EVS30 Symposium
Stuttgart, Germany, October 9 - 11, 2017

Modular battery design for Automated battery manufacturing in Niche applications: AMPLiFII Project

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Abstract

The UK is aiming to position itself as a centre for battery & EV development and maintain its strong niche vehicle sector. In order to support this aim, Innovate UK funded the AMPLiFII (Automated Module to Pack & Pilot Line for Industrial Innovation) project to develop a modular battery architecture based on 18650 format cylindrical cells. The delivery of a facility capable of flexible automated production of such a battery module, which can support either high power or high energy density applications has been a key output. The modules are controlled by a common BMS which is used by multiple partners.

The work has included the development of a scalable battery module manufacturing facility, analytical development of a cooling system for high-power application in addition to design and process validation of prototype modules and packs. This has served to strengthen the UK supply chain in key areas, provided a significant enhancement in R&D skills and created a full "concept to pilot application" capability in the UK. In this paper, we present the flexible module manufacturing concept of the demonstrator battery systems, outline the design trade-offs between applications and provide the manufacturing cost modelling which supports this approach. The modules are designed for battery packs for applications from high performance EV sport cars, luxury PHEV SUVs, backhoe loader and public service bus, the architectures of which are outlined.

1 Objectives

The AMPLiFII project will develop the UK supply chain for fully Lithium-ion battery packs to suit hybrid and electric vehicles across a broad range of markets. The project will design a modular battery architecture, based on 18650 cylindrical cells, developed for both high power and high energy requirements. The common architecture will allow supply chain to combine demand for components for many applications and benefit from economies of scale. Additionally, the common architecture enables the use of a shared battery module manufacturing facility. The pilot line hosted at WMG supports the manufacture of high quality pre-production prototypes, combining appropriate levels of manual and automated assembly methods. Once the AMPLiFII project is complete, the pilot line will become an open facility operating as part of the Energy Innovation Centre located in the International Automotive Research Centre at WMG.

2 Module Design

The module design objectives were to enable a common cell orientation and footprint within the common assembly line but to allow flexibility in terms of the cell pitch, module carrier components and cooling system. Packing of cells within a module is always a trade-off between the desire to achieve maximum volumetric energy density and the requirement to ensure the necessary thermal performance suited to the application and duty cycle of the intended application. Two different module concepts were developed within the project; one more focused for power applications where cooling and flexible configuration for lower volume applications was a higher priority, the other for energy applications where energy density was optimised and potential for higher volume production.

Hexagonal packing is the most efficient method of space filling with equally sized cylinders as demonstrated by Legrange & proved by Thue [1] and this was targeted as the ideal to maximise energy density. Using this method in the energy module, it was found difficult to offer enough structural support from the cell carrier. Therefore a packing of repeating triangle cell groups in direct contact with neighbouring cell pairs was established, allowing high packing density with adequate support from the plastic carriers. In this module design, cell cooling is achieved by an aluminium coldplate supplied with water / glycol coolant fluid in thermal contact with the module bus-bar and cell electrical connection, thereby extracting the heat axially from the cell. This limits the cross minimum cross sectional area for thermal transfer to approximately 40mm^2 per cell at the cell to bus-bar joint.

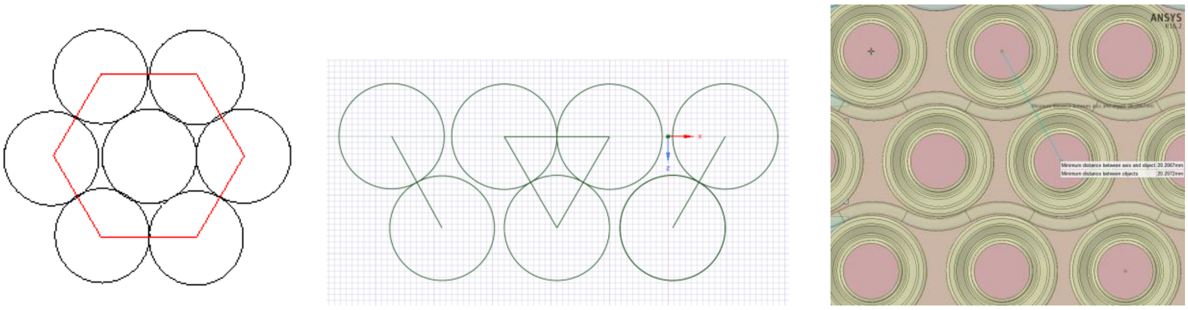


Figure 1a) Hexagonal close packing b) close packed triangle group c) Orientation of cells in power module allowing inter-cell coolant conduits

By comparison, the power module trades the volumetric energy density to allow use of a conformable cooling system with a serpentine path between the cells. These consist of flexible conduits constructed from polymer film material, ultrasonically welded to rigid injection moulded plates which contain the coolant distribution manifold and form the end wall of the module carrier. This design is the subject of a patent application and will be the subject of future publications which detail its construction and fabrication. This achieves a larger heat transfer surface down the length of the cell with cooling system contact on both sides of the cell. With thermal contact to approximately one sixth of the cell circumference and nearly full cell height (10 x 60 = 600mm^2). The inter-cell spacing within this module is 20.80 mm.

The performance of these two differing approaches to thermal management will be significantly influenced by the one to two orders of magnitude better thermal conductivity in the axial directions by comparison to the radial direction in cylindrical cells [2][3]. This work will be completed in the final phase of the project.

The power optimised module uses a repeating 5-cell plastic carrier to allow construction of module between 10 and 140 cells which could be manufactured in the AMPLiFII project facilities. The injection-moulded carrier components may be assembled into module carriers of various sizes using snap-fit features.

The energy optimised module was developed with selective laser sintered rapid prototype carrier which represented a single dedicated plastic moulding to evaluate the design performance. This was produced as a single 99 cell parallel group, three of which were connected in series to produce the 3s99p module. The negative busbar is of a flat sheet construction, whilst the positive busbar is of a tabbed construction allowing variance in vertical cell position to be accommodated.

The electrical interconnects between cell groups in both designs shared significant similarities. In the power module these were composed fabricated from two sheet metal components, one of 0.30mm thickness CW008a material, the other of 2.0mm thickness material of the same grade and joined by laser welding to achieve good electrical connection. The thinner of these sheets forms the tabs for electrical connection to the cells, the thicker sheet provides adequate current carrying capability for the peak electrical current.

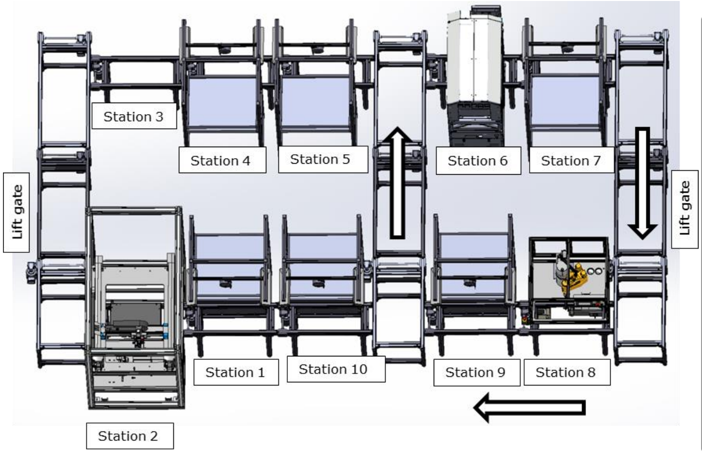
The power module is produced in three main configurations; 2s50p, 3s30p and 4s20p. The details of these module architectures are shown in Table 1 below.

Series	#	3	2	3	4
Parallel	#	99	50	30	20
		Energy	**Power 1**	**Power 2**	**Power 3**
Cell capacity	Ah	3.18	2.05	2.05	2.05
Cell Nominal voltage	V	3.60	3.60	3.60	3.60
Cell Min Voltage	V	2.50	2.50	2.50	2.50
Cell Max voltage	V	4.20	4.20	4.20	4.20
Nominal Energy	kWh	3.40	0.74	0.66	0.59
Nominal Capacity	Ah	314.8	102.5	61.5	41.00
SOC Window	%	85%	85%	85%	85%
Usable Energy BOL	kWh	2.89	0.63	0.56	0.50
Usable Energy EOL (80% BOL)	kWh	2.31	0.50	0.45	0.40
Voltage					
Nominal Voltage	V	10.8	7.2	10.8	14.4
Min Voltage	V	7.5	5	7.5	10.0
Max Voltage	V	12.6	8.4	12.6	16.8

Table 1: Module configurations used in AMPLiFII project

3 Manufacturing

The manufacturing process is based around the assembly of 18650 cells into a modular plastic carrier. The modules are transported through the operations on a modular Bosch Rexroth conveyor system using a WT2 240 x 400mm pallet [4]. All cells supplied to the line are assembled to the carriers using an automated cell loading station which picks groups of 30 cells from a tray, in which they are simultaneously tested for OCV and 1kHz impedance. Any cells outside specification are not transferred to the module carrier. All cells placed in the module are traceable by cell position to cell test result and to cell supplier batch code. All cell data is written to the manufacturing database against the module 'In-process' part number. Cell Open Circuit Voltage and Impedance tests have been applied because the facility is used for different cell types, from different sources, therefore these tests act as a protection against excessive variation of cell state of health or cell state of charge for the incoming material. Without this control, the risk that a batch of cells stored inappropriately or taken from another region of the population (as cells are often graded by impedance) may be mixed within the module, leading to a risk of premature degradation of the module's performance.



Station	Energy module	Power module
1	Load top tray	Assemble cell carriers
2	Automated cell test and load	
3	Install thermistor, top tray	Install cooling system, assemble cell carriers
4		Cell carriers welding
5	Bus bar fitment	
6	Ultrasonic wedge bonding	
7	Rotate module, bus bar fitment	Rotate module, bus bar fitment
8	Pulsed arc welder	
9	Fit harness, thermal pad, cover	Weld test, fit cover
10	Module test and unload	

Figure 2: Module Manufacturing Line

Two different plastic carrier designs are used, each of which is designed with capability to manage the radial tolerances between 18650 format cells from different cell manufacturers. The insertion of the cooling system between the cells is aided by the conformable nature of the polymeric cooling channels designed by Delta Motorsport. Owing to the conformable nature of the coolant channels, the system is relatively easily inserted between the rows of cells. Assembly aids are used to guide the channels into position and the system is secured to the carrier by plastic thread-forming screws.

Welding of cells to bus-bars is achieved by Pulsed DC-TIG welding, although other welding process may be flexibly swapped within the line. The choice of joining process, the time per cell joined and the number of active weld points available is an important consideration in sizing the takt time and throughput of the module manufacturing line. The merits of the alternative welding processes are considered in terms of their productivity and capital investment.

Module End of line quality tests are conducted prior to issuance of a module part number. The test protocol comprising electrical isolation, OCV & impedance, thermistor and voltage sensor, cooling system pressure test and electrical dynamic stress test to determine the voltage and thermal response of the module under a short charge / discharge cycle. All in process and end-of-line birth history data is maintained to Industry 4.0 data traceability standards.

All stations on the manufacturing line are controlled via a ProfiNET network. Two types of data are captured for all relevant manufacturing actions:

- **Traceability Data** which captures an identifier such as the serial number of each component which is used to make a module as it enters the process path and groups this data together within the module.
- **Quality Data** which captures the result and timestamp of measurement operations within a process. This data is useful in developing the manufacturing process as the data can be analysed against the results and the process can be altered to improve the final results.

The database server (Traceability and Quality Server) resides on the network running throughout the facility captures this data from the manufacturing operations. A bespoke service running on the server reads and writes to a data block designed for each station via a Kepware OPC server running the Simatic suite. This server supports an SQL database (TAQDB) and a bespoke Traceability and Quality server application (TAQ). The TAQ system communicates to the stations via an Open Platform Communication (OPC) protocol using an industry standard OPC server, Kepware Server EX. This enables the TAQ to read and write a data structures defined within each individual stations controller's memory.

The quality data comprises of:

- In process quality information captured by the process equipment and stored in the database.
- In process test results from test stations stored in the database.

- Test results from the End-of-line tests stored as files on the server with locations and notes stored within the database when uploaded via a bespoke TAQ Portal application.

4 Cost model

A cost model has been developed which outlines the indicative module cost based upon two different volume scenarios, one for a niche vehicle application and the other for a high volume application. The architectures of the vehicle battery systems for each of the cost scenarios will be outlined. The model includes the facility investment costs, amortisation assumptions, number of operators required, shift operation patterns and material costs; both for cell and non-cell components.

The module bill of materials costs by percentage are outlined in the chart below. This analysis is conducted throughout for the 10.5 kWh high power application. A key area for cost reduction from these initial development parts is the cost of the busbars. The present high costs are associated with the copper material cost and the costs of forming and laser welding the tab sheet in the busbar. This is being tackled by use of an alternative coining process which require more tooling investment but offers a piece less than five percent of the present price. This cost reduction is considered in the higher volume BOM cost chart shown below; cell prices have been fixed in this analysis

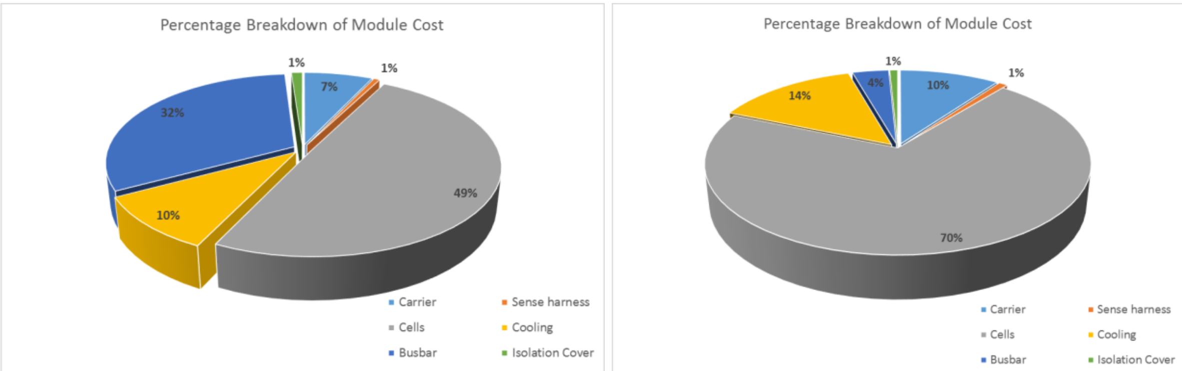
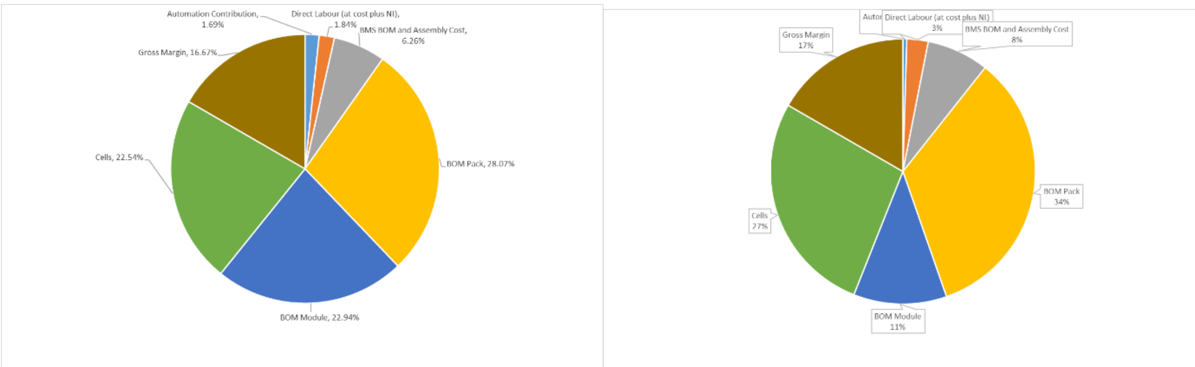


Figure 3: Breakdown of battery module bill of material cost a) 5 day / week, one shift b) 7 day / week, 4 shift

The cost contributions from each of the two volume scenarios are shown below, the pack BOM cost is not adjusted in this analysis as it is not a focus of this work.



5 Supplier Development

A key aspect of the work of the project has been the engagement of the wider UK supply chain. A number of the key partners within the project are SMEs with experience of battery systems design and manufacturing. The AMPLiFII project has enabled the challenges of higher volume automated manufacturing to be explored. Much of the automated assembly and welding equipment has been sourced from UK companies, enabling learning regarding the requirements for in-process test, measurement and reliability and availability in higher volume application. New suppliers and technologies have been introduced into the supply chain, such as photo-chemical etching, coining & fine blanking of busbars, ultrasonic welding & plasma treatment of plastics. This is all enabling an expansion of capability and engagement in the UK electric mobility supply chain.

6 Conclusions

The project has generated significant learning in relation to the aggregation of market demand through flexible module design which can accommodate significant product variation to suit different applications. This is achieved by basing the design on a widely commercially available cell format and incorporation of features to manage cell retention despite minor geometric variation between different cell manufacturers. The cost analysis work has highlighted key commodities where effort to introduce new processes should be targeted; key amongst these have been the busbar and cooling systems and the cell joining process. Work in this area will be the subject of further publications.

7 Acknowledgments

The work outlined above was carried out as part of AMPLIFII, a collaborative research project supported by Innovate UK & UK Government Office for Low Emission Vehicle (contract reference 102490). The project consortium includes the University of Warwick (coordinator), Alexander Dennis Ltd., Ariel Motor Company Ltd., Augean plc, Axion Consulting Ltd., Delta Motorsport, HORIBA MIRA Ltd., Jaguar Land Rover Ltd., JCB Service, Potenza Technology Ltd., Trackwise Designs Ltd. and the University of Oxford."

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