MAHLE Powertrain

Ultra-fast Charging
Urban Delivery Vehicles

Contents

Abstract

A novel Lithium Carbon battery cell technology, which combines the benefits of super capacitors with the energy storage capacity of lithium-ion cells, could revolutionise the way in which future battery electric vehicles are used and recharged. The use of such a technology to enable ultra-fast charging capable battery electric vehicles, with small battery packs, suited to frequent, short, journeys such as urban delivery applications has been investigated. This study examines the requirements for an urban delivery eMoped application and proposes the recharging hardware necessary to enable a fleet of eMopeds to be charged rapidly from a domestic power supply. The target charging rate will allow vehicles to recharge fully in just a few minutes, enabling an opportunistic charging strategy with frequent top-ups, eliminating the need for a large battery pack.

Ultra-fast charging

Allotrope battery cell technology designed to accommodate ultra-fast charging capabilities of light duty urban delivery vehicles

1 Summary

The rise of the on-demand economy has led to a rapid increase in the delivery of meals from restaurants and fast-food outlets by delivery drivers using bicycles, mopeds, cars and light-vans [1]. Urban delivery is dominated by internal combustion engine powered vehicles, from take-away delivery mopeds to diesel powered delivery vans, which contribute to urban air quality issues. Grocery and parcel deliveries are handled as efficient multi-drop deliveries with vans covering typically 20-60 km per day, depending on the level of urbanization [1-2]. Take-away delivery and postal courier activities are fulfilled as a hub-centred series of short (<4 km) journeys, but with insufficient time to recharge [1-2]. To decarbonise these industries, so far, the only way to do this is to use electric vehicles with an excessive range compared to their requirements, which leads to heavier than necessary vehicles, with reduced payload capacity and increased energy consumption [3]. Higher purchase costs due to large battery packs also slows adoption of electric vehicles, reducing the potential rate of decarbonisation.

If the recharging time for a vehicle can be reduced to only 2-5 minutes for a full charge, then this enables the re-optimisation of the battery pack to a very small size. Two main challenges associated with ultra-fast recharging times are the ability of cells to accept very high charging rates over the full capacity and the charging infrastructure required to supply this power at the voltage required [4].

Allotrope Energy's novel Lithium Carbon battery cell technology combines the benefits of super capacitors with the energy storage capacity of lithium-ion cells. MAHLE Powertrain have used Allotrope's technology to design an ultra-fast charging, aggressively downsized battery pack for an urban delivery eMoped application. MAHLE Powertrain have also devised the recharging hardware necessary to enable a fleet of eMoped to be charged rapidly from a domestic power supply. The target charging rate will allow vehicles to recharge fully in just a few minutes, enabling an opportunistic charging strategy with frequent top-ups, thus eliminating the need for a large battery pack.

1 Introduction

Traditional battery electric vehicles have large batteries to enable long driving ranges to be achieved, as it is deemed desirable to have a driving range comparable to a conventional diesel or gasoline powered vehicle. Consequently, the resulting battery packs are heavy, expensive and can have a low lifetime if subjected fast charging on a regular basis. Urban delivery vehicles typically only cover relatively short daily driving distances and thus require only a modest electric driving range. Typical electric vehicles therefore have battery packs that have a significantly greater energy storage capacity than is required for these roles.

MAHLE Powertrain and Allotrope Energy are investigating a concept for an ultra-fast charging battery system optimized for optimised for urban delivery vehicles. The target is to enable a full battery recharge to be achieved in a similar time to re-fuelling and internal combustion powered vehicle, of around 2 to 5 minutes. The battery is based on Allotrope Energy's lithium carbon battery technology, which has similarities to super capacitors, but with a greater energy storage capacity. Battery-super capacitor hybrid devices (BSH) are typically constructed with a high-capacity battery-type electrode and a high-rate capacitive electrode, have attracted significant interest, as they have the potential to significantly enhance the capabilities of future electric vehicles and smart grids [3].

This feasibility study investigates the suitability of the Allotrope's cell for an eMoped and eVan. The context for both applications will be urban delivery and were considered as it is believed that these represent an initial upper and lower vehicle size for which the technology may be suited. Further, broader, applications could include short term rental, taxi, private vehicles, and automated transport. The technology could also be extended to bus, or light rail, applications with a pantograph arrangement to provide a top-up charging at each bus stop or platform. The technology may also have wider applications in PHEV, Hydrogen fuel cell and high performance MHEV applications.

This study also investigates the ecosystem necessary for this radical and potentially disruptive technology, including charging infrastructure needed to enable such fast recharging to be achieved.

3 Allotrope Cell Technology

Allotrope Energy has developed new cell chemistries, based around the use of carbon within a lithium ion battery. Three cell derivatives have been developed, the electric double layer capacitor (EDLC), the lithium-carbon cell and the lithium-ion capacitor.

In contrast to the electrochemical nature of traditional batteries, the EDLC stores energy through the capacitive interaction of opposing charges at the interface of high surface area (2000 m^2/g) carbon and the ions in an organic electrolyte. The instantaneous action of the charge storage mechanism allows for charge times in single digit seconds, efficiency approaching 99 %, even at charge rates of over 500C, with lifetimes measured in thousands of cycles. Despite these qualities, the low gravimetric and volumetric, energy density and high price per kWh has limited market appeal, leading to the development of the lithium-ion hybrid cell.

Initially patented by Glenn Amatucci, the Lithium-Carbon battery is one of two new technologies referred to as a lithium -ion hybrid, so called due to its use of both battery and EDLC materials.

Comprising a high-rate battery anode and high capacity EDLC cathode, the Lithium-Carbon cell technology demonstrates considerable advantage over more common ultra-capacitor or high-power battery technology, giving a ten-fold increase in the gravimetric and volumetric energy density of the EDLC, reaching 60 Wh/kg and 80 Wh/litre, yet also maintaining a ten-fold power density of high-power battery alternatives, achieving 15 to 20 kW/kg, with negligible direct current internal resistance (DCIR) values.

However, contrast to common high power battery technologies, the nano-carbon cathode and high conductivity organic electrolyte both minimises parasitic heat generation via a low equivalent series resistance (ESR), but also minimises the deleterious effect of any subsequent heat build-up, suffering none of the thermal degradation effects commonly seen in the lithium containing metal oxide cathodes. In combination, these qualities allow the cell to run at over 100C continuously for full (0-100 %) state of charge (SOC), for both charging and discharging, without impacting stability, even without the constant voltage phase at high SOC. The ease at which the technology handles high C-rate charge procedures allows for simplistic single minute charging battery packs, requiring neither external cooling systems nor elaborate battery management systems (BMS).

The characteristics of these three cell types under development by Allotrope Energy are summarised in Table 1.

Tab. 1 Summary of Allotrope Cell Characteristics

Property	Units	EDLC	Lithium carbon	Lithium-ion capacitor
Power density	kW/kg	70	15	8
Energy density	Wh/kg	22	60	105
Energy density	Wh/litre	26	80	200
Cycle life	cycles	>1 M	~100 K	1 – 2 K

4 Battery Pack Requirements

There is an increasing use of on-demand e-commerce. This is particularly prevalent in the numbers of online orders for delivered "take-away" meals, typically provided by fast-food outlets [1]. A recent analysis of the same-day delivery market and operations in the UK [2], provides an insight into usage patterns for eMopeds and eVans in London. This report showed eMopeds are predominantly used in the fast-food delivery sector and that grocery and non-food parcel delivery was predominantly van-based. Therefore, when defining the requirements for the battery packs for these two vehicle types, the focus has been to determine the requirements in the context of the associated delivery scenario.

4.1 eMoped

The eMoped is prevalent in the fast-food delivery sector and is typically used for short distance deliveries, with frequent collections from food outlets to collect fresh deliveries. A typical eMoped in this category is shown in Figure 1. The specifications for an eMoped is summarised in Table 2. Take-away meal delivery services operate on a point-to-point basis with a regular return to base. In London, delivery drivers typically operate a 5 hour shift pattern and have 2-3 trips per hour, with typical distances covered per trip of up to 4 km per trip [2]. Thus, there are typically 10-15 deliveries per 5 hour shift, with a total driving distance of between 30 to 50 km. Moped based delivery, for smaller cities and towns, is assumed to be similar to that of London, with drivers covering similar distances in a shift, but perhaps with fewer numbers of deliveries, if the destinations are more widely spread. A fast-food vendor in a town is likely to service a wider catchment area than in a more densely populated city, but with perhaps fewer people living within the catchment area, and with a lifestyle that less frequently includes fast food delivery. A maximum range of 25 km is therefore assumed to be a generally suitable target for the eMoped study.

Fig. 1 NUI N1s eMoped

Tab. 1 Summary of Allotrope Cell Characteristics

Parameter	Units	Value
Maximum speed	Km/h	45
Continuous Motor Power	kW	1.6
Range	km	51
Battery cells	-	18650
Range	V	60
Battery cells	Ah	29

Typical energy usage of the type of eMoped shown is around 20 Wh/km, based on published range data from eMoped manufacturers and also from the urban driving measurements for an eMoped study conducted by Cenex [6]. Therefore, a 25 km range would only require 500 Wh of useable energy. A battery of this size would require a full recharge at some point during a shift because the target range is 30-50 km. Using traditional lithium-ion battery packs, which are becoming dominant in this segment, a fast charge at 2C would take more than 30 minutes. This length of charging, mid-shift, is impractical to accommodate in an eMoped urban delivery context, as operational efficiency would suffer.

The solutions employed to deliver manageable range in eMopeds so far use larger battery packs to enable the greater range required for a full day of driving. These batteries could still require recharging between shifts, unless they are very large, potentially reducing operational efficiency. Fast charging also tends to reduce battery life, which can be in the range 250 to1000 cycles for the type of fast charging cells required. This would correspond to battery replacement requirement every 1 or 2 years under heavy use. The larger battery packs, of course, raise initial purchase costs significantly and require larger amounts of raw materials and energy to manufacture and recycle.

A different solution to large battery packs is battery swap technology, where one battery charges slowly, whilst another is in use, before being swapped over quickly once the battery in the vehicle becomes depleted. This requires the purchase of additional battery packs, resulting in additional up-front investment. This technology is being pioneered in Asia, where it is common to be able to remove the battery from an eMoped and take it to the office or into the home for recharging when not in use [5], or exchange at a public battery swap station [7].

An alternative approach is, however, to enable ultra-fast charging of battery packs in a few minutes or less, without the need to remove them from the vehicle. This means that the battery can be fully or partially recharged whilst the next delivery is collected or loaded. This would result in no loss of efficiency either during, between or after a working shift. It is also insensitive to failed charging events or operators forgetting to connect the charging power. This type of issue or mistake would take only minutes to rectify.

Allotrope Energy's Lithium carbon cell is very well suited to this type of application. A 0.5 kWh capacity is achievable within the available packaging space and it can be recharged in very short time. Recharging at 20 kW, for example, requires a charging C-rate of 40C, which is within the capabilities of these cells and would yield a recharge time of 90 seconds. This size of battery pack might need recharging every 2 to 3 hours or every 10trips, but as already mentioned should not delay any activities due to the very short charging duration.

The cell technology could support even higher charging rates, potentially enabling even further downsizing of the battery pack and reducing further the manufacturing costs. Maintaining the same charging power, would simply decrease charging times, potentially to less than a minute, whilst still retaining useable driving ranges between charging.

4.2 eVan

Same-day multi-drop and grocery deliveries are typically undertaken using small vans. Multi-drop delivery vehicles, typically making 10 deliveries per day, with an average distance of 2 km per delivery in London, and a daily driving range of 20 km, undertaken as a single, multi-drop, journey [2].
In smaller, less densely populated, cities and towns, less data is available to determine the distance covered by each delivery type. Informal surveys of parcel delivery drivers in the Northampton area, conducted as part of this study, suggest that daily driving distances can increase to around 60 km when delivering in towns. The route in these regions encompass a wider catchment area and may include extra-urban driving, moving from one town, or village, to another. Journeys in smaller cities are more likely to be of the order of 40 km per day. Based on this data, it has suggested that three scenarios are reasonable for considering urban parcel delivery vehicle requirements, all of which consist of an 8 hour shift pattern, with a 30 minute, mid-shift, break:

1. London or densely populated metropolis = 20 km/day;
2. Small-city = 40 km/day;
3. Urban with extra-urban sections = 60 km/day

To robustly assess the requirements of the eVan battery pack, a simulation of an eVan operating over a special urban delivery drive-cycle has been undertaken. The study showed that during usage in densely populated urban areas, the van requires 20 kWh energy to complete the daily usage profile. The simulation included estimated winter heating demands, which, along with the parasitic losses associated with running the vehicle, dominate the energy consumption of the vehicle over the 8 hour operating shift.

4.2.1 eVan drive-cycle simulation

A model was initially constructed to simulate the energy use of two different types of electric van, a car derived van and a larger light duty van. Generic specifications for these vehicles were used, based on data from a variety of sources. Table 3 shows a summary of the parameters used in the modelling of these two vehicles. The drive system efficiency and battery characteristics were also based on generic data. The simulated energy consumption of each vehicle was correlated against published data for the WLTP test cycle to ensure a good basis for the further work.

Tab. 3 Specifications for the two generic eVans considered in this study

Parameter	Units	Car-derived van	Light-duty van
Kerb weight	kg	1540	1875
Maximum payload	kg	865	1225
CdA	m²	1.35	1.45
Rolling resistance coefficient	N/1000N	0.011	0.011

The two vans were then analysed over several differing standard test cycles. Figure 2 shows a comparison of the cycle averaged power consumption verses cycle averaged vehicle speed across a wide array of differing drive-cycles, for a variety of payloads, for the light-duty van. As would be anticipated, there is a clear trend, that increased payload leads to increased vehicle energy consumption. Also, for the cycles with a cycle averaged speed of above 30 km/h, there is a clear trend of increasing cycle averaged energy consumption with increasing cycle averaged speed.

The simulation model included a constant discharge power of 0.5 kW to account for the average consumption of the vehicle electrical consuming systems, such as lights, infotainment/navigation and other electrically powered devices, based on empirical data derived from MAHLE Powertrain experience. The influence of this fixed parasitic load on the cycle averaged energy consumption of the vehicle is most prevalent on drive-cycles with a low cycle averaged speed, where the parasitic load becomes a significant proportion of total energy consumption. This can be seen in Figure 2, where the cycle averaged power consumption can be seen to increase for cycles with a cycle averaged speed of less than 30 km/h.

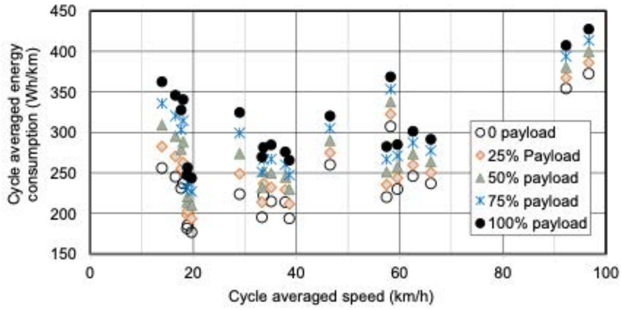


Fig. 2 Simulated effect of average vehicle speed on energy efficiency for the light-duty van with a range of payloads

A special cycle was created, shown in Figure 3, to reflect the distance and usage pattern typically experienced during urban delivery usage profile. The vehicle operates for 8.25 hours, with a single 3 to 5 minute recharge undertaken during the shift. The total distance covered during the drive-cycle is just over 20 km and the maximum speed is 82 km/h. The energy required to propel the vehicle over this cycle ranged from 230 to 285 Wh/km (ignoring parasitic loads) for the different vehicle sizes analysed. The vehicles were assumed to start the day at their gross vehicle weight (GVW), which then decreases steadily as deliveries are made during the drive-cycle, finishing at the vehicle kerb weight plus driver. Typical total daily driving distances are quite small, with 20 km total daily distances common in densely populated city centre routes, increasing to 40 km in less densely populated environments.

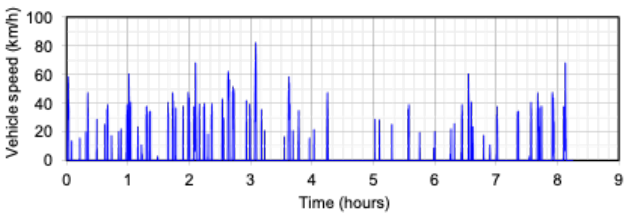


Fig. 3 Urban delivery drive-cycle used for the eVan study

The vehicle is powered-up for the full 8 hour shift, which results in high energy use to power the supporting systems. Again, the simulation model included a fixed discharge power of 0.5 kW to account for the average consumption of these systems. This increased the vehicle energy consumption, over the urban-delivery drive-cycle, to between 470 to 525 Wh/km. Finally, adding modest winter heating, or summer cooling, requirements of 1 kW, assuming that some advanced techniques could be employed, such as direct heating, or the use of a heat pump to enable recycling of waste heat from the traction system, the final energy consumption during winter, or summer, increased to between 950 to 1005 Wh/km.

To enable the worst case to be accommodated, a minimum of 20 kWh of total battery energy storage capacity for the full 8-hour shift is required. With the short mid-shift recharge, the battery size could be halved to give the selected final specification of 10.5 kWh of usable capacity, which has been used for the subsequent studies. Figure 4 shows the calculated battery SoC, for both the car-derived van and the light-duty van, during the urban-delivery cycle.

To minimise any impact of the recharging on the vehicle utilisation, the recharging time clearly needs to be minimised. It may be possible to integrate the charging of the vehicle into the break time of the driver, however, this may not always be possible. The lithium ion capacitor cell technology supports theoretical "flat-to-full" re-charging rates up to 20C, which corresponds to a recharging time of 3 minutes. This is unlikely to add significant inefficiency to a working day and was deemed to be acceptable for this study. It is unnecessary in this scenario to need the 50-80C rates offered by the lithium carbon technology and the superior energy density of the lithium ion capacitor cells provides significant benefits for battery pack weight and package volume. Therefore, the lithium ion capacitors were selected for the eVan application.

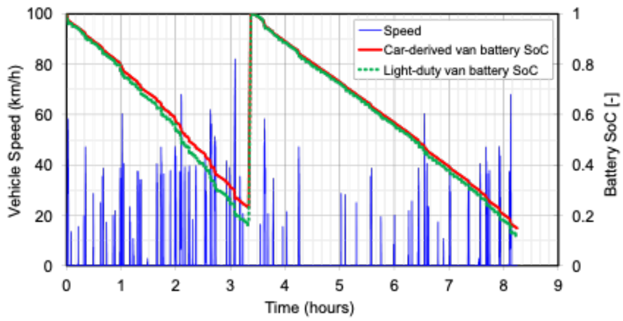


Fig. 3 Calculated battery SoC for the two eVans during the urban delivery cycle

The simulation also revealed that a battery discharge power capability of 100 kW is needed to propel the vehicle over the urban deliver cycle used in this study. Peak regeneration power available is 75 kW, although there is little impact to the total energy recuperated if the maximum recuperation capability of the vehicle is reduced to 20 kW.

5 Battery Pack Specifications

The simulation work conducted enabled the definition of the specification for the battery packs for the eMoped and the eVan. The specification of the cells selected for each of these applications are shown in Table 4.

Tab. 4 eMoped and eVan cell specifications

Parameter	Units	eMoped	eVan
Cell type	-	Lithium carbon	Lithium-ion capacitor
Capacity	Wh	6.5	50.2
Dimensions	mm	150 x 70 x 8	280 x 140 x 6.4
Weight	g	132	470
Maximum voltage	V	3.2	3.2
Minimum voltage	V	1.6	1.6
Maximum charge rate	C	40	20

The eMoped can achieve up to 25 km of riding between recharge events and can be recharged in under 2 minutes. A 60 V architecture was chosen following a market study of the current state of the art in electric mopeds. This deviates from the normal automotive best practice of 48 V, as set out in LV148 [8], but has the benefit of reducing electrical current and therefore ohmic losses, for a given power. The specifications for the eMoped pack is summarised in Table 5. The specification for the eVan pack is also summarised in Table 5.

Tab. 4 eMoped and eVan pack specifications

Parameter	Units	eMoped	eVan
Pack capacity	kWh	0.50	10.5
Maximum voltage	V	58	400
Minimum voltage	V	38	280
Output power	kW	1.5	100
Charging power	kW	20	210
Charging time	seconds	90	180
Cell mass	kg	9.5	120
Configuration	-	18S-4P	128S-2P

6 eMoped Battery Pack Concept Design

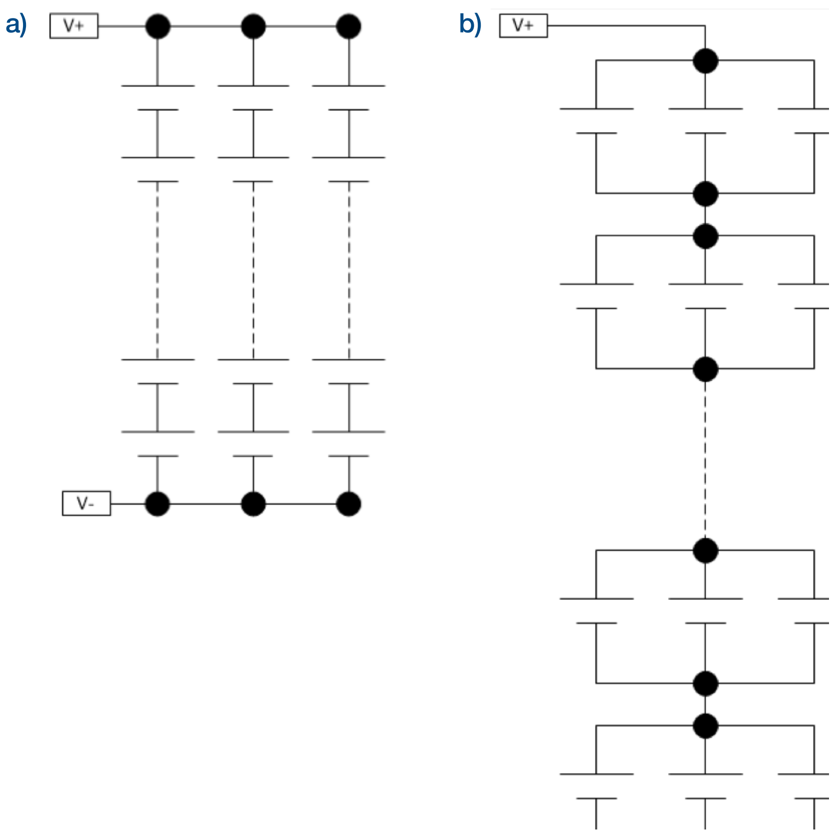
A concept design for the eMoped battery pack has been completed. The pack concept design has been successfully packaged into the target eMoped application and the details of the design are presented.

6.1 Electrical architecture

The battery comprises 72 cells, to achieve the required 0.5 kWh capacity, and adopts a configuration of 18 cells in series to achieve the required voltage, with 4 strings of the 18 cells in parallel to achieve the target capacity (18S4P). To minimise size, weight and complexity, these parallel strings have been integrated into one structural assembly. For this study a small format cell (150 x 70 mm) was assumed to fit with a common, anticipated size for initial prototype manufacturing of the cells. It would be feasible to adopt a larger format cell (e.g. 300 x 100mm), which is becoming a common form factor in the automotive industry. This would decrease the complexity of the design slightly and yield small weight and package size benefits.

The relative merits of arranging the strings in parallel using either full series strings (as depicted in Figure 5a) or by paralleling the cells within a single string (as depicted in Figure 5b) were assessed. Benefits in BMS complexity and cost can be realised by paralleling the cells within the string, but the increased complexity of the welding of the cell tabs was identified as a potential drawback to this concept. Both concepts were considered during this study.

Fig. 5 Cell parallelisation options; a) Parallelised strings; b) Parallelised cells



6.2 Battery pack structural design and optimisation

For the concept design, the cells are mounted in polymer racking frames which provide protection for the cells as well as structural rigidity and control of the loads applied to the cell during its lifetime. Within the frame assembly separator plates and thermal interface materials are used to enable electrical isolation between cells, even compression of the pouch cell, and a method by which heat can be transferred out of the cell during use. Special attention was given to the compressive force applied to the cells throughout their lifetime, from initial compression during assembly, to the end of life, where cell swelling will increase the compressive loading on the cells. The swelling is accommodated using a compressible thermal interface material between the cells and a load spreading cooling plate. Finite element analysis (FEA) techniques were used to analyse and optimise the stresses within the system. The basic principle is shown in Figure 6, which shows an early design, which was further optimised for reduced weight and stress concentrations.

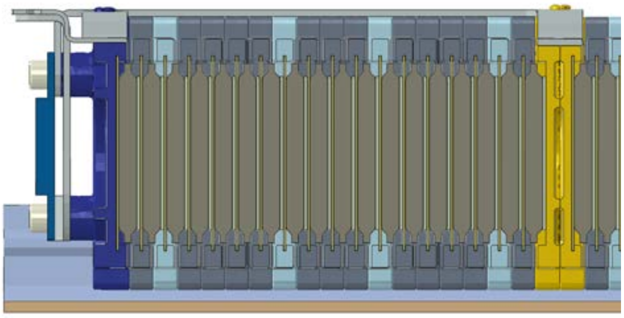


Fig. 6 Sectional view through the early concept design showing the structure of the cell and frame assembly

In addition to the compressive loads imposed on the cells, the forces acting on the cell assembly during use, and extreme shock loading events were also analysed. To enable a battery pack to be shipped, or used in vehicle on a public highway, it must be demonstrated to meet the relevant applicable standards. Transportation of batteries is covered by Article 38.3 of Part 3 of the UN Manual of transport tests and standards for dangerous goods [9]. In Europe electric vehicles must also comply with UNECE regulation 100 [10]. Both regulations require the battery to be subjected to mechanical shock and vibration tests. The test profiles stipulated are generally regarded to be more arduous than those encountered during normal use. These vibration profiles were simulated and applied to the pack design using FEA. Overall, FEA-based optimisation was carried out with regard to assembly loading, cell swelling, modal response, vibration response and shock response.

An example of the modal response analysis can be seen in Figure 7. In this case, the response at a specific frequency of 160 Hz is shown. This frequency sets up a deflection in the positive busbar. Stiffening the busbar through further geometric optimisation changed the response frequency beyond the anticipated frequency range.

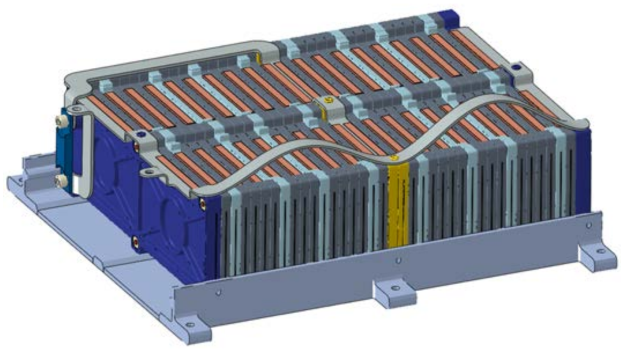


Fig. 7 Modal response of an early design concept

The simulation results guided the detailed optimisation of the pack design. Modifications were made to reduce stresses, eliminate unnecessary material and improve stiffness. As a result, a more robust design was achieved, and significant weight savings were made. Stress profiles of the final assembly are shown in Figure 8.

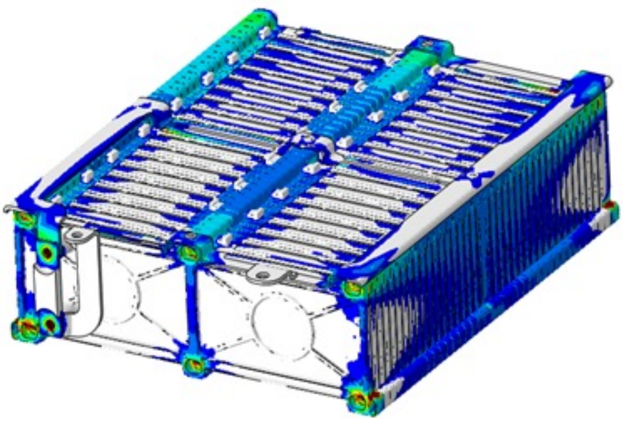


Fig. 8 FEA stress concentration after optimisation

6.3 Thermal simulation and design optimisation

In additional to the structural optimisation, the thermal behaviour of the battery pack was considered in detail using Computational Fluid Dynamics (CFD) techniques. Particular attention was paid to the thermal interaction between the conductors and cells. Heat is generated within the cells and electrical conductors, and the relative temperatures of each component drives the heat flow. The cells have an upper temperature limit of 65 °C, which is limited by degradation of the electrolyte above this temperature. The Lithium carbon and Lithium Ion super capacitor cells are not prone to thermal runaway.

To simulate use of the battery in very hot climates, the initialisation temperature for the thermal analysis was set at 50 °C and a 90 second, 20 kW, charging event was simulated as a worst-case condition. The CFD analysis results reveal the current flow within the whole of the battery electrical system as well as the heat flow. The current density within the tab-to-busbar connection and in the conductors enabled detailed optimisation of the conductor design to reduce weight, cost and complexity. For example, Figure 9 shows the current flow from a cell, through a weld line, into the current conductor. In this case, the biasing of the current density toward the end of the cell tab furthest away from the dead end of the conductor can be seen. This enabled reduction of the material at the dead end of the current carrying conductors because, as can be seen in Figure 9, no current flows through certain portions of the material.

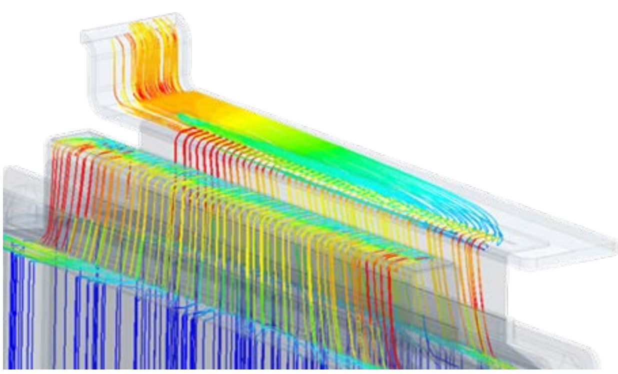


Fig. 9 Current flow from a cell to the current carrying conductor

To enable the reduction of the analysis time, studies were completed to establish the potential for simplifying the model. It was established that a cut-down model, as shown in Figure 10, yielded the same level of accuracy in terms of the calculated temperature of the cells at the end of each string, in the vicinity of the connection to the conductors, and of the conductors themselves. This significantly reduced the total number of battery cells required to be included within the simulation model.

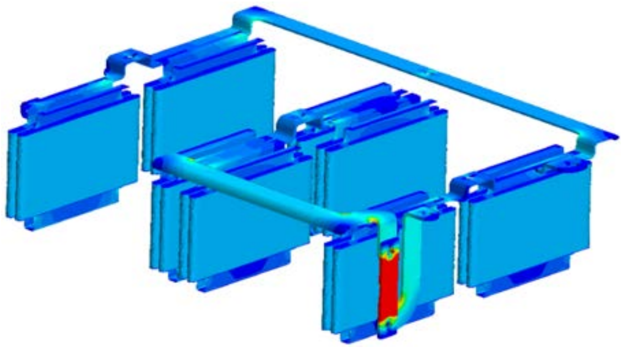


Fig. 10 Reduced complexity CFD model of the complete battery system showing ohmic heating

In the resulting battery design, the conductors are partially used as a dynamic heat-sink, which helps to keep the cells below their temperature limit during the very short charging events. The CFD simulation was also used to optimise the effect of the structural aluminium separator plates as cooling components and to optimise the parallelising tab connectors in the single-string parallel cell concept that was shown in Figure 5b. The result of the simulation and design optimisation showed significant improvements in system mass as well as confirmation that the cells could be kept within the recommended temperature limits, even with very high ambient temperatures. Further simulation studies indicated that charging at even higher power levels, but for shorter durations, could also be achieved by using the structural plates as heat sinks, potentially enabling even faster charge times in the future.

6.4 Integrated Battery Management System

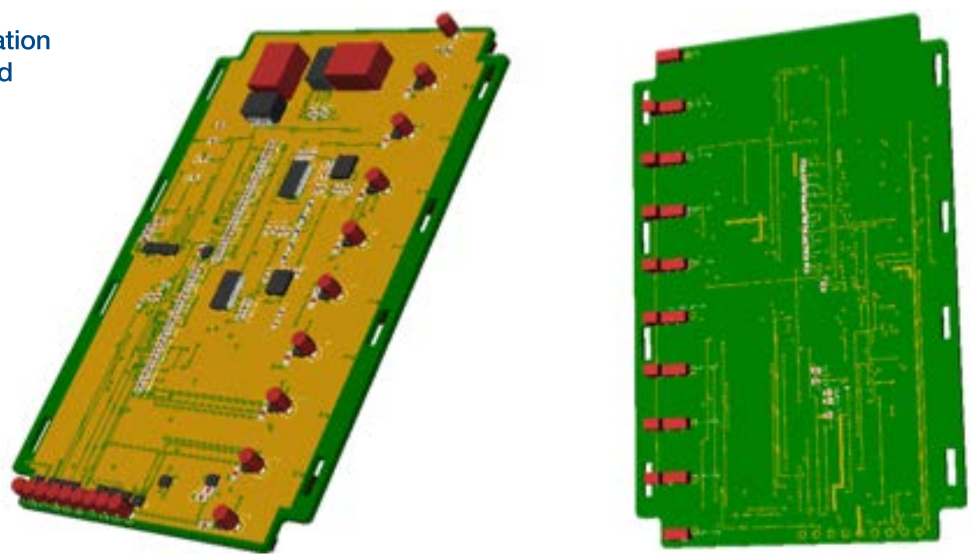
The battery management system (BMS) monitors the voltages, temperatures and current flow of the battery pack and calculates the state of charge (SOC) and condition of the battery pack, it also transmits safety and performance related information to the vehicle as required. The two different concepts for parallelisation of the series cell strings, pictured in Figure 5, require differing amounts of BMS hardware and balancing capability. When paralleling locally (as per Figure 5b), the parallel cells act as a single cell, reducing the quantity of voltage measurements needed and they can be balanced as a group, rather than individually, reducing the required number of balance resistors and control hardware.

For the detailing of the design, the most complex system was used to establish the upper bound of packaging challenge and cost. Simplification studies were then undertaken to develop a more compact, cost-optimised system. Due to the unconventional electrical architecture, it was found that existing, off-the-shelf, hardware was not suitable for this application, due to the pack using 18 cells in series. Typically, lithium ion battery management systems a designed for strings of 12 cells. In this case, this would result in the need to use inefficient combinations of cell sensing circuit (CSC) boards, which provide the connection to the individual cells to measure the voltage and temperature. For example, two 12 channel CSC boards are required per 18 cell string, with 6 redundant channels.

To address this issue, and to provide maximum flexibility and component optimisation for this, and any other, battery design, an adaptable, scalable CSC was designed, which is readily adapted for different shapes, sizes and number of channels. This CSC board is shown in Figure 11. The design uses some key features to minimise complexity, maximise robustness and enable very fast installation time during series production build sequences. The aim was to embed as many functions onto the board as possible and minimise external connections, including no requirement for soldering or crimping of voltage or temperature connections.

The CSC clips into place on top of the battery module, using fixing features in the plastic cell mounting frame, with no additional fixings required. The voltage contacts on the CSC board contact the cell tabs via spring-loaded contactors, so that soldering is not required. The tab temperature, which has a known relationship with the main body of the cell, is sensed in the same way. The only connections required are to the main BMS control circuit, which is located on the end of the battery pack, using a small CAN harness and a very simple voltage sensing PCB on the underside of the pack. The CSC board consolidates the individual voltage and temperature signals into CAN messages, minimising the wires required to connect to the BMS master controller. The electrical circuit was been designed and optimised using an electrical circuit simulation software package.

Fig. 11 CAD representation of the integrated CSC design



A rendered image of the final battery assembly is shown in Figure 12. The master BMS controller is mounted to the end cap for easy installation. An electro-magnetic interference (EMI) shielding cage can be fitted over the master controller to prevent corruption from external EMI sources. The power measurement board is integrated into the negative current conductor. The whole battery assembly is mounted inside a casing, which provides location and secure mounting for the cell assembly as well as protection from water ingress. A dual function breather and venting valve is incorporated to accommodate changes in ambient pressure as well as allow gasses to escape in the event of cell venting. The cells should not be capable of thermal runaway due to the absence of any metal oxide at the cathode, which, in lithium ion cells, decompose under high temperatures, feeding the thermal reactions. However, if the electrolyte is overheated, it can vaporise, necessitating a vent valve.

The whole assembly will fit in the space available on the eMoped with no significant requirement for modification. The charger connection is mounted closely, above the battery, to minimise the length of current conductor necessary due to the high electrical current when charging at 20 kW with only 50 to 60 V. The assembly is not designed to be quickly removed from the eMoped, as is common in this segment, because it can be charged in less than 2 minutes. The design has been completed to enable a first prototype to be constructed for proof of concept.

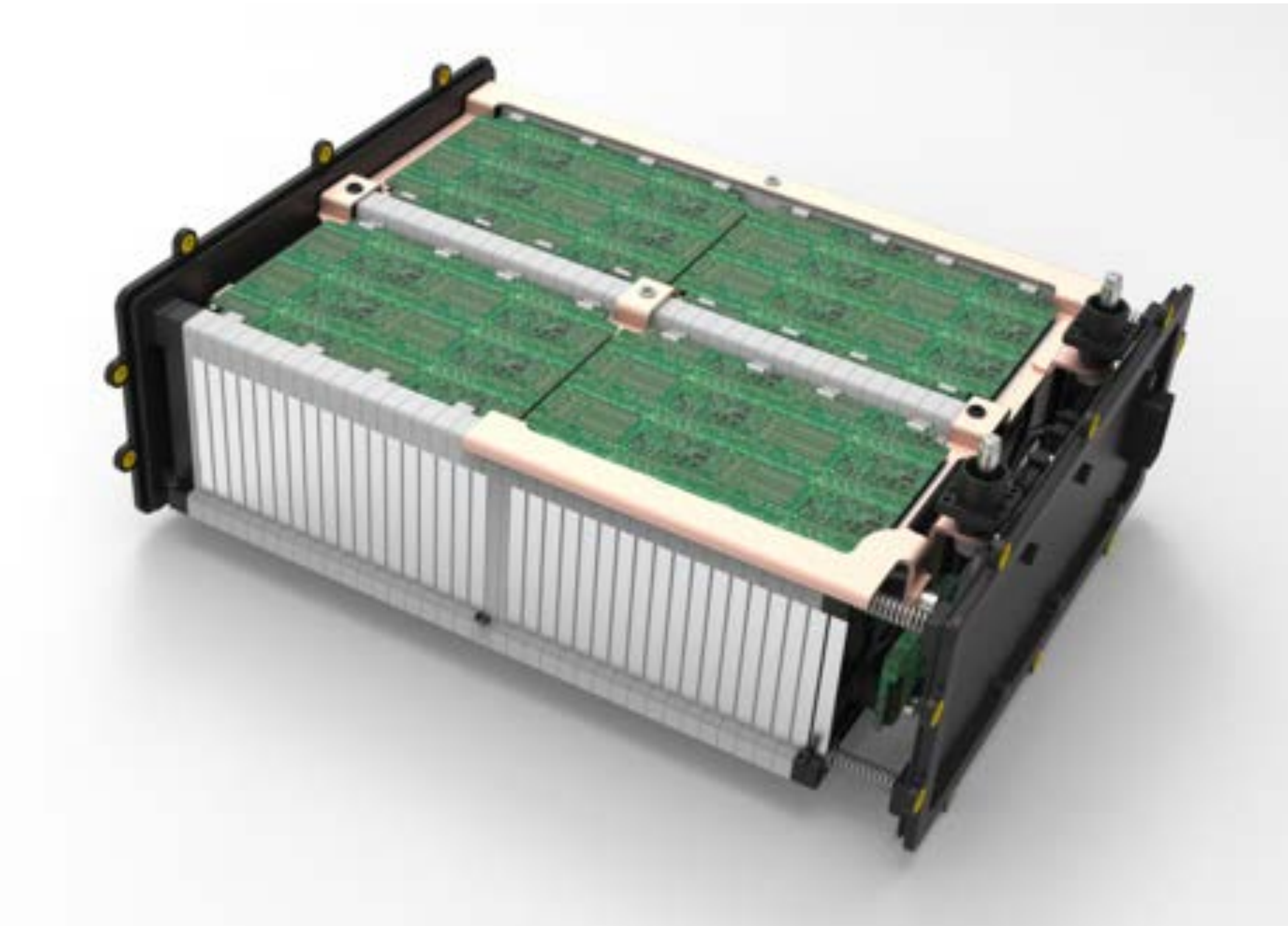


Fig. 12 Rendered image of the final battery pack design, showing the integrated CSC boards and BMS master controller

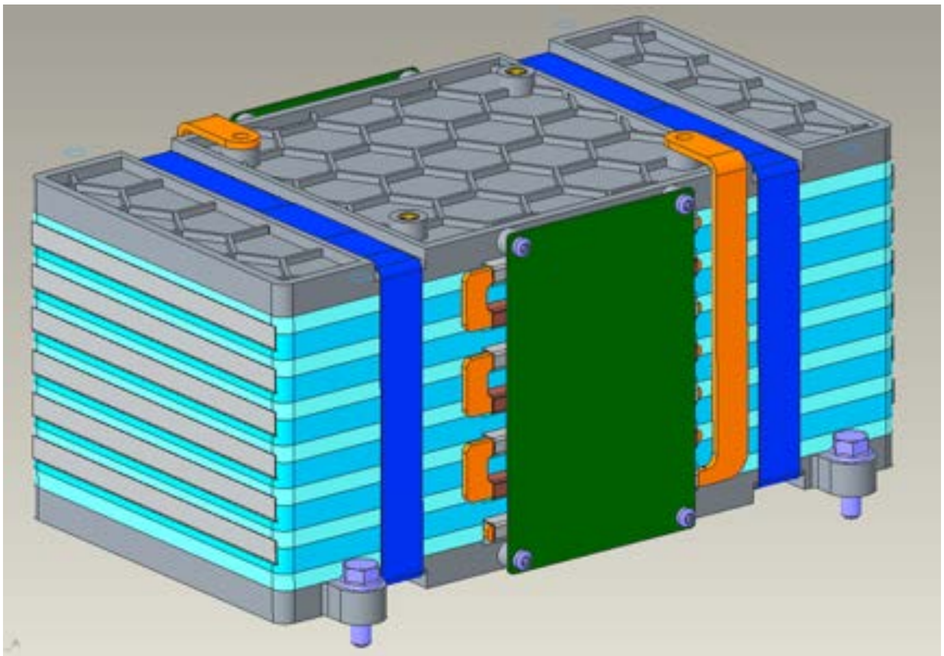
7 eVan Battery Pack Concept Design

The battery pack for the eVan is much larger, both physical size and in energy storage capacity, than that designed for the eMoped. It uses multiple modules of cells to achieve the higher voltage, storage capacity and overall performance.

A concept design for the eVan battery pack has been completed to assess the packaging potential, rather than complete the level of detailed design applied to the eMoped pack. For the eVan concept, the alternative cell parallelisation strategy has been employed, as per Figure 5b. For this pack a 128S-2P architecture is required to achieve the 10 kWh capacity and 400 V architecture. This pack uses the alternative Lithium-ion capacitor cell technology, which has a significantly higher energy density than the Lithium carbon cells used in the eMoped pack. They cannot be charged at such high rates, but are sufficient for this application and should enable recharging times of approximately 3 to 5 minutes to be achieved.

Each module has 14 cells arranged as a 7S-2P format, resulting in a maximum voltage of 22.4 V. The pack contains 18 modules in series for a total pack maximum voltage of 403 V. The pack has a usable capacity of 10.5 kWh. Figure 13 shows the individual module concept design. The cells are connected in parallel using a common current conductor, to which they are laser welded. Each conductor then connects in series to the next pair of cells. The cell pairs are housed together within the module, between separator plates and a compressible thermal interface material to accommodate cell swelling. The BMS CSC boards are similar in concept to those shown for the eMoped battery design, integrating the various functions into module-mounted, CAN connected boards.

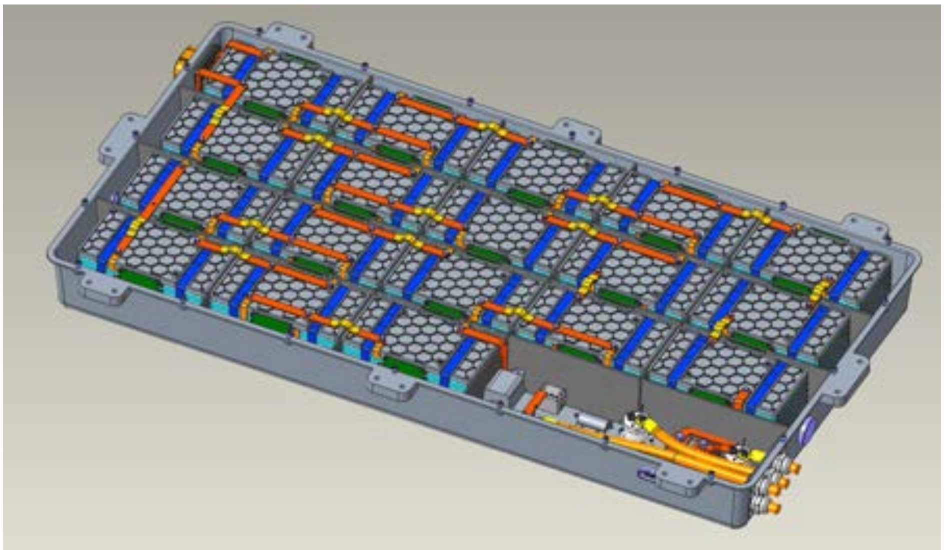
Fig. 13 eVan module concept design



The structure of the module design is similar to that of the eMoped battery pack, utilising a robust polymer frame design. In this variant, the trays are strapped together using lightweight tension bands. FEA was used to confirm that this method is sufficient accommodate the forced imposed by cell expansion and the necessary shock and vibration tests. The aluminium separator plates are designed, in this instance, with an external return, which could be combined with an external cooling plate to remove heat from within the module. It is not anticipated that this will be needed with the Allotrope cell technology due to the anticipated low internal resistance of the cells. This will be validated during testing of cell samples and the design modified accordingly. The battery pack concept design can be seen in Figure 14.

The modules are separated within the main casing using fire-resistant panels, to mitigate the very small risk of thermal propagation (as mentioned, the cell chemistry does not support thermal runaway). An air gap is left above the modules and separators to enable the vented gasses to exit the enclosure via a venting disk. The electrical junction box is integrated into the design and contains the required contactors, fuses, BMS master controller, pre-charge system and filters to create a stand-alone product. The pack is designed, initially, as a retro-fit option to enable simple demonstration in an existing vehicle, but could be readily tailored to suit other vehicle applications.

Fig. 13 eVan module concept design



8 eMoped Charging System Concept

To compliment the unique battery pack specification of the 60 V eMoped application, the charging system required to enable recharging of a small fleet of vehicles to be recharged rapidly via a domestic power socket has been investigated. Such charger systems are not yet available on the market, so a bespoke design is required. The charger system contains in-built energy storage, using Allotrope's lithium ion capacitor technology for ultra-long lifetime. This enables the vehicle to be charged at power levels of up to 20 kW, necessary to achieve the very fast target charging times (about 90 seconds), from a 7 kW domestic supply.

To enable a small fleet of vehicles to be recharged at a reasonable frequency, a 3 kWh energy storage battery has been integrated into the design for the charging system. This should enable a reduction in the cost and complexity of the installation of the charger by eliminating the need for expensive power grid system upgrades. The system should be able to run from a typical 7kW single phase connection, common in most commercial and industrial buildings and also accessible in domestic networks.

This approach ensures that the local electricity grid infrastructure is not overloaded, as high-power peaks are managed by the internal energy storage system, with average load taken at lower power from the grid. The charger concept uses existing 3rd party power electronic sub-assemblies, where available, to enable low-cost prototyping to be undertaken. An optimized, bespoke, electrical system design has also developed to investigate the requirements of an optimised system.

8.1 Charger electrical topology

The topology of the charger design was analysed at a high level, with the concept, shown in Figure 15, proposed as a lowest cost solution that also provides the ability to draw charge from both the internal battery within the charging unit and mains supply simultaneously. Each electrical stage of the charger, shown schematically in Figure 15, has been analysed in detail to enable the most suitable topology to be selected. The resulting architecture is:

- AC-DC converter:
  > Active front end
- DC-DC converters:
  > DC-DC Converter 1: Controlling the SOC of the battery – Dual active bridge with synchronous rectifier and 2:1 isolation transformer
  > DC-DC Converter 2: Buck Converter stepping down the voltage from 400V to 60V – Dual active bridge with synchronous rectifier and 6.66:1 isolation transformer

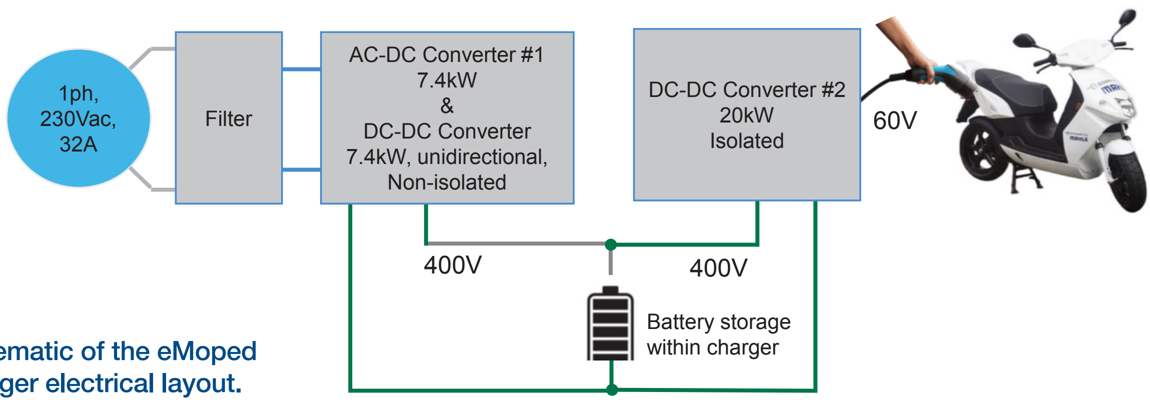


Fig. 15 Schematic of the eMoped charger electrical layout.

With the basic architecture of the charger systems defined, components were identified that could be used to develop a working prototype of the system for a simplified proof of concept.

Subsequently, for each part of the system, a study into the most appropriate technology for each component has been conducted. Component sizing calculations have also been undertaken to enable the complete system design to be developed. The resulting design has been simulated using an electrical circuit simulation software package to confirm the system concept.

8.1.1 AC-DC Converter

A model of the AC-DC converter has been constructed using an electrical circuit simulation software package which enables a full electrical layout to be investigated and designed. This model enables operation of the system in a virtual environment to replicate the operating characteristics and confirm that the desired output levels can be achieved. In this case, the circuit required to enable conversion of electricity from single phase AC at 240 V to DC at 400 V has been constructed and tested. The results confirmed correct output behaviour from the system, with 400 V DC being delivered with an 18 A output and minimal voltage ripple (+/- 0.6 V).

This system delivers conversion of 7.2 kW of grid electricity to DC power which is either used to recharge the energy storage system within the charger unit or directly recharge the battery of the eMoped. When charging the eMoped, the remaining 12.8 kW will be delivered by the energy storage system within the charger.

8.1.2 DC-DC Converters

A similar component sizing and selection process was conducted on both DC-DC converters within the eMoped charger application. Each DC-DC converter fulfils a different requirement. The first DC-DC converter (DCDC1) converts from the 400 V DC output of the AC-DC converter to the voltage required to charge the energy storage system within the charger unit at up to 7.2 kW. DCDC1 also serves to limit the power draw from the grid connection.

The second DC-DC converter (DCDC2) converts from the voltage of the energy storage system, which will be between 200 and 400 V depending upon SOC, and reduces it to the eMoped battery charging voltage. This will, again, vary depending on the SOC of the eMoped battery and the charging rate required, but will never exceed the maximum eMoped battery voltage. Again, DCDC2 serves as the current control device for the charge rate of the eMoped battery pack.

8.2 Concept design for eMoped Charger

A simple CAD layout has been created using an integrated AC-DC and DC-DC1 system, complete with high frequency switching controller. Similarly, DCDC2 is represented by a combined system.

A 3 kWh energy storage system, comprised of two parallel strings of 125 Lithium Ion capacitor cells in series, provides the short term power that enables 20 kW ultra-fast charging of the eMoped battery pack. The design of the battery modules is based on the eMoped module design, demonstrating the easy adaptability of the design.

A battery management system, including contactors, power measurement and manual service disconnect has been included. A small ECU module enables interaction with the battery management system, power electronics, vehicle, and user information screen. The completed design is shown in Figure 16.

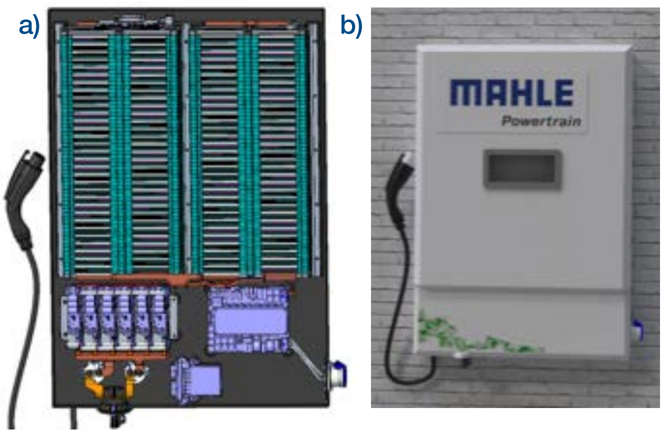


Fig. 15 eMoped charger concept; a) internal view; b) rendered external image

9 eVan Charging System Concept

To complete the investigation into the requirements and design of the novel battery systems required to enable this shift to a fundamentally different approach to powering and using urban delivery vehicles the charging infrastructure needed for the eVan application has also been considered. The charging target for the eVan requires an input power of at least 210 kW, at up to 400 V. This specification is satisfied by the current generation of public fast charging points. This means that the necessary products have already been developed and are already in the market-place. They do require a high-power connection to the power grid, but this is unavoidable with the transition to full fleet electrification.

10 Conclusions

Allotrope Energy's novel Lithium Carbon battery cell technology combines the benefits of super capacitors with the energy storage capacity of lithium-ion cells which enable ultra-fast charging rates to be achieved. MAHLE Powertrain have used Allotrope's technology to design an ultra-fast charging, aggressively downsized battery pack for an urban delivery eMoped application. The battery pack concept design has been extensively analysed to ensure thermal stability and mechanical integrity.

To compliment the unique battery pack specification of the 60 V eMoped application, the charging system required to enable recharging of a small fleet of vehicles to be recharged rapidly via a domestic power socket has been investigated. Such charger systems are not yet available on the market, so a bespoke design is required. The charger system contains in-built energy storage, enabling the eMoped to be charged at power levels of up to 20 kW from a 7 kW domestic supply in under 2 minutes.

The requirements of an urban delivery van have also been investigated and a pack suited to this larger vehicle application have also been developed. This is compatible with existing vehicle fast charging infrastructure.

The study has demonstrated that the Allotrope cells could enable a new range of fast charging urban mobility and delivery solutions to be realised. The study also showcases the battery and power electronics design and development capabilities of MAHLE Powertrain.

Further development of the battery cell is underway and subsequently a functioning demonstrator vehicle could be produced.

11 Acknowledgements

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