being added to the cooling system and reduce the temperature of the cell terminals which are subjected to heating not only from the internal resistance of the cell, but also direct heating of the terminals though resistive losses and also heat generated by the busbars, which must be carried down through the terminal, through the cells and out to the cooling system.

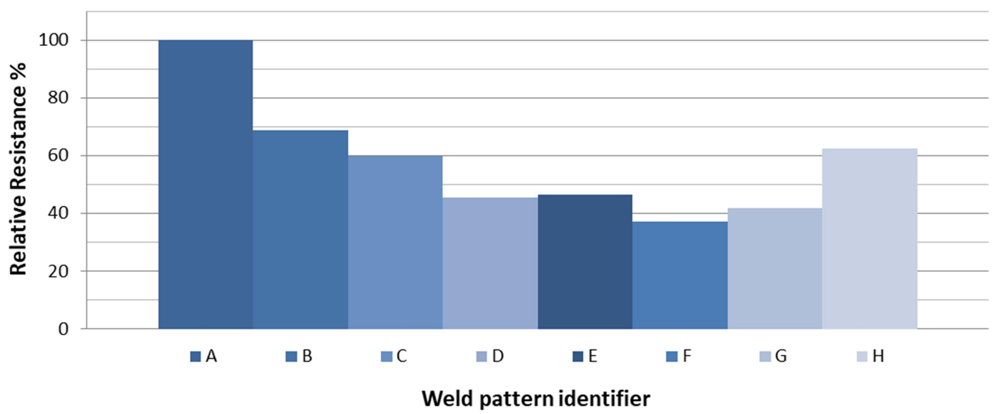


Figure 9: Relative resistive losses due to the different weld patterns tested

Finally, an electrically isolating but thermally conductive interface layer was placed between the cells and the cooling plate to eliminate an electrical path to ground through the casing in the event of an internal cell failure.

The final overall assembly of the battery pack can be seen in the picture in figure 10, which is an exploded show-version of the final prototype battery pack.

Figure 10: Exploded view of the battery pack, showing the individual sections (upper = BMS enclosure, lower = cell enclosure)

Following the completion of the validation test process which is currently under way at the time of writing, the battery pack will be installed in the demonstrator vehicle and subjected to an extended suite of tests over a suite of legislative tests and on-road real world usage. The cooling system performance will be evaluated and the overall fuel consumption benefits of the hybrid system will be established. The techniques and experiences gained and developed during the design and development process outlined in this paper will be refined and applied to MAHLE Powertrain's design and development process for future R&D, client and proprietary battery pack designs.

4. Summary

MAHLE Powertrain has designed, developed and constructed a prototype battery pack with very high power, specifically for 48V MHEV applications. Effort has been employed to minimise resistive losses within the system for optimisation of efficiency and minimisation of heat loading to the battery cells. The cells themselves have been characterised under different temperature and power conditions to inform the design of the battery pack. The performance targets have been demonstrated to be feasible with active cooling and potential fuel consumption savings have been identified, which will be validated during the final phase of this project.

References

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