Final report

1.1 Project details

Project title	Component to control fast charging of electric vehicles
Project identification (program abbrev. and file)	EUDP 13-I, J.nr. 64013-0103
Name of the programme which has funded the project	Energiteknologisk Udviklings- og Demonstrations Program Området: Energieffektivitet
Project managing company/institution (name and address)	Lithium Balance A/S
Project partners	None
CVR (central business register)	29391130
Date for submission	12 November 2017

1.2 Short description of project objective and results

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Paper
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1.2 Short description of project objective and results

Dansk:

Formålet med projektet var at udvikle, implementere og demonstrere CHAdeMO og IEC62196-3 lynladningsfunktionalitet i et batteristyresystem til litium-ion batterier til brug i elektriske biler og industrielle maskiner. Da IEC standarden først blev færdig i sin endelige version meget sent i projektet, og de nødvendige elektronikkomponenter til denne standard ikke blev tilgængelige i projektperioden, blev det besluttet istedet at implementere den kinesiske GB/T lynladningsstandard i tillæg til CHAdeMO versionen. Det lykkedes derfor i løbet af det 2 årige projekt forløb, at udvikle en standardkomponent, som gør elbiler kompatible med to af de tre store internationale lynladningsstandarder. Det udviklede lynladningsinterface blev den første kommercielt tilgængelige komponent, der understøtter de to valgte lynladningsprotokoller.

English:

The purpose of the project was to develop, implement and demonstrate CHAdeMO and IEC62196-3 DC fast charging functionality in a battery management system for lithium ion batteries for use in electric cars and industrial machines. As the IEC standard was not finished until late in the project, and the necessary electronic components for this standard turned out not to become available in the project period, it was decided to implement the Chinese GB/T standard for fast charging instead and in addition to the CHAdeMO version. During the 2-year project a standard component, that makes electric cars compatible with two of the three dominating international fast charging standards were successfully developed. The developed fast charging interface become the first commercially available component that supports the two chosen fast charge protocols.

1.3 Executive summary

The physical connection, topology and communication requirements for the Plug-In Electric Vehicle (PEV) fast charging are standardized by International Electrotechnical Commission (IEC). Based on these standards several distinct fast charging methods are currently being commercialized: CHAdeMO (DC) currently the most widespread fast charging standard, GB/T (AC) the fast charging standard published in China, and COMBO/Combined Charging System (CCS) (DC). All three fast charging methods can be supported by the Fast Charge Interface Module (FCIM) developed by Lithium Balance in the project supported by EUDP, which provides the vehicle side implementation of the fast charging infrastructure.

The FCIM fills a non-trivial role in the safety architecture of the fast charging solution. On one hand there is the energy storage system and the battery management system of the PEV, with many safety requirements relating to fire hazards, electrical hazards and so forth. On the other hand there is the charging station with a safety architecture relating to electrical hazards, grounding faults, sparks etc. The FCIM is included in both safety cases and acts as a bridge between the two.

Since both the charging station and the BMS will detect and react to malfunctions in the FCIM it is imperative that the FCIM maintains a very high level of reliability. In order to accomplish this the FCIM has been designed using exclusively highly reliable automotive grade components, an EMC robust 6 layer board design and an automotive safety integrity level (ASIL D) rated microcontroller suitable for safety critical subsystems in road vehicles.

The CHAdeMO and GB/T implementations are technically straightforward since they do not include the highly specialized PLC communication used by CCS. Furthermore, the CCS implementation largely uses the same elements as the CHAdeMO and GB/T implementation. Based on these two observations the FCIM was designed as a base platform that contains all functionality required to support CHAdeMO or GB/T fast charging. With an expansion module the FCIM also supports the CCS standard (not developed in this project, as the necessary PLC components supporting the CCS standard where not available within the project period). Using this modular topology it is possible to address all three standards without incurring extra cost due to superfluous hardware components for either implementation.

It is also necessary to have a flexible firmware design with possibilities to configure the unit for different working environments (different vehicle systems, different uses of platform etc.). Hence the firmware is designed to allow customization of the platform functionality via firmware/settings during vehicle integration. The FCIM can communicate with any battery management system and can therefore be integrated or retrofitted onto any PEV thus reducing development cost and effort of new PEV with fast charge support. The flexibility of the FCIM also simplifies support of an international distribution of a PEV, since the difficulty of managing various national standards is managed exclusively by the FCIM.

The advantages of implementing the vehicle side of the fast charging in a stand-alone module include:

1. Reduction of development cost and time to market for new PEV products,
2. Possibility to retrofit fast charging support in existing PEV fleets,
3. Support for multiple fast charging standards within a single PEV product line can be managed by upgrade of only the FCIM and replacement of the charging plug,
4. Possible to sell fast charging support as an optional module hence supporting product diversification.

The test protocol developed by Lithium Balance to verify that the fast charging module fully complies with the CHAdeMO standard has subsequently been adopted by the test institution APPLUS IDIADA in Spain as an official CHAdeMO certification test of vehicle side fast charging controllers, and the Lithium Balance fast charging module was tested and as the first of its kind officially certified by IDIADA in October 2015.

1.4 Project objectives

Description of the project objectives and the implementation of the project. How did the project evolve? Describe the risks associated with the project. Did the project implementation develop as foreseen and according to milestones agreed upon? Did the project experience problems not expected?)

1.5 Project results and dissemination of results

1.5.1 Analysis of standards

To identify the requirements for the development of the FCIM many standards and implementations of fast charging were analysed.

The results of this analysis for two selected implementations are briefly summarized in table 1.

Table 1: Analysis of DC fast charging standards

	CHAdeMO	CCS
Communication physical	CAN	GreenPHY PLC
Communication data	Custom CAN	**Network**: IPv6 **Transport**: TCP, UDP **Session**: V2GTP, HTTP **Presentation**: EXI **Application**: Smart charge protocol, SLAAC, DHCP
Physical signals	Charge sequence 1, Charge sequence 2, Connector detection, Charge Enable, GND CAN H, CAN L	Control Pilot, Proximity, Detection, GND
Connector	CHAdeMO 10 pin	IEC 62196-2-3 SAE J1772
Control logic	State machine	State machine

1.5.2 Requirement specification

To achieve an effective implementation of a FCIM for real life application it is important to understand how the FCIM will fit into the overall functional and safety architecture of the PEV. The analysis takes a PEV without fast charging support as the starting point. The key components of the PEV that are involved in the implementation of the fast charging are;

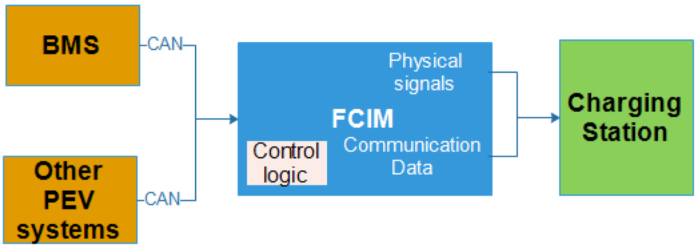
1. The battery management system (BMS). Arguably the most important actor in the implementation of the fast charging the BMS is responsible for setting set points for allowed charge current, maintaining safe and reliable operation of the battery and communicating all relevant battery diagnostic data on the Controller Area Network (CAN)

2. The vehicle control unit (VCU) may or may not interact with the BMS to set the system into “charge mode” and provide the vehicle driver with information about charge status.

3. The on-board charger, should in most cases be disconnected during fast charging but needs to be considered in the functional and safety analysis of the fast charging solution.

In order to keep the FCIM simple to integrate and universally applicable the interface has been limited to a CAN bus interface to the BMS. Any information to the driver or charger will be managed by the BMS, just as if the vehicle is charging using the on-board charger. The FCIM uses the information from the BMS to control the fast charging process in a way that is consistent with the safe operational parameters set by the BMS. See Figure 1.

Figure 1: General FCIM design logic



This architecture supports fast charging using both systems of type A (CHAdeMO) and C (CCS), provided the FCIM is engineered to comply with a number of system level requirements:

- One CAN bus interface to the BMS and other PEV systems
- One CAN bus interface to CHAdeMO chargers. This interface must be galvanically isolated from the BMS interface.
- Driver output for relays controlling the connection to the charger
- Power Line Communication (PLC) interface to CCS chargers.
- Diagnostics of the charging process
- Data logging for the CAN bus traffic for diagnostic purposes
- Processing capability to support communication on two high-speed CAN bus networks at once

1.5.3 Functional safety

The FCIM fills a non-trivial role in the safety architecture of the fast charging solution. On one hand there is the energy storage system (ESS) of the PEV, with many safety requirements relating to fire hazards, electrical hazards and so forth.

On the other hand there is the charging station with a safety architecture relating to electrical hazards, grounding faults, sparks etc.

The FCIM acts as the intermediary between these two safety critical systems. In summary:

1) The BMS is responsible for maintaining the safety of the battery pack at all times.
2) The charging station is responsible for maintaining the safety of the charging post and the user at all times.
3) The FCIM is included in both safety cases and acts as a bridge between the two.

Since both the charging station and the BMS will detect and react to malfunctions in the FCIM it is imperative that the FCIM maintains a very high level of reliability.

In order to accomplish this the FCIM has been designed using exclusively highly reliable automotive grade components, an EMC robust 6 layer board design and an automotive safety integrity level (ASIL D) rated microcontroller suitable for safety critical subsystems in road vehicles.

1.5.4 Hardware design considerations

The CHAdeMO implementation is technically straightforward since it does not include the highly specialized PLC communication used by CCS.

Furthermore the CCS implementation largely uses the same elements as the CHAdeMO implementation.

Based on these two observations the FCIM was designed as:

a) A base platform that contains all functionality required to support CHAdeMO fast charging.

b) A modular concept of expansion modules where the first module developed is used to support the CCS standard. Future modules can be developed to support other fast charging standards.

Using this modular topology it is possible to address both standards without incurring extra cost due to superfluous hardware components for either implementation. It also makes the FCIM a platform secured for the future by assuring that upcoming fast charging standards can be supported with a minimum of effort.

1.5.4.1 Base platform

To cover the requirement for the data communication the base platform supports two galvanically isolated CAN bus interfaces in order to accommodate the interface with on-board systems and separate bus with the charger.

To meet the electrical requirements of the CHAdeMO specification the base platform contains three outputs capable of driving PEV high power relays with typical specifications.

To cover the requirement of data recording (logging) the base platform supports data logging to an automotive grade Secure Digital (SD) card and a real time clock (RTC) with a 10 year onboard battery to add time stamps to the data logging.

To cover the requirement of supporting multiple standards the system is designed including two detachable expansion modules which are able to communicate with base platform and control independent I/O’s directly.

1.5.4.2 CCS expansion module

To cover the requirement for the data communication the CCS expansion module includes a PLC modem.

To cover the requirement of hardware signals the expansion module includes dedicated IO controls according to the CCS specifications.

The CCS module in controlled directly from the base module using an internal high speed communication bus commonly used in automotive electronics designs.

1.5.4.3 Design reusability

The system designed for the support of fast charging is in fact a very flexible and powerful platform. The capability of adding new hardware functionality in the form of expansion modules as well as a boot loadable high performance safety rated automotive microcontroller gives the platform nearly limitless possible applications.

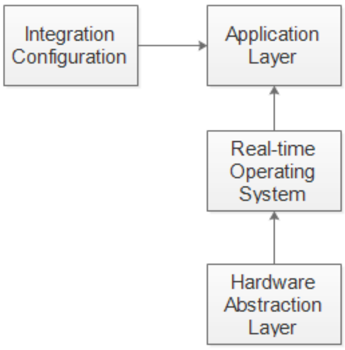
Some examples include; CAN bridging, data logging, fleet management, VCU, DC charging system type B implementation, etc.

1.5.5 Firmware design consideration

1.5.5.1 Base platform

In order to accommodate functionality described in previous sections it is necessary to have a flexible firmware design with possibilities to configure the unit for different working environments (different vehicle systems, different uses of platform etc.). Hence the firmware is designed to allow customization of the platform functionality via firmware/settings during vehicle integration.

Figure 2: General FCIM base platform firmware design



1.5.5.2 Expansion module

The expansion module is designed to run its own customized firmware supporting the protocol and application layer of the CCS standard. The main challenges in regards to implementing the expansion module firmware for CCS fast charging is the implementation of the communications protocol stack.

The communications protocol stack for the CCS follows the Open Systems Interconnection model (OSI) and identifies the requirements for implementing common internet based protocols with addition to some custom protocols that are fast charging specific for type C. This includes the requirement for IPv6, TCP implementation alongside with XML parser implementation for session and application layers.

1.5.6 Fast charging applications

The most well-known application of fast charging is a public charging station somewhere alongside the highway or in a parking lot in city centre.

PEVs are seen in increasing numbers in society as cheaper (fuel wise) and cleaner (emissions wise) means of transport, which is becoming more and more relevant due to more strict standards for emission regulation, decreasing prices on PEV’s and an increased public environmental awareness.

In industrial and public applications there may already be charging infrastructures in place for fleets of electric vehicles (powered predominantly by lead acid batteries). In this segment the application of a fast charging infrastructure seems like a logical next step.

1.5.6.1 Private and commercial PEV

One key driver for the introduction of a fast charge interface in a private and commercial PEVs is to make it more attractive for a customer in terms of reducing the so called “range anxiety” which is a common phenomenon when a private person or a company consider using/buying an EV. Providing the vehicle owners with fast charge capability and charging network increases the attractiveness of EV by reducing the charging time (closing the gap between time that takes to fill up a gas tank in standard vehicle and charging an EV) and enabling the driver to make long range trips (trips that would require the driver to charge EV at least once).

In this area the FCIM provides the manufacturers of PEVs with simple and straight forward implementation for common fast charge standards.

1.5.6.2 Industrial and public PEV

Industrial and public EVs such as forklifts, trucks, garbage trucks, busses, light transporters etc. is another attractive market for use of FCIM.

Providing a facility to reduce charge times means a higher utilization of the PEV, less downtime and faster return of investment of the vehicle purchase.

While regular charging is sufficient to cover the vast majority to travel distances for private and commercial PEV's and the role of fast charging can be considered mostly psychological for this segment the industrial and public PEV fast charging can in fact bring about radical improvement in fleet utilization.

Furthermore, when considering fast response vehicles (fire trucks, ambulances etc.) fast charging could be considered a requirement by end customers to enable electric drives in these vehicles.

Often fleets of PEV's use custom made chargers and charging system that are chosen due to lack of information and the relatively complicated implementation of charging system standards. However conformance to such standards could be advantageous because of broad (and increasing) supply of chargers conforming to the mentioned standards. The benefits of using such charger would come in form of improved safety, service, maintenance and supply. In addition the utilization of a standardized charger interface would allow the vehicles to charge from public charging posts.

The FCIM is a great fit for such applications because often the manufacturers of such PEVs have low volume production (compared to series production of private cars) thus making it challenging to develop proprietary systems for conformance with international fast charge standards.

1.5.7 Fast charging impact on battery life

When considering fast charging impact on batteries the common belief is that the fast charging will significantly decrease the useful life of battery, but in fact very little has actually been published on the long term effects of fast charging on lithium-ion batteries.

However, recently some car manufacturers who offer fast charge in their PEVs have given their batteries the same extent of warranty periods independent on charging method applied, which suggests that the real world data collected indicates that the fast charging does not have significant impact on battery life.

One published study [1]suggests that the fast charging might cause accelerated cell degradation due to physical limitations of cell, where cells swell and shrink during charge/discharge process.

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[1] Current-induced transition from particle-byparticle to concurrent intercalation in phaseseparating battery electrodes, Yiyang Li et al. Available at http://www.nature.com/

Other unofficial studies that Lithium Balance A/S has been given access to through our research network suggest that the impact on the battery life when fast charging can be associated with side effects that are caused by fast charge but not the fast charge process itself. From these side effects the most significant is considered the temperature increase on the battery cell due to the heat generated by the internal resistance, which contributes to higher heat dissipation with higher currents.

In order to contribute to the knowledge base about the batteries and to support customers with the system design and integration of the battery packs in the design Lithium Balance A/S in cooperation with Danish Technical Institute (DTI) performed tests on different battery cells that are available in the market and commonly used for different EV applications.

The task was to investigate the impact of fast charge on the degradation and useful lifetime of two different lithium-Ion batteries. The cells were cycled between 20% SoC and 80% SoC throughout the test to minimize impact from known degradation sensitivity at extreme SoC. The test was performed at 0.5C, 2C and 3C, which corresponds to a charge time of 72 minutes, 18 minutes and 12 minutes respectively at 25°C.

1.5.7.1 Battery tests

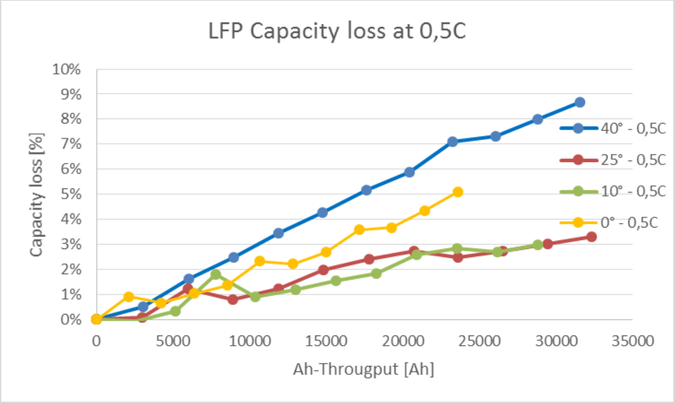
Twelve LiFePO4 (LFP) cells and twelve Ni1/3Mn1/3Co1/3O2 (NMC) cells were cycled at three different C-rates and at four different temperatures as shown in the test matrix. The LFP cell was a 20Ah pouch cell and the NMC cell was a 27Ah prismatic cell. All cells were cycled between 20% SoC and 80% SoC (State of charge) with a charge rate as shown in the test matrix and a 0.5C discharge rate for all cells. It is shown in literature [2] that the amount of charge, and where in the capacity range a partial charge is added, may affect the degradation at low temperatures. However, this effect should be negligible, since the cells were cycled between 20% SoC and 80% SoC throughout the test.

Cycle test matrix

Test No.	**Temp.**	**Charge-rate**	
		LFP	**NMC**
1	0	0,5	0,5
2	0	1	2
3	0	2	3
4	10	0,5	0,5
5	10	2	2
6	10	3	3
7	25	0,5	0,5
8	25	2	2
9	25	3	3
10	40	0,5	0,5
11	40	2	2
12	40	3	3

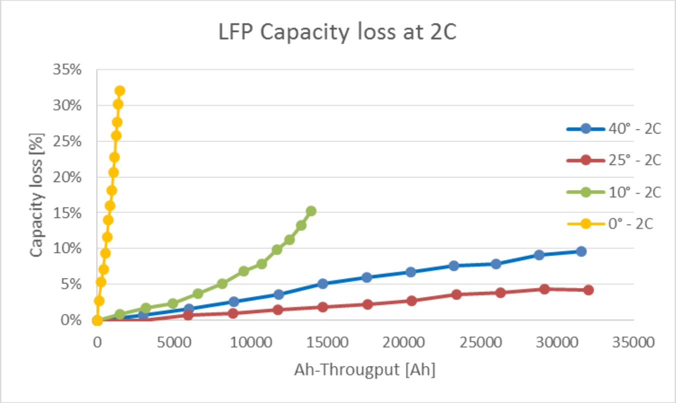
Four Binder temperature chambers were used to provide the four temperatures whereas the electrical stimuli and measurements were provided by a Maccor 4000 test system.

The results presented in this section are all data measured during the lifetime test performed.



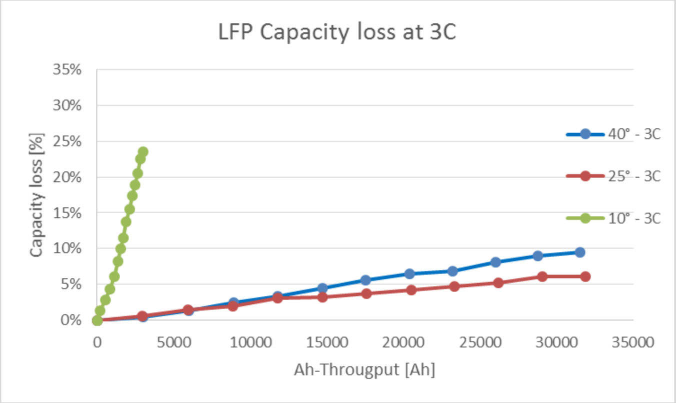
At 0.5C charge rate, the LFP capacity loss at 40°C is more than twice as high as the loss at 25°C and 10°C, whereas the loss at 0°C lies in between.

Figure 3: LFP Capacity loss at 0,5C charge rate and at four different temperatures.



At 2C charge rate, the LFP capacity loss at 40°C is still more than twice the loss at 25°C. The LFP Capacity loss at low temperatures however is much higher, even though the Ah-throughput is much lower than the throughput at 25°C.

Figure 4: LFP Capacity loss at a 2C charge rate and at four different temperatures.



A LFP cell was planned to cycle at 0°C and 3C, but the cell was not able to perform at these conditions. At low temperature, the LFP cell showed a much higher capacity loss than the cells cycled at higher temperatures.

Figure 5: LFP Capacity loss at 3C charge rate and at three different temperatures.

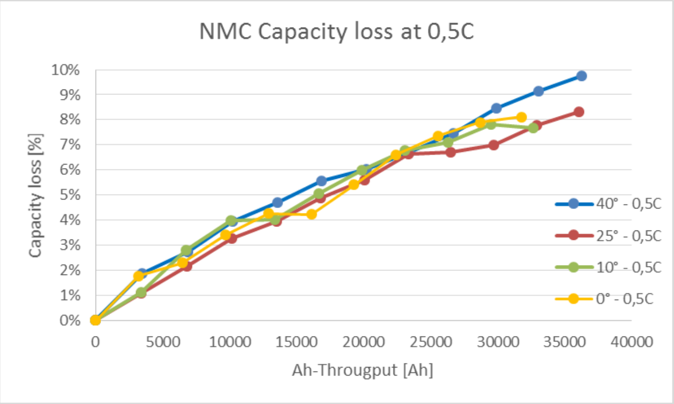


Figure 6: NMC Capacity loss at 0.5C charge rate and at four different temperatures.

The NMC cells cycled at 0.5C show almost the same capacity loss regardless of the temperature. The capacity loss at 40°C equals the corresponding LFP cell, but the loss at the three other temperatures is higher.

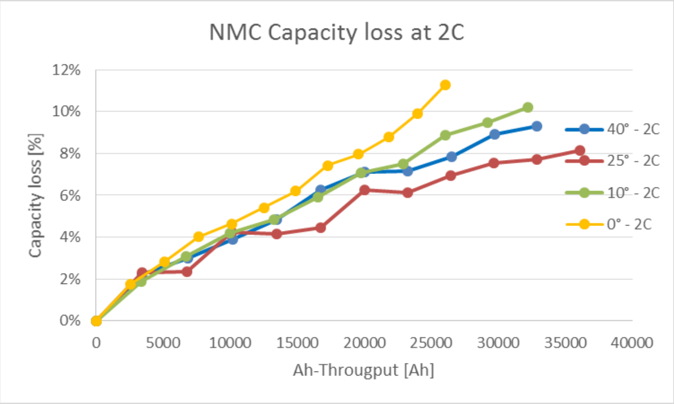


Figure 7: NMC Capacity loss at 2C charge rate and at four different temperatures.

The 2C NMC capacity loss at 25°C and at 40°C are almost unchanged from 0.5C to 2C, but at 2C the loss at 0°C has taken an increasing trend. Compared to the corresponding LFP cells the low temperature loss is much lower for NMC.

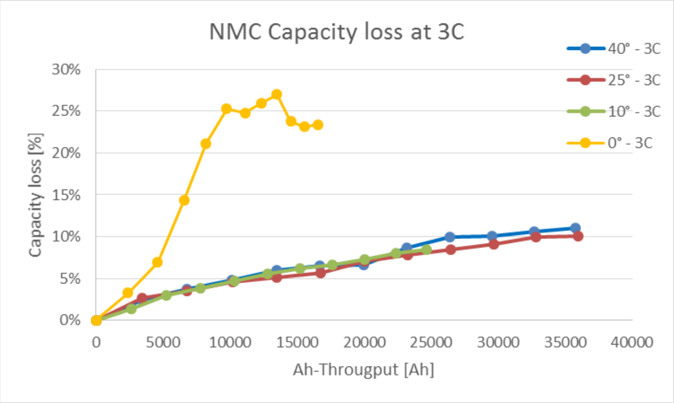


Figure 8: NMC Capacity loss at 3C charge rate and at four different temperatures.

At 3C, the NMC capacity loss at 25°C and at 40°C has increased about 2% compared to the loss at 2C. The loss at 10°C and 3C is nearly the same as at 2C, but less capacity is processed in each cycle. The 0°C NMC loss curve starts as an exponential curve like the LFP loss curve at 10°C and 3C, but suddenly the curve flattens and then the loss even decreases. The NMC cell cycled at 0°C processed less Ah amount than those cycled at higher temperatures.

The results of the lifetime test show that the capacity loss at temperatures below room temperature is highly affected by the C-rate, whereas the capacity loss at temperatures above room temperature is barely affected by the C-rate. Therefore, fast charge of batteries without suitable thermal management operated in colder regions in the wintertime may impose a risk of wearing out the battery pack much faster than expected.

To avoid excessive wear a BMS (Battery Management System), which can control the charge current with respect to the actual temperature, should be applied. Hence, specific knowledge about the battery chemistry and its degradation characteristic must be implemented in the BMS.

In budget battery systems, the BMS can limit the charge current to a safe level at low temperatures, as it is done in many electrical cars – causing must longer charge periods. If Fast charge is required, a thermal management system with preheating capability must be installed so that the BMS can allow higher charge currents without excessive battery wear.

1.5.8 Commercial and dissemination activities

The fast charging interface module from Lithium Balance provides a simple, safe and reliable solution to the vehicle side of fast charging. It can swiftly and conveniently be integrated in both electric vehicles for the consumer segment and into industrial vehicles.

Already during the project as well as post-project Lithium Balance was able to attract quite some attention from potential customers for the developed fast charge interface, which supports the worldwide adoption of standards for fast charging both by the development of new novel products and by being able to offer battery qualification and testing in cooperation with DTI for fast charging application of commonly used battery chemistries.

1.5.8.1 Dissemination activities

- Presentation at CHAdeMO General Assembly; Munich, October 2014
- Exhibition, eCarTec, Muncih, October 2014
- Presentation at FIAT group, Torino, December 2014 (Event arranged by the Danish Foreign Ministry)
- Exhibition, Hannover Messe, April 2015
- Paper, at EVS conference, Korea, May 2015
- Poster at AABC, Advanced Automotive Battery Conference, Mainz, January 2016
- Article: Electric and Hybrid Vehicle Technology, June 2016

1.5.8.2 Product test and demonstration activities

The fast charge interface first prototype successfully passed environmental HALT tests at DELTA in Denmark. Subsequently the fast charge interface had to pass functional testing at IDIADA in Spain, the only CHAdeMO test facility outside Japan. In consultation with IDIADA and the CHAdeMO organisation it was agreed to lift the test protocol we had developed for the test into an official certification test, authorized by the CHAdeMO organisation. As our fast charge interface successfully passed the certification test at IDIADA, the product became the first officially certified product of its kind in the World, which resulted in significant attention among the target customers.

After the official certification we were ready to move onto the demonstration phase in an actual vehicle. The demonstration was performed in cooperation with Turkish electric vehicle manufacturer BD Otomotive on an electric Renault Kangoo and with CHAdeMO compatible fast chargers from ABB. The demonstration was performed in Q4 of 2015 in Istanbul with success, and BD Otomotive thereafter became the first customer for the fast charge interface.

1.5.8.3 Customer interest

As the fast charge interface was promoted at exhibitions, at conferences, in journals and in customer meetings from the beginning of the project, we attracted quite some interest from potential customers both during and after the projects. We received the first orders for customer trials from automotive OEMs in Europe, Asia and America before the project was completed. Post project these customers are still in their vehicle development stage, so the first volume orders are expected in 2018.

One Chinese OEM during the project requested us to develop the Chinese GB/T fast charging standard version, which was done before the project ended. This was done instead of finishing the CCS version, because components for the CCS add-on board was still not commercially available in the market at the end of the project. But the fast charge interface is prepared for the upgrade to CCS.

1.5.9 Project challenges

The main challenge for the project was the delayed approval of the CCS/Combo 2 fast charging standard. The protocol was not approved until the final stages of the project which meant that the CCS compatible PLC modems (a component for the fast charge PCB) did not become commercially available within the project scope in spite of the decision and approval to delay the project with 7 months until December 2015. For this reason it was decided to implement the Chinese GB/T fast charging protocol in addition to the Japanese CHAdeMO protocol. Both version where completed and delivered to customers at the end of the project.

The other main challenge was the delayed start of the battery life testing at DTI. It took longer than expected to define the test protocols as well as to source appropriate batteries for the tests. With the approved 7 months delay it was possible to conclude the accelerated battery life time test within the project deadline as well as integrate the results into the control algorithms of the fast charge interface.

The project therefore took 24 months to complete, ad in this period it was possible for the project to succeed in realising all of its objectives.

1.6 Utilization of project results

Lithium Balance fully intends to utilize the results of the project.

Lithium Balance will (and has) post project continue to promote the fast charge interface to customers Worldwide. The fast charge interface is now an integral part of the company battery management solutions and business plan.
Lithium Balance has also identified the need to finish the development of the CCS(Combo2) version of the fast charge interface for the European market in a subsequent project. We will also for a specific customer develop a version of our BMS were the fast charge functionality is embedded on board. Finally, the standards continue to develop, and Lithium Balance must therefore continue to update the fast charge interfaces to comply with future versions – of which focus is on

adoption of V2H and V2G in the fast charge protocols as well of increasing the allowed currents from 50 kW up to 250 or 350 kW.

Post project we have only identified a couple of competitors, none of them going through the costly certification process. In reality the main competitor is the automotive OEMs themselves, if they chose to develop the interface internally for their own vehicles. Some of the prefer this option for very high volume car models (i.e. 100.000s of cars/year), whereas they are generally very attracted to our off-the-shelf solution for lower volume programs (from 100s to 10.000s of cars/year) or when time is limited.

1.7 Project conclusion and perspective

The project ended very successful in the sense that:

- 2 new products, Fast Charge Interfaces supporting CHAdeMO and GB/T were developed, implemented, demonstrated and put in production before the end of the project
- The CHAdeMO interface became the first officially certified product of its kind in the World, and it was sold to customers for trial and development projects by the end of the project
- The GB/T interface was developed for a specific Chinese automotive OEM, who is now implementing the interface in its vehicles for the Chinese market, before the end of the project
- Lithium Balance together with DTI created important knowledge about the degradation of batteries during fast charge and how to avoid it

The project has therefore strengthened the product portfolio and business potential of Lithium Balance. But the project has also opened the door to possible new research and development projects in the area of V2G and V2H implementations, as all of the three international fast charging standards intends to include these applications in their standards. The fast charge interface is therefore very interesting as a facilitator for the electric car manufacturers, not only to support fast charging of their vehicles, but also that their cars can support to grid or a home as a flexible energy storage asset.

Annex

Poster: AABC, Advanced Automotive Battery Conference, Mainz, Jan 2016

Fast charging at low and high temperatures and influence on battery life

How does fast charging of electrical vehicles at low or high temperature affect battery life? This study investigates degradation rates at different temperatures and charge rates for two battery chemistries and influence of high rates on battery wear.

Experimental setup

- 12 LFP ($LiFePO_4$) and 12 NMC ($Ni_{1/3}Mn_{1/3}Co_{1/3}O_2$) based batteries are tested at cell level.
- 12 different test cycles at 3 different C-rates and 4 different temperatures for each chemistry.
- Cells are cycled between 20 % SoC and 80 % SoC.
- The discharge rate is 0.5C

Overall results

- Capacity loss at low temperatures is highly affected by the charge C-rate.
- Capacity loss at high temperatures is only slightly affected by the charge C-rate.

Conclusion

- Specific knowledge of battery chemistry and degradation should be implemented in the BMS (Battery management system) to avoid excessive battery wear by limiting high charge currents at critical temperatures.
- If fast charge is required at low temperatures, a thermal management system with preheating capability is highly recommended.

Results illustrated

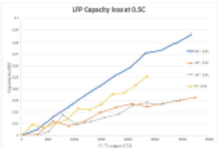
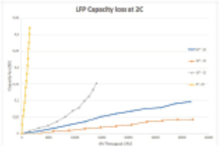


Figure 1: LFP capacity loss at 0.5C charge rate and at four different temperatures.

At 0.5C charge rate, the LFP capacity loss at 40°C is more than twice as high as the loss at 25°C and 10°C.

Figure 2: LFP capacity loss at a 2C charge rate and at four different temperatures.

The LFP capacity loss at low temperatures is very high compared to 25°C and 40°C.



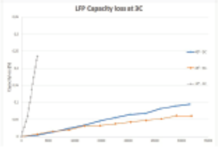
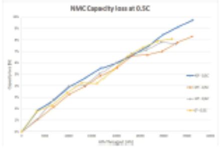


Figure 3: LFP capacity loss at 3C charge rate and at three different temperatures.

At low temperature, the LFP cell showed a much higher capacity loss than the cells cycled at higher temperatures.

Figure 4: NMC capacity loss at 0.5C charge rate and at four different temperatures.

The NMC cells cycled at 0.5C show almost the same capacity loss regardless of the temperature. The capacity loss at 40°C equals the corresponding LFP cell, but the loss at the three other temperatures is higher.



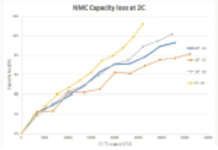
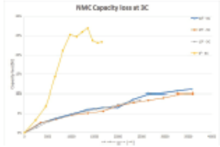


Figure 5: NMC capacity loss at 2C charge rate and at four different temperatures.

The 2C NMC capacity loss at 25°C and at 40°C are almost unchanged from 0.5C to 2C, but at 2C the loss at 0°C has taken an increasing trend.

Figure 6: NMC capacity loss at 3C charge rate and at four different temperatures.

The NMC cell cycled at 0°C process less Ah amount than those cycled at higher temperatures.



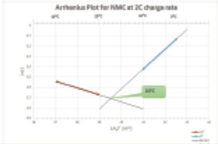


Figure 7: NMC Arrhenius plot for NMC at 2C charge rate.

Arrhenius plot suggest that the capacity loss is related to temperature by the Arrhenius equation (1), but with one set of coefficients (Ea and A) for high temperatures and a second set of coefficients at low temperatures. This indicates that one degradation mechanism, SEI layer formation, is dominant at high temperatures, while another degradation mechanism, lithium plating, is dominant at low temperatures.

Further tests in this area are on-going in the DTI battery laboratories.

Cooperation and knowledge sharing are welcome.

Acknowledgements
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Fast-charging architecture

This new vehicle-side fast-charge interface module can be easily implemented in existing plug-in electric vehicles to comply with CHAdeMO, GB/T and CCS fast-charging standards

The physical connection, topology and communication requirements for plug-in electric vehicle (PEV) fast charging are standardized by the International Electrotechnical Commission (IEC). Based on these standards, several distinct fast-charging methods are currently being commercialized: CHAdeMO (DC), currently the most widespread fast-charging standard; GB/T (AC), the fast-charging standard published in China; and the COMBO/Combined Charging System (CCS) (DC). All three can be supported by Lithium Balance's Fast Charge Interface Module (FCIM), which provides the vehicle-side implementation of the fast-charging infrastructure.

The FCIM fulfills an important role in the safety architecture of the fast-charging solution. On one hand, there is the energy-storage system and the battery management system of the PEV, which has many safety requirements relating to potential fire and electrical hazards, etc. On the other hand, there is the charging station with a safety architecture designed to protect against electrical hazards, sparks, grounding faults, etc. The FCIM is included in both safety cases and acts as a bridge between the two.

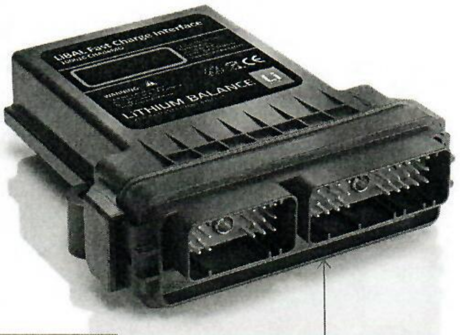
As both the charging station and the battery management system will detect and react to malfunctions in the FCIM, it is imperative that the FCIM maintains a very high level of reliability. To accomplish this, Lithium Balance's FCIM has been designed using highly reliable automotive grade components, a robust EMC six-layer board layout, and an Automotive Safety Integrity Level D-rated microcontroller suitable for safety-critical subsystems in road vehicles.

Implementation of CHAdeMO and GB/T are technically straightforward as they do not require highly specialized PLC communication as used in the CCS. Furthermore, implementation of the CCS mainly uses the same elements as CHAdeMO and GB/T. Based on these two observations, the FCIM was designed as a base platform that contains all the functionality required to support CHAdeMO and GB/T fast charging. With an expansion module, the FCIM also supports the CCS standard. Using this modular topology it is possible to address all three standards without incurring extra cost from superfluous hardware components needed for their implementation.

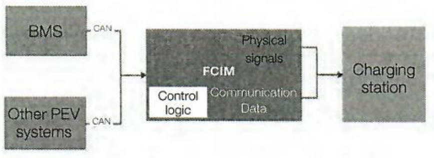
It is also necessary to have a flexible firmware design, which provides the ability to configure the unit for different working environments (different vehicle systems, different uses of platform, etc). Hence the firmware is designed to enable customization of the platform functionality via firmware/settings during vehicle integration. The FCIM can communicate with any battery management system and can therefore be integrated or retrofitted into any PEV thus reducing development cost and efforts for new PEVs with fast charge support. The FCIM is also extremely flexible; it complies with various international standards and thus supports the worldwide distribution of PEVs.

The advantages of implementing the vehicle side of the fast-charging system in a standalone module include the following: a reduction in development cost and time to market for new PEVs; the ability to retrofit fast-charging support into existing PEV fleets; support for multiple fast-charging standards within a single PEV product line can be managed by the upgrade of only the FCIM and replacement of the charging plug; and fast-charging support can be sold as an optional module supporting product diversification.

The test protocol developed by Lithium Balance to verify that the fast-charging module fully complies with the CHAdeMO standard has subsequently been adopted by Applus IDIADA in Spain as an official CHAdeMO certification test of vehicle-side fast-charging controllers. The Lithium Balance fast-charging module was officially certified as the first of its kind by IDIADA in October 2015.



The functionality of Lithium Balance's Libal Fast Charge Interface can be easily setup using a PC configuration tool via CAN bus



Charging systems of type A and B are supported by the modular, adaptable FCIM

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Fast Charging of Electric Vehicle, New Solutions and Concepts

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Abstract

In Asia, Europe and North America more and more effort is being put into standardization, development and deployment of fast charging stations for electric vehicles. This will over the next few years create an increasing demand for off-the-shelf components to build the vehicle side of the fast charging infrastructure. This paper will give a brief overview of the dominant standards within the field of fast charging and present a cheap, powerful and flexible solution to address the different fast charging standards from a global perspective. The paper will also briefly cover implementation of formal functional safety for fast charging application. Finally the paper will cover independent cell testing and characterization to enhance understanding of cell behavior and performance degradation of cells under fast charging condition.

Keywords: Fast charging, DC charging, functional safety, cell characterization, international standards

1 Introduction

The physical connection, topology and communication requirements for the Plug-In Electric Vehicle (PEV) fast charging are standardized by International Electrotechnical Commission (IEC), see [2] and [3].

Based on these standards several distinct fast charging methods are currently being commercialized with more emerging on the horizon. Some important implementations:

A. CHAdeMO, direct current (DC) fast charging implementation that is the defacto standard in Japan and currently the most widespread fast charging standard in Europe
B. GB/T, alternating current (AC) fast charging standard published in China
C. COMBO/Combined Charging System (CCS), DC fast charging implementation targeting European and North American markets

The Fast Charge Interface Module (FCIM) by Lithium Balance A/S provides the vehicle side implementation of the fast charging infrastructure. Systems of type A and C are supported right out of the box, but the FCIM has been designed using a modular concept that allows for fast adaptation for systems of type B as well as other upcoming fast charging solutions. The FCIM can be integrated or retrofitted onto any PEV thus reducing development cost and effort of new PEV with fast charge support.

The flexibility of the FCIM also simplifies support of an international distribution of a PEV, since the difficulty of managing various national standards is managed exclusively by the FCIM.

The FCIM can be integrated with any battery management system, but come prepared out of the box with a well-tested integration with the battery management systems from Lithium Balance A/S.

Besides implementing DC fast charge vehicle side support it is relevant to study what impact does fast charge (high C rate, ≥2C) have on PEV battery packs. It is generally assumed that fast charge can significantly decrease the useful life of the battery, however few results are available on the matter and there are reasons to argue that fast charge in itself does not significantly decrease the useful life of the battery, but the side effects of fast charge (especially increased temperature due to internal resistance) play a more significant role in the decrease of useful life when fast charging the battery pack [1].

2 Fast Charge Interface Module

Fast Charge Interface Module (FCIM) implements the vehicle side of the fast charging infrastructure for systems of type A and C. The advantages of implementing the vehicle side of the fast charging in a stand-alone module include:

- Reduction of development cost and time to market for new PEV products
- Possibility to retrofit fast charging support in existing PEV fleets
- Support for multiple fast charging standards within a single PEV product line can be managed by replacement of only the FCIM (and the associated fast charging plug in most cases)
- Possible to sell fast charging support as an optional module hence supporting product diversification

2.1 Analysis of standards

To identify the requirements for the development of the FCIM many standards and implementations of fast charging were analysed. The results of this analysis for two selected implementations are briefly summarized in table 1.

Table 1: Analysis of DC fast charging standards

	CHAdeMO	**CCS**
Communication physical	CAN	GreenPHY PLC
Communication data	Custom CAN	**Network**: IPv6 **Transport**: TCP, UDP **Session**: V2GTP, HTTP **Presentation**: EXI **Application**: Smart charge protocol, SLAAC DHCP
Physical signals	Charge sequence 1, Charge sequence 2, Connector detection, Charge Enable, GND, CAN H, CAN L	Control Pilot, Proximity, Detection, GND
Connector	CHAdeMO 10 pin	IEC 62196-2-3 SAE J1772
Control logic	State machine	State machine

2.2 Requirement specification

To achieve an effective implementation of a FCIM for real life application it is important to understand how the FCIM will fit into the overall functional and safety architecture of the PEV. The analysis takes a PEV without fast charging support as the starting point. The key components of the PEV that are involved in the implementation of the fast charging are;

1. The battery management system (BMS). Arguably the most important actor in the implementation of the fast charging the BMS is responsible for setting set points for allowed charge current, maintaining safe and reliable operation of the battery and communicating all relevant battery diagnostic data on the Controller Area Network (CAN)
2. The vehicle control unit (VCU) may or may not interact with the BMS to set the system into "charge mode" and provide the vehicle driver with information about charge status.
3. The on-board charger, should in most cases be disconnected during fast charging but needs to be considered in the

functional and safety analysis of the fast charging solution.

In order to keep the FCIM simple to integrate and universally applicable the interface has been limited to a CAN bus interface to the BMS. Any information to the driver or charger will be managed by the BMS, just as if the vehicle is charging using the on-board charger. The FCIM uses the information from the BMS to control the fast charging process in a way that is consistent with the safe operational parameters set by the BMS. See Figure 1.

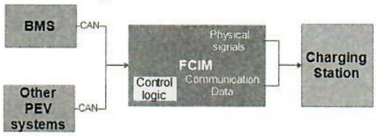

Figure 1: General FCIM design logic

This architecture supports fast charging using both systems of type A (CHAdeMO) and C (CCS), provided the FCIM is engineered to comply with a number of system level requirements:

- One CAN bus interface to the BMS and other PEV systems
- One CAN bus interface to CHAdeMO chargers. This interface must be galvanically isolated from the BMS interface.
- Driver output for relays controlling the connection to the charger
- Power Line Communication (PLC) interface to CCS chargers.
- Diagnostics of the charging process
- Data logging for the CAN bus traffic for diagnostic purposes
- Processing capability to support communication on two high-speed CAN bus networks at once

2.3 Functional safety

The FCIM fills a non-trivial role in the safety architecture of the fast charging solution. On one hand there is the energy storage system (ESS) of the PEV, with many safety requirements relating to fire hazards, electrical hazards and so forth. On the other hand there is the charging station with a safety architecture relating to electrical hazards, grounding faults, sparks etc. The FCIM acts as the intermediary between these two safety critical systems. In summary:

1) The BMS is responsible for maintaining the safety of the battery pack at all times.
2) The charging station is responsible for maintaining the safety of the charging post and the user at all times.
3) The FCIM is included in both safety cases and acts as a bridge between the two.

Since both the charging station and the BMS will detect and react to malfunctions in the FCIM it is imperative that the FCIM maintains a very high level of reliability.

In order to accomplish this the FCIM has been designed using exclusively highly reliable automotive grade components, an EMC robust 6 layer board design and an automotive safety integrity level (ASIL D) rated microcontroller suitable for safety critical subsystems in road vehicles.

2.4 Hardware design considerations

The CHAdeMO implementation is technically straightforward since it does not include the highly specialized PLC communication used by CCS. Furthermore the CCS implementation largely uses the same elements as the CHAdeMO implementation.

Based on these two observations the FCIM was designed as:

a) A base platform that contains all functionality required to support CHAdeMO fast charging.
b) A modular concept of expansion modules where the first module developed is used to support the CCS standard. Future modules can be developed to support other fast charging standards.

Using this modular topology it is possible to address both standards without incurring extra cost due to superfluous hardware components for either implementation. It also makes the FCIM a platform secured for the future by assuring that upcoming fast charging standards can be supported with a minimum of effort.

2.4.1 Base platform

To cover the requirement for the data communication the base platform supports two galvanically isolated CAN bus interfaces in order to accommodate the interface with on-board systems and separate bus with the charger.

To meet the electrical requirements of the CHAdeMO specification the base platform contains three outputs capable of driving PEV high power relays with typical specifications.

To cover the requirement of data recording (logging) the base platform supports data logging to an automotive grade Secure Digital (SD) card and a real time clock (RTC) with a 10 year on-board battery to add time stamps to the data logging.

To cover the requirement of supporting multiple standards the system is designed including two detachable expansion modules which are able to communicate with base platform and control independent I/O's directly.

2.4.2 CCS expansion module

To cover the requirement for the data communication the CCS expansion module includes a PLC modem.

To cover the requirement of hardware signals the expansion module includes dedicated IO controls according to the CCS specifications.

The CCS module in controlled directly from the base module using an internal high speed communication bus commonly used in automotive electronics designs.

2.4.3 Design reusability

The system designed for the support of fast charging is in fact a very flexible and powerful platform. The capability of adding new hardware functionality in the form of expansion modules as well as a boot loadable high performance safety rated automotive microcontroller gives the platform nearly limitless possible applications. Some examples include; CAN bridging, data logging, fleet management, VCU, DC charging system type B implementation, etc.

2.5 Firmware design consideration

2.5.1 Base platform

In order to accommodate functionality described in previous sections it is necessary to have a flexible firmware design with possibilities to configure the unit for different working environments (different vehicle systems, different uses of platform etc.). Hence the firmware is designed to allow customization of the platform functionality via firmware/settings during vehicle integration.

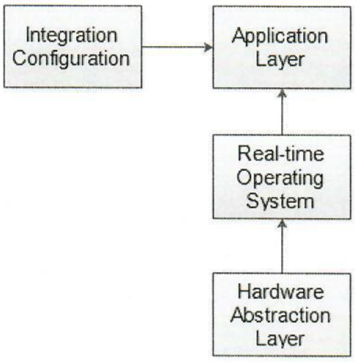

Figure 2: General FCIM base platform firmware design

2.5.2 Expansion module

The expansion module is designed to run its own customized firmware supporting the protocol and application layer of the CCS standard. The main challenges in regards to implementing the expansion module firmware for CCS fast charging is the implementation of the communications protocol stack.

The communications protocol stack for the CCS follows the Open Systems Interconnection model (OSI) and identifies the requirements for implementing common internet based protocols with addition to some custom protocols that are fast charging specific for type C. This includes the requirement for IPv6, TCP implementation alongside with XML parser implementation for session and application layers.

3 Fast charging applications

The most well-known application of fast charging is a public charging station somewhere alongside the highway or in a parking lot in city centre.

PEVs are seen in increasing numbers in society as cheaper (fuel wise) and cleaner (emissions wise) means of transport, which is becoming more and more relevant due to more strict standards for emission regulation, decreasing prices on PEV's and an increased public environmental awareness.

In industrial and public applications there may already be charging infrastructures in place for fleets of electric vehicles (powered predominantly by lead acid batteries). In this segment the application of a fast charging infrastructure seems like a logical next step.

3.1 Private and commercial PEV

One key driver for the introduction of a fast charge interface in a private and commercial PEVs is to make it more attractive for a customer in terms of reducing the so called "range anxiety" which is a common phenomenon when a private person or a company consider using/buying an EV. Providing the vehicle owners with fast charge capability and charging network increases the attractiveness of EV by reducing the charging time (closing the gap between time that takes to fill up a gas tank in standard vehicle and charging an EV) and enabling the driver to make long range trips (trips that would require the driver to charge EV at least once).

In this area the FCIM provides the manufacturers of PEVs with simple and straight forward implementation for common fast charge standards.

3.2 Industrial and public PEV

Industrial and public EVs such as forklifts, trucks, garbage trucks, busses, light transporters etc. is another attractive market for use of FCIM. Providing a facility to reduce charge times means a higher utilization of the PEV, less downtime and faster return on investment of the vehicle purchase.

While regular charging is sufficient to cover the vast majority to travel distances for private and commercial PEV's [5] and the role of fast charging can be considered mostly psychological for this segment the industrial and public PEV fast charging can in fact bring about radical improvement in fleet utilization.

Furthermore, when considering fast response vehicles (fire trucks, ambulances etc.) fast charging could be considered a requirement by end customers to enable electric drives in these vehicles.

Often fleets of PEV's use custom made chargers and charging system that are chosen due to lack of information and the relatively complicated implementation of charging system standards specified in [2] and [3]. However conformance to such standards could be advantageous because of broad (and increasing) supply of chargers conforming to the mentioned standards. The benefits of using such charger would come in form of improved safety, service, maintenance and supply. In addition the utilization of a standardized charger interface would allow the vehicles to charge from public charging posts.

The FCIM is a great fit for such applications because often the manufacturers of such PEVs have low volume production (compared to series production of private cars) thus making it challenging to develop proprietary systems for conformance with international fast charge standards.

4 Fast charging impact on battery life

When considering fast charging impact on batteries the common belief is that the fast charging will significantly decrease the useful life of battery, but in fact very little has actually been published on the long term effects of fast charging on lithium-ion batteries.

However, recently some car manufacturers who offer fast charge in their PEVs have given their batteries the same extent of warranty periods independent on charging method applied, which suggests that the real world data collected indicates that the fast charging does not have significant impact on battery life [4].

One published study [1] suggests that the fast charging might cause accelerated cell degradation due to physical limitations of cell, where cells swell and shrink during charge/discharge process. Other unofficial studies that Lithium Balance A/S has been given access to through our research network suggest that the impact on the battery life when fast charging can be associated with side effects that are caused by fast charge but not the fast charge process itself. From these side effects the most significant is considered the temperature increase on the battery cell due to the heat generated by the internal resistance, which contributes to higher heat dissipation with higher currents.

In order to contribute to the knowledge base about the batteries and to support customers with the system design and integration of the battery packs in the design Lithium Balance A/S in cooperation with Danish Technical Institute (DTI) are currently performing tests on different battery cells that are available in the market and commonly used for different EV applications.

4.1 Battery tests

4.1.1 Objectives

The objectives of this test are as follows:

- Identify impact of fast charge at different C rates on battery life over extended periods of time.
- Identify the impact of fast charging at different ambient temperatures on battery life over extended periods of time.
- Analyse the results and identify correlation between cell temperatures, possible temperature increase on the cell during fast charging on the increase in battery life degradation.
- Identify possible test procedures and configurations for further cell tests and offer the knowledge as an external service.

4.1.2 Units under test

For units under test market available cells with different chemistries are chosen. Cells are chosen based on common chemistries found in EVs in the market. The test includes cells with the following chemical compositions:

- Lithium Ferrophosphate (LFP)
- Nickel Manganese Cobalt Oxide (NMC)
- Lithium Titanate Oxide (LTO)

For each chemistry one cell model is chosen based on preliminary technical specification offered by cell manufacturers.

4.1.3 Test matrix

Table 2: Test matrix for fast charge cell test

Test No.	Temp [°C]	C-rate		
		A	B	C
1	0	0.5	0.5	0.5
2	0	2	2	2
3	0	5	5	5
4	10	0.5	0.5	0.5
5	10	2	2	2
6	10	5	5	5
7	25	0.5	0.5	0.5
8	25	2	2	2
9	25	5	5	5
10	32	0.5	0.5	0.5
11	32	2	2	2
12	32	5	5	5
13	40	0.5	0.5	0.5
14	40	2	2	2
15	40	5	5	5

The A, B and C refers to the cell type where:

- A – LFP
- B – NMC
- C – LTO

In case the manufacturer of the specific cell under test does not specify that 5C rate is achievable lower C rate which is equal to maximum C rate specified by the manufacturer shall be used. No cells with lower C rate than 2 is considered for the testing.

4.1.4 Test procedure

The cells are tested in a controlled climate chamber where the ambient temperature is kept at a constant level during both charge and discharge of the cells. The test chamber temperatures used are indicated in Table 2.

The cells are cycled with the specified charging C rate and 0.5C discharge rate with 1/2h rest periods between the events. The discharge rate is chosen low to minimize the impact of discharge degradation on the test. The cells are cycled between 20% and 80% SoC.

After every 120 cycles the capacity and internal resistance is measured in performance test which is done at 25°C with 1C charge and discharge rate.

The test is run for 1080 cycles. This number is chosen taking into account cycles expected from a real-world vehicle.

4.1.5 Results

The results shall be analysed according to the objectives of the study stated in 4.1.1. The result report shall be available from Lithium Balance A/S and shall be presented after the tests have concluded.

It is expected that the test results shall be available early 2016.

5 Conclusion

The fast charging interface module from Lithium Balance A/S provides a simple, safe and reliable solution to the vehicle side of fast charging. It can swiftly and conveniently be integrated in both electric vehicles for the consumer segment and into industrial vehicles.

Lithium Balance A/S supports the world wide adoption of standards for fast charging both by the development of novel products and by independent battery qualification and testing for fast charging application of commonly used battery chemistries.

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