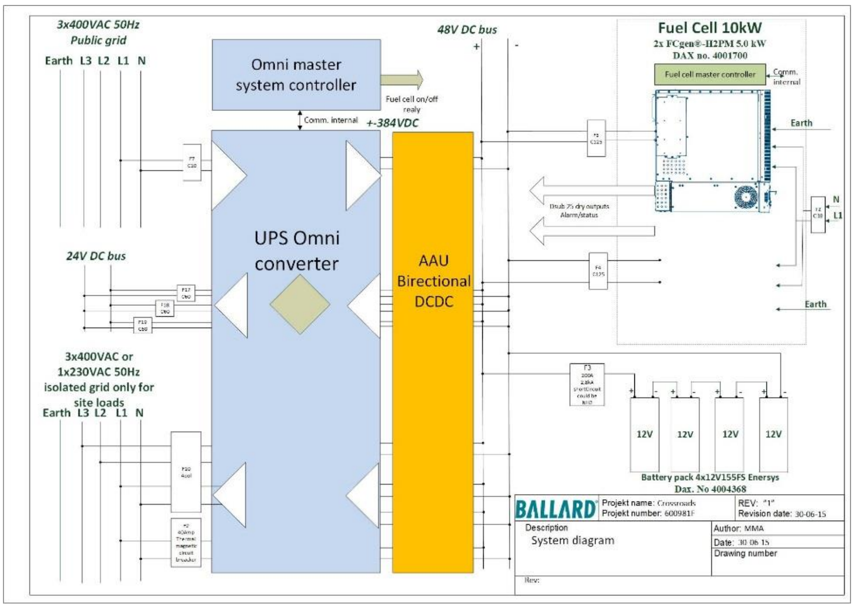
Final report

1.1 Project details

Project title	CrossRoads	
Project identification (program abbrev. and file)	64014-0564	
Name of the programme which has funded the project	EUDP	
Project managing company/institution (name and address)	LeanEco A/S	Report compiled and submitted by Ballard Power Systems Europe
Project partners	LeanEco Ballard Power Systems Europe (former Dantherm Power) Aalborg University	
CVR (central business register)	30804996	
Date for submission	09-10-2018	

1.2 Short description of project objective and results

The project's objective was to develop a highly reliable, uninterruptible power supply system for use in fibre networks, mobile networks and railroad systems. The system is based on fuel cells for power generation. The overall solution exhibits substantial and unique customer benefits beyond the generic advantages of the fuel cell technology.



1.3 Executive summary

The overall objective of the project was to increase the participants ability to successfully enter the competitive markets of un-interruptible power supply solutions for mobile networks, fibre networks and railroads — and, at the same time, to establish a unique and sustainable competitiveness. This was pursued by combining the well-known positive characteristics of fuel cell technology with the unique LivingPower™ system solution (patented), thereby creating an innovative, attractive solution offering a broad range of unique customer benefits. At the same time, the project pursued important progress on the key parameters of large networks: reliability, lifetime and a reduced need for maintenance. Load behaviour over time can strongly impact the reliability and lifetime of fuel cells – often to levels far below the inherent performance of the technology. This may be critical in such applications where the application determines the load at any time. In this project, substantial advances in reliability and lifetime of the fuel cell technology will be pursued by optimising the fuel cell load behaviour over time e.g. by exploiting a new way of sharing load among several fuel cell modules. The project should develop new schemes for managing the load in all phases like starting, operating or shutting down – including exploiting the energy reservoir of the UPS system.

The project should develop the associated interfaces and power converters handling the boundary among one or several fuel cell modules and the UPS system. At the same time, we will adopt the latest achievements within power conversion, energy efficiency and reliability.

In order to include the support of DC loads, the project should develop a multifunction high-efficiency power converter that is capable of operating in three different ways. As such, identical converter modules can operate as rectifiers, inverters – or DC/DC converters. Thereby, the system can supply power to AC equipment (IT) as well as DC equipment (Telcom) – using physically identical power modules. This also allows the system on-the-fly to optimise performance by autonomously moving or re-configuring power modules. The result is increased up-time (availability), higher reliability, less space, reduced power losses, lower initial cost and reduced maintenance cost – at the same time.

The project will build, install and operate a system in a specific realistic customer application. The project results will be available after a test period for direct comparison with existing installations.

1.4 Project objectives

The project worked on the achievement of the following objectives:

- Initial cost and total-cost-of-ownership must be competitive vs. classic solutions
- Installation must be simpler, more elegant and less costly than traditional solutions
- Reliability must be substantially higher than classic solutions – and well proven. The experience is that even minor faults may be considered to disqualify a new technology – despite the fact that traditional solutions can be far from reliable e.g. due to the use of lead acid batteries and diesel engines similarly, maintenance efforts must be visibly less and also less complicated than for classic
- The solutions must be robust in order to sustain odd use, misunderstandings or even faults when installing and using the systems
- Fuel solutions and logistics must be easy to understand, easy to implement – and scalable. (A new and different fuel is often considered to be a challenge, despite the fact that is takes exactly the same handling and care as a traditional type of fuel).

1.5 Project results and dissemination of results

1.5.1 WP 1 Project management (LE)

The objectives of WP1 were:

- To secure successful implementation of the project.
- To ensure that the project progresses, and reporting is compliant to the formal rules and conditions set out by EUDP.
- To enable that problems and matters are settled in due time.

LeanEco was project coordinator and responsible for the project management. LeanEco was declared bankrupt before the project end, for each reason the remaining partners, with Ballard Power Systems Europe as lead, had to take the formal closure of the project over.

1.5.2 WP 2 System design (LE, BPSE, AAU)

The objectives of WP 2 were:

- Ensure coherency among the different subsystems, including management of change
- Settle trade-offs across subsystems and system components
- Enable a united project environment across partners and subsystems in order to identify and pursue innovative opportunities created by merging end users, experts, applications and new technology.

An overall system design (Figure 1) was developed. The system integrated all the partners technologies and how they could benefit in a complete system. LeanEco was supposed to deliver the system controller that should control the other products.

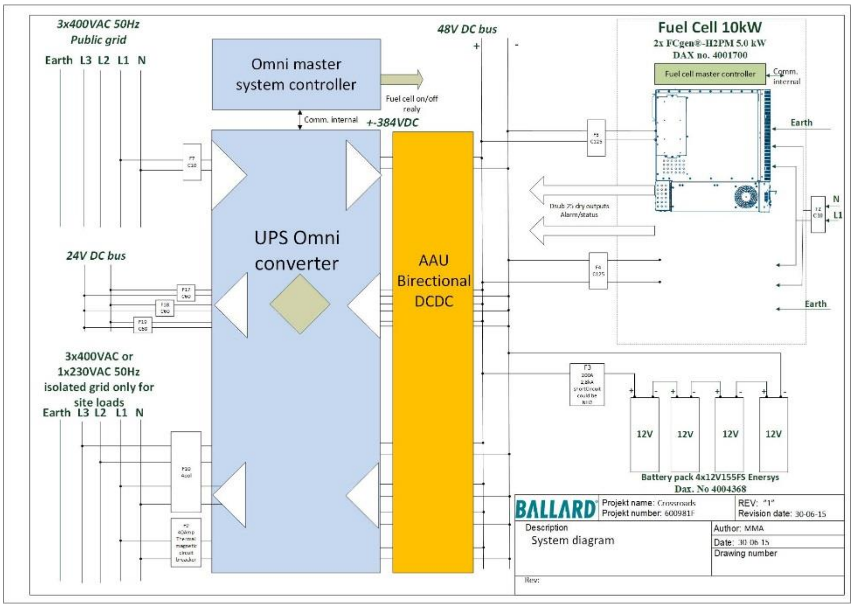


Figure 1 System design

The LeanEco Omni converter should be able to draw power from different power sources and distribute them differently depending on configuration. This could be 230/400 VAC and/or 24/48 VDC.
This task was never finalized

AAU should develop the missing Bidirectional DCDC converter in the system design. This would allow the system to draw power and charge batteries connected to the system.

This objective was achieved, and it should have been finalized in a prototype built by LeanEco.

BPSE had to deliver the fuel cell unit that should be able to extend the backup period or power boost depending on the load.

1.5.3 WP 3 System availability boost (BPSE)

The objectives of WP3 were:

- Pursue a major boost of system availability, reliability and lifetime by means of a new load management scheme for the fuel cells.
- The project shall be based on the inherent characteristics of the fuel cells (as is), but ensure that the system gets the best out of the individual fuel cell and that the system availability is improved

System availability boost

The major boost in availability and lifetime is achieved by developing a master controller.

The master controller has two key functions.

1. Linking 12 systems as a complete 60 kW backup unit.
2. Control power management amongst the connected systems.

The master controller can control 1-12 5 kW fuel cell systems. The system is now a complete scalable unit from 5-60 kW.

Figure 2 shows how the Master controller connects through a communications cable to all 12 fuel cell systems. The master is powered through the connection cable of the first fuel cell system.

The master second function is to balance the load between the connected systems. This also gives the possibility of running with a redundant system if needed.

The balancing of the fuel cell system load is done to increase the performance and reliability of the systems.

Optimizing Reliability and lifetime:
The load sharing is configured so each connected fuel cell system is operating in the best performing area with the highest potential lifetime.

The type of fuel cell used in Ballard Power Systems Europe's back up applications (FCgen®-H2PM 5.0 kW) are a LTPEM (Low Temperature Proton Exchange Membrane) fuel cell.
Some of its benefits are the fast start up time and low operation temperature.
To maintain the fast start up time it is important to operate the stack with a certain load.
Figure 3 shows how the membrane will suffer from Platinum Oxide growth if the system is operation with a low load for an extended period of time. The platinum oxide contaminates the catalyst and prevent it from reacting with the hydrogen. This results in a slow start up and low performing fuel cell stack.

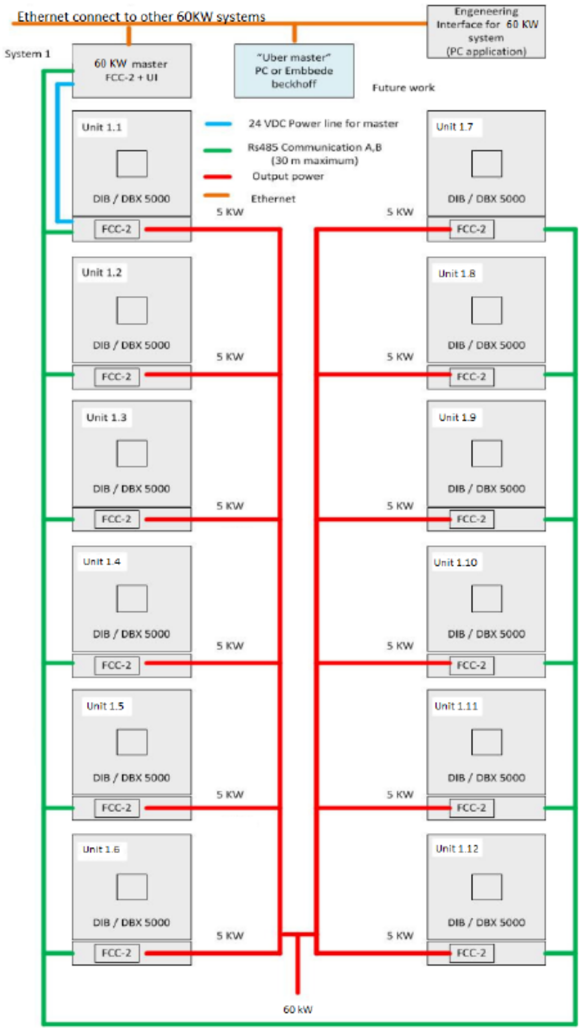


Figure 2 Master controller can connect to 12 5,0 kW units.

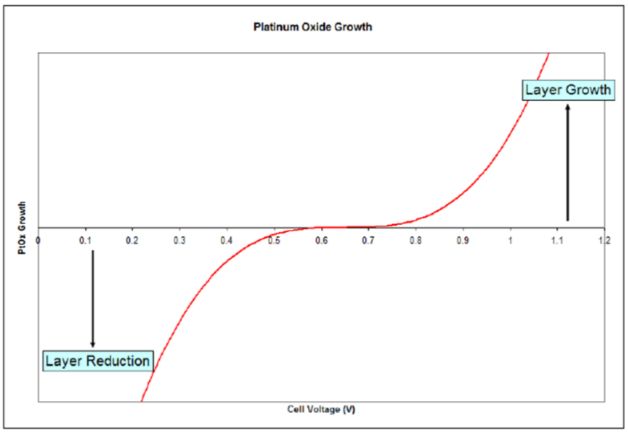


Figure 3 Platinum Oxide Growth

To prevent this occurring, it is important that each system is operating with a load between 2000-4500 W. In this area the fuel cell will have a cell voltage close to 0,7 Volt. This is the natural area where there is no platinum oxide growth. The system will also try to reduce the growth by doing what is called current pulsing. This draws a high current by short-circuiting the stack for short period of time (milliseconds).

Turn down function
When a system with a master goes into back up all connected system will turn on. Exact load is unknown. The master controller therefore starts up all system to ensure the needed load

can be supplied. When all systems are powered up the master calculates the total need load and adjust accordingly.

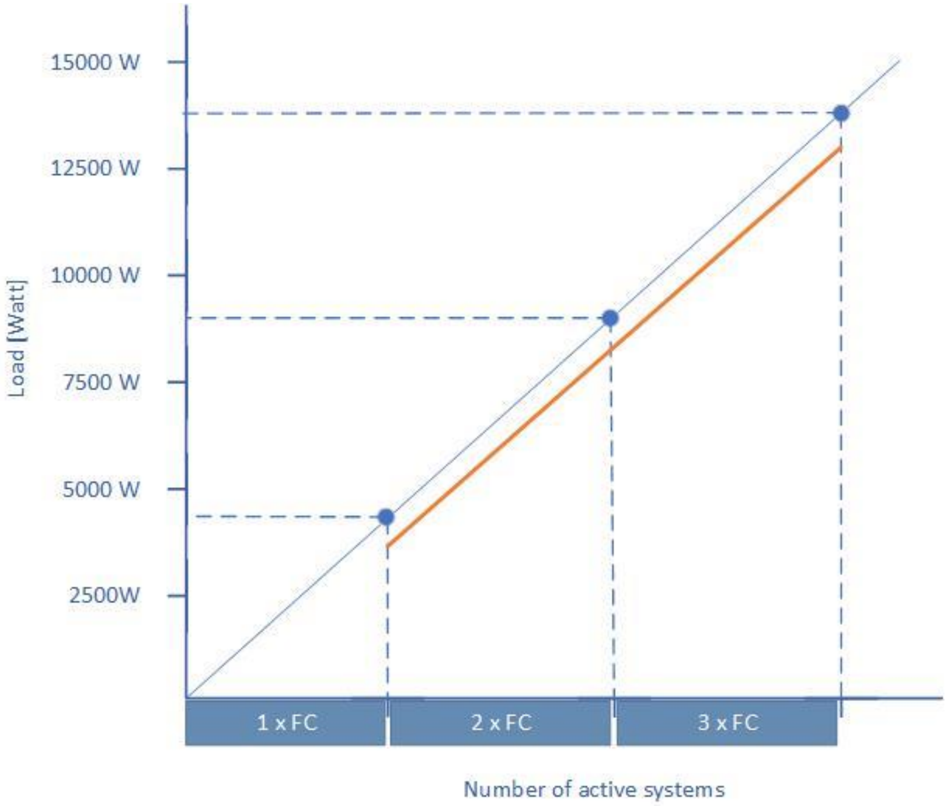


Figure 4 Master turn down function

Figure 4 shows how the master, depending on the total site load, will turn on or turn off the systems connected to the master. The master is default set to turn on an additional system each time the load is higher than 4500W per active system.
The master will turn off systems when the load per system is lower than 4000 W.
This will ensure that the systems are operated where they have the best performance and lifetime. The master will also track each systems operation hours. If a redundant system is present, the master will lock at operating hours and chose witch systems that should operate. In this way, the hours of operation will be balanced between the installed systems.

1.5.4 WP 4 Implementation of system availability boost

The objective of WP4 was to implement the system components and interfaces derived by WP3

The overall system design is based on the design idea illustrated in Figure 1

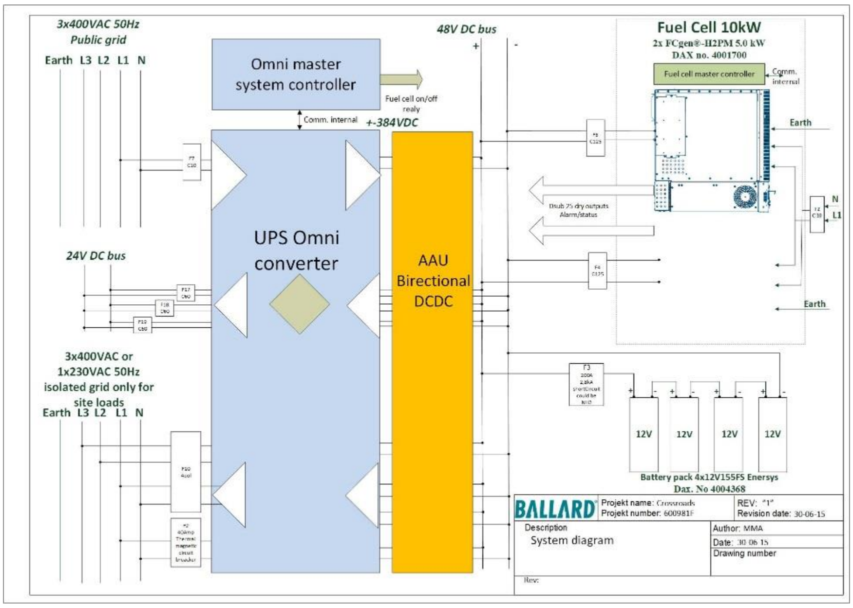


Figure 5 System design

Fuel cell implementation:

BPSE have implemented the master controller functions into a small master controller unit that fits the design of the FCgen®-H2PM 5.0 kW fuel cell system. Figure 6 shows the design of the master controller. The master unit fits into the 19" racks that the fuel cell system is design for. The master used the same Controller as the Fuel cell to minimize cost of the product. The software installed is especially designed for the master controller and its functions. The master has the 12 connections in front for linking all the systems to the master.

Figure 6 Master controller design

On the screen of the master, it is possible to see all connected systems, shutdown all systems and reconfigure how they operate together.

One requirement for the controller when connection to the complete system with LeanEcos Omni converter design is a connection that can handle force on and off. This is implemented in the master controller and it is now possible to force the system to turn on without it detecting the line voltage dropping. This feature where needed when connecting the fuel cell system to LeanEcos system design.

LeanEco system implementation:

LeanEcos system will have the overall control of UPS. The system will use its own batteries for main supply in back up mode. When the system needs more power, or the batteries are depleted the system will be able to activate the fuel cell system and draw power from there.

LeanEco system relies on the development of the Bidirectional converter. Aalborg university has developed a bidirectional converter used in the system. This was a key component to make the overall system work.

1.5.5 WP 5 Implementation of Omni-converter (LE)

The objective of the WP5 was:

- To implement a variant of the LeanEco UPS power module that is capable of three functions: Rectifier, Inverter and DC/DC converter

The WP will be based on an existing development derived from former EUDP projects

Specification

After several rounds of discussions, the final spec for the DC/DC converter is shown in Table I.

Table I. Specifications of the converter under design. **Input voltage range ***	346 - 420	[Vdc]
Output voltage range	35 – 110 (48 (43.2->55.2), 110 (-10%, +15%), 220 (-10%, + 15%))	[V]
Output maximum current (3kW @ 48V)	62,5	[A]
Maximum power output	5000	[W]
Voltage tolerance	1	[%]
Maximum allowed output ripple and noise	0,5	[%]
Target efficiency	> 95	[%]
Galvanic isolation	Yes	
Operating temperature range	0 – 43	[°C]
Dimensions	440 mm x 180 mm x 80 mm	

Topology selection

During the topology selection phase, bi-directional phase-shift full bridge (BDPSFB) converter has been analyzed and compared with the dual-active bridge (DAB). In the end DAB is chosen because its better performance. BDPSFB is inferior in boost mode (reverse power flow) due to strong ringing in the switching waveforms and, furthermore, DAB provides more flexibility in PWM which allows soft switching at a broader operating area as well as a symmetrical topology for bidirectional power flow.

Due to the very wide output voltage range (35-110 V), it has been decided to design two versions of converters for 48V and 110V outputs, respectively. Besides, considering the high input voltage 800V (+/- 400V), two DAB modules with series input instead of a three-level topology (NPC, ANPC, T-type, etc.) have been chosen for better efficiency and flexibility. Consequently, for 48 V output, two 48 V version DABs can be applied with their outputs in parallel. For 110 V output, two 110 V version DABs can be applied with their outputs in parallel. For 220 V output (to give customers more options), two 110 V version DABs can be applied with their outputs in series. As shown in Figure 7.

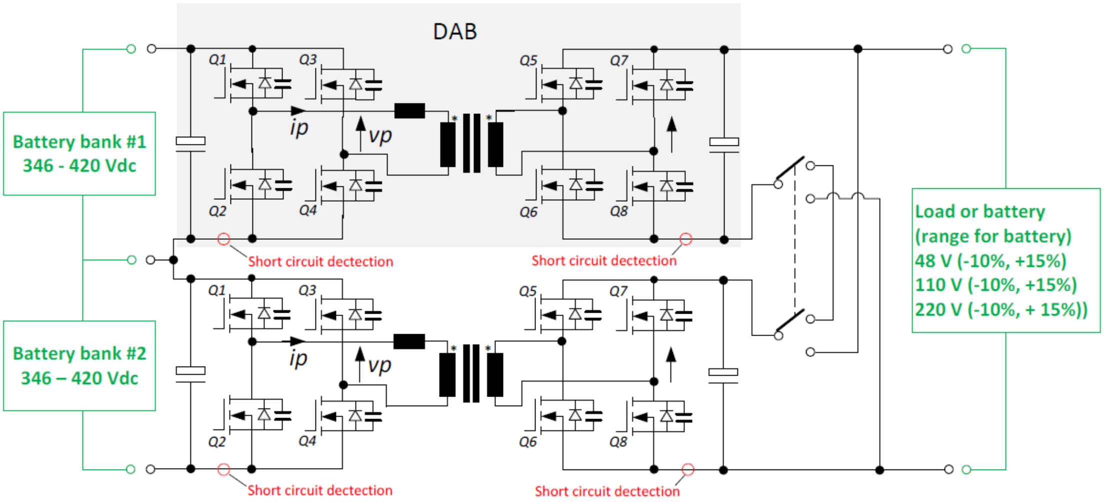


Figure 7 Topology of the converter under design.

Prototypes and test results

a. 48 Version

A photo of the prototype is shown in Figure 8, including a power stage and a control board. The control algorithm is implemented digitally, and the software flowchart is shown in Figure 11. A portable thermal camera was used to roughly measure the temperature of the converter, and a thermal picture is shown in Figure 9. The efficiency of the converter is shown in Figure 10. The voltage balancing capability of the converter has also been tested as shown in Fig. 7. The two voltage sources are used to mimic the high voltage side batteries, which can be seen in Fig. 2. According to the results in Fig. 7, the battery with lower voltage (lower state of charge) is discharged with 4 lower power, and thereby the two battery banks will be eventually achieved the same state of charge.

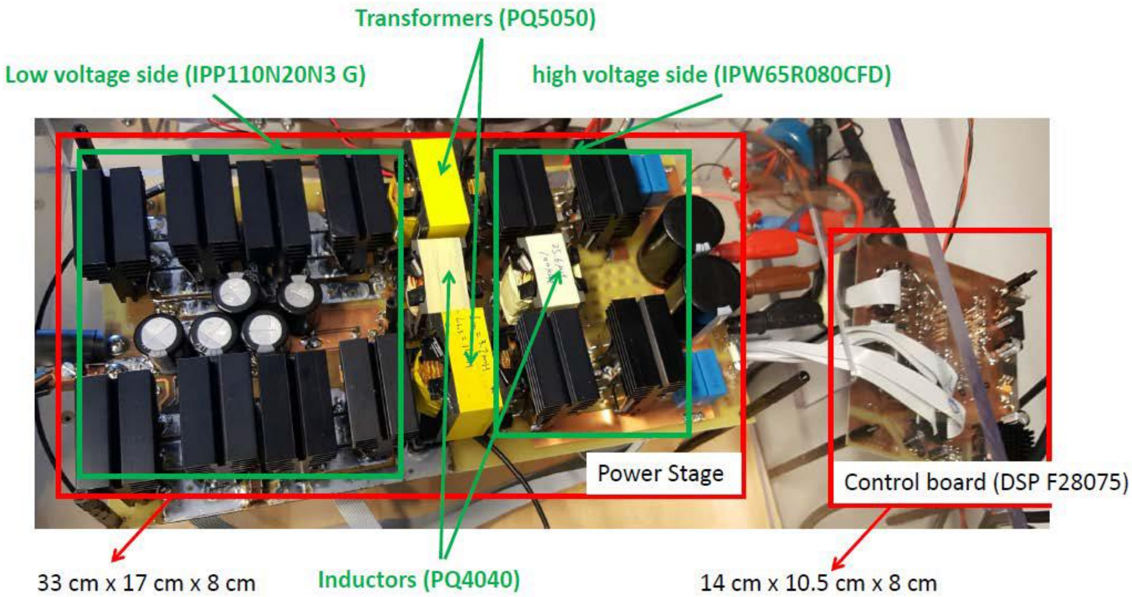


Figure 8 A prototype of the 48 V version converter.

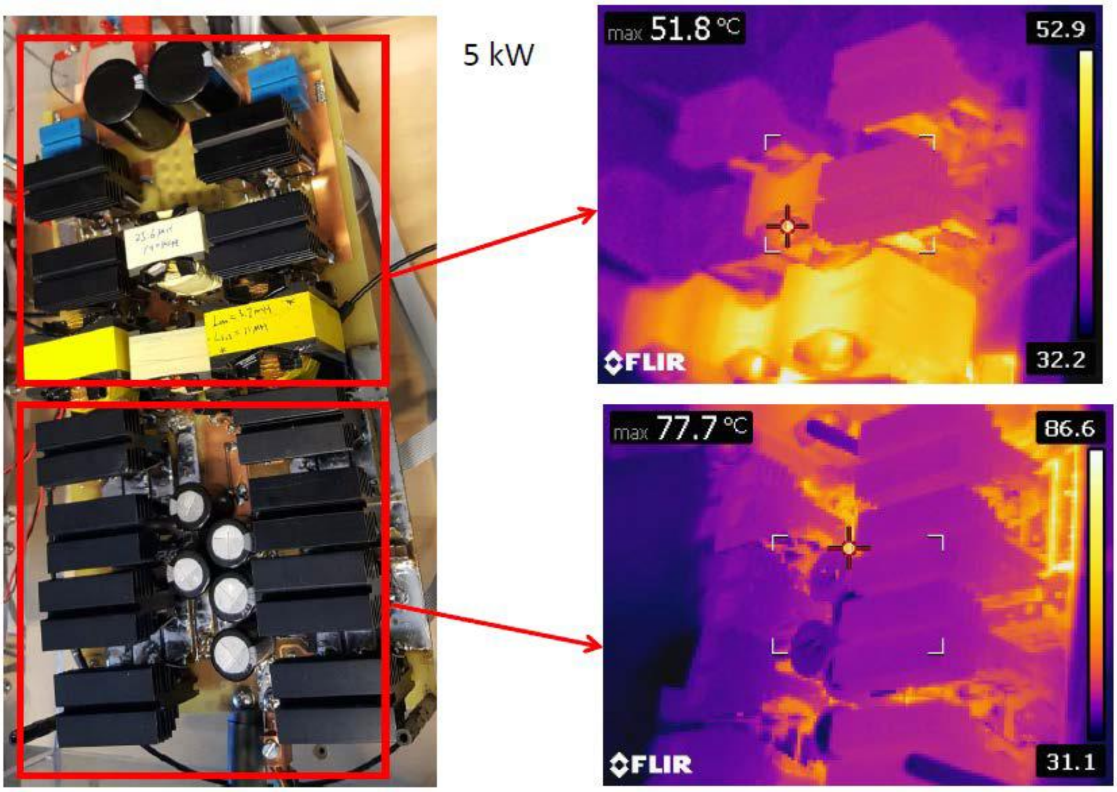


Figure 9 A thermal picture of the 48 V version converter operating with full load after 30 mins.

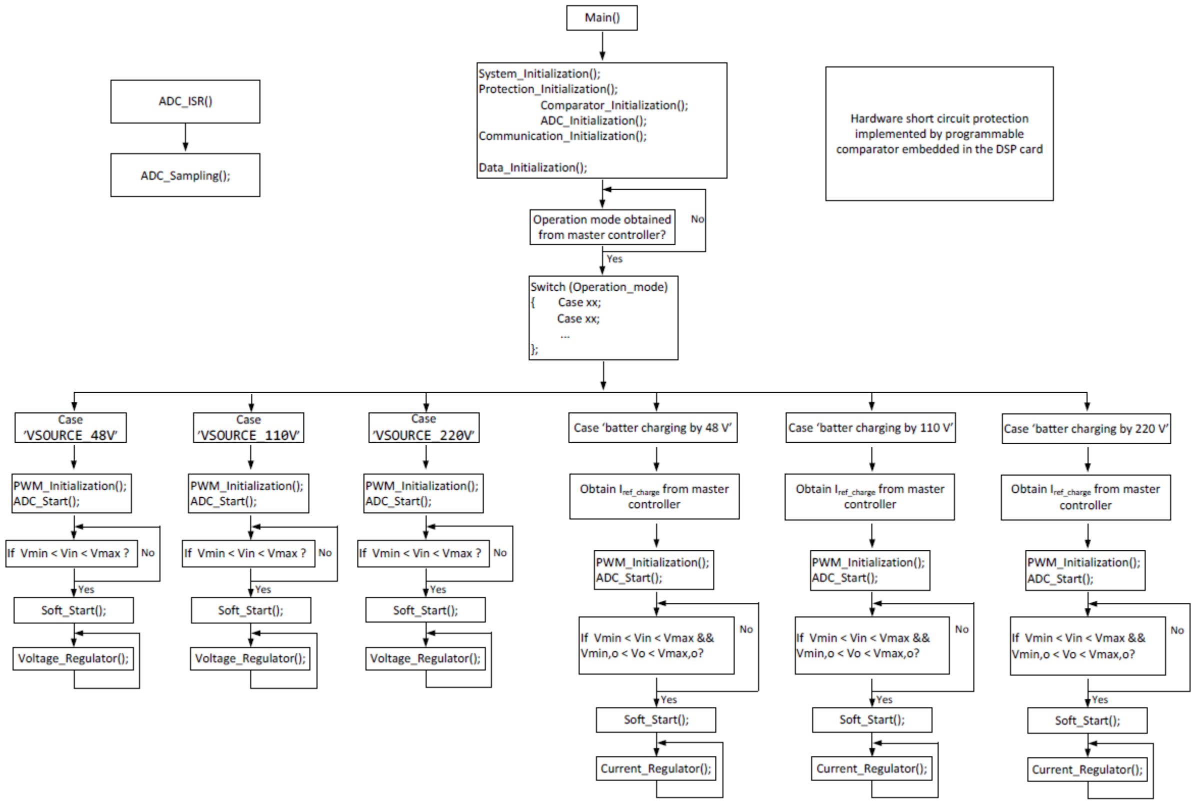


Figure 11 Flowchart of the software.

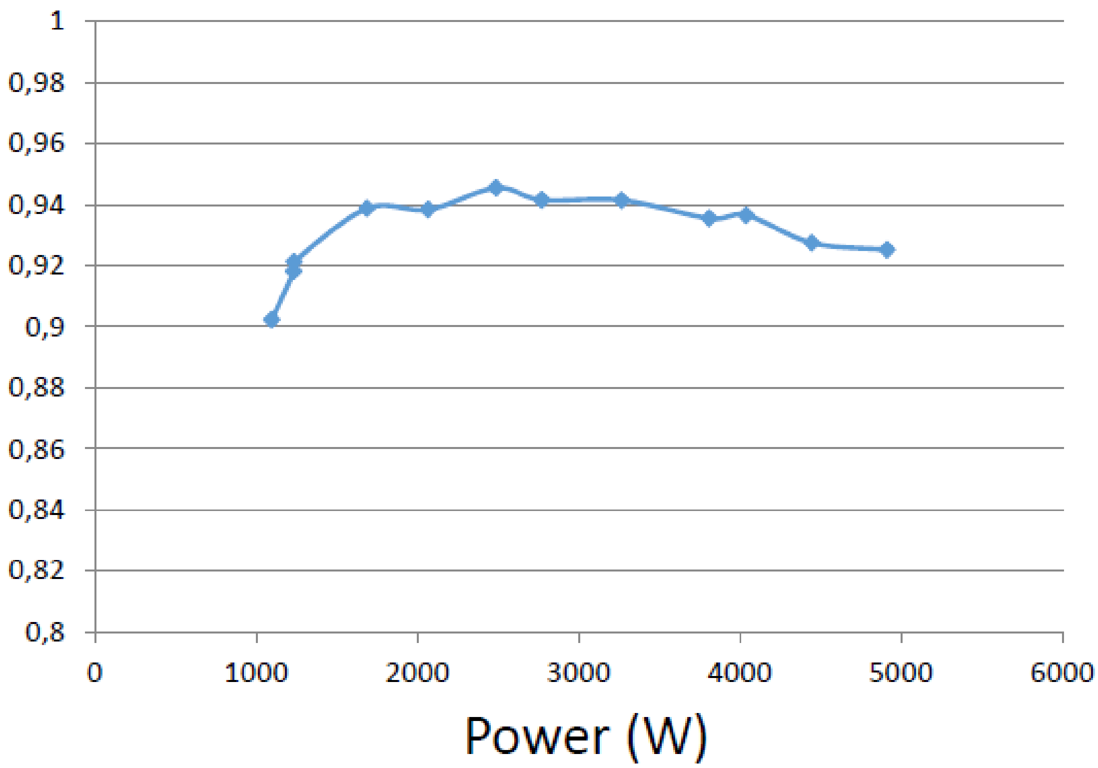


Figure 10 The efficiency curve of the 48 V version converter.

Figure 12 High voltage side battery voltage balancing.

b. 110 V/220 V Version

A photo of the 110 V/220 V version prototype is shown in Fig. 8. The layout of the topology is very similar with the 48 V version and the same control board can be used. The software flowchart is the same as shown in Fig. 5. A thermal picture is shown in Fig. 9. The efficiency in different operation modes has been tested and shown in Fig. 10 and Fig. 11. The low voltage side voltage balancing when the two DAB modules are connected in series has been tested and the results are shown in Fig. 12. The output voltages of the two DAB modules are shown on the multi-meters. As seen, the output voltage difference between the two modules is very little.

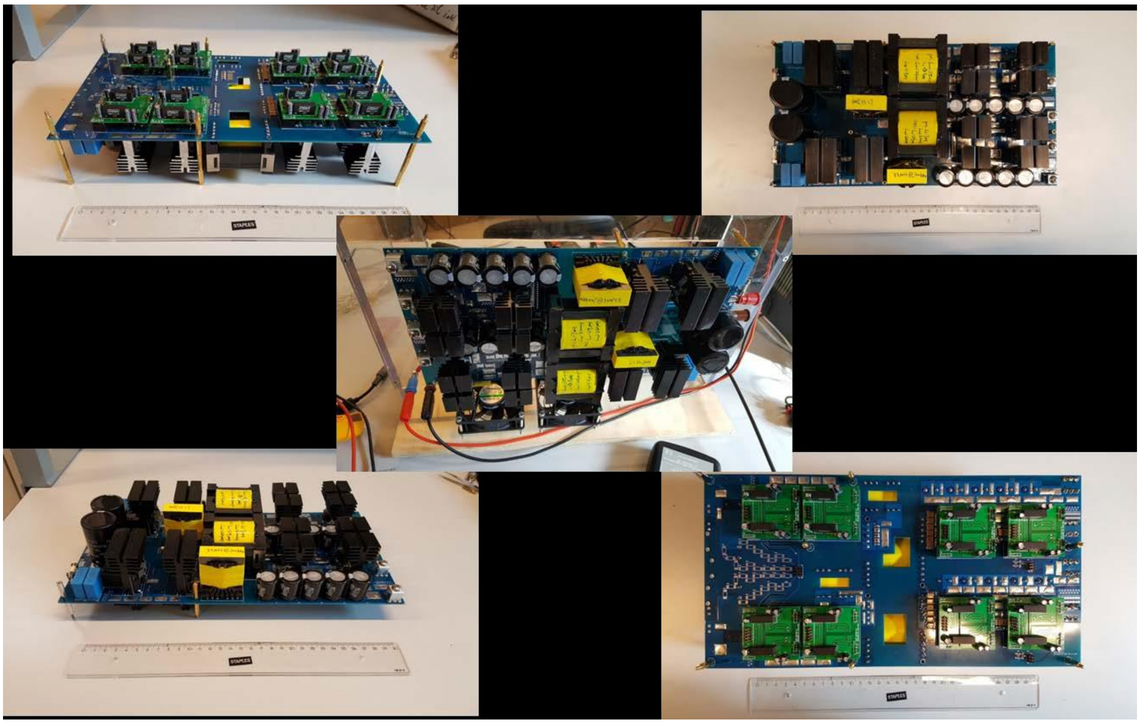


Figure 13 A prototype of the 110 V/220 V version converter.

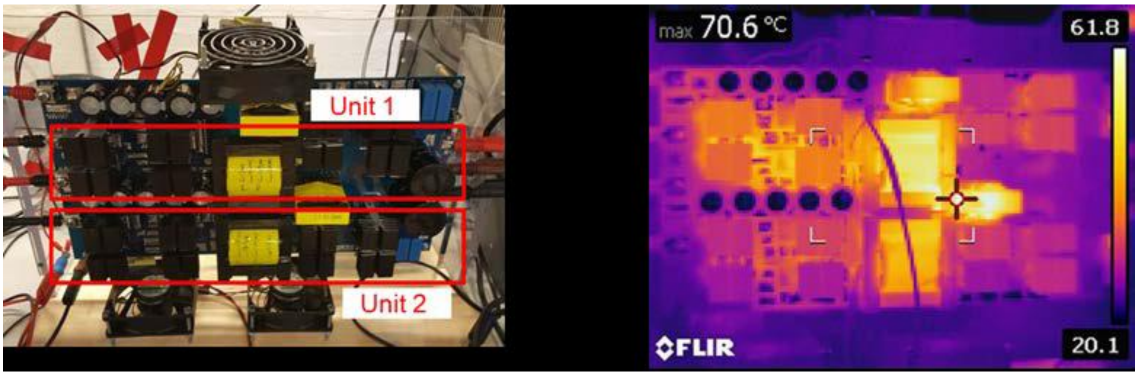


Figure 14 A thermal picture of the 110 V/220 V version converter operating with full load after 30 mins.

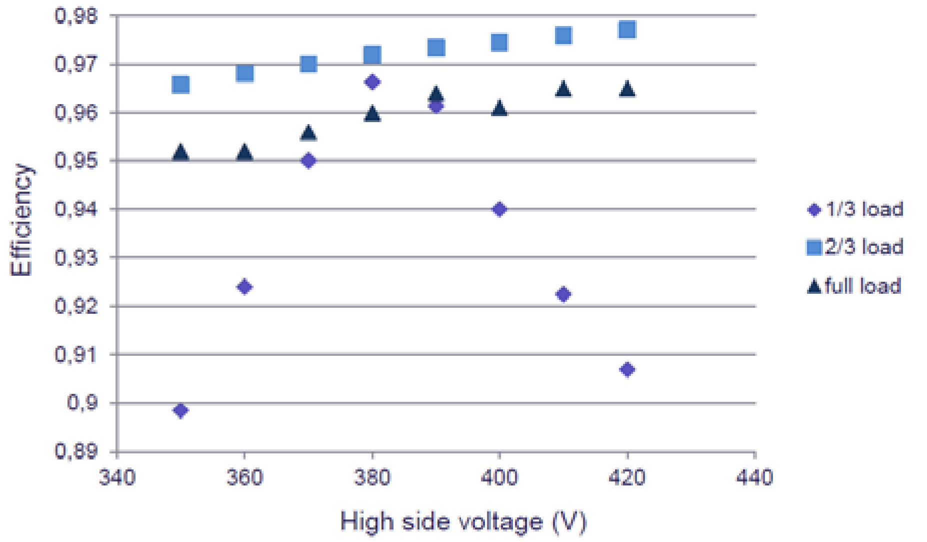


Figure 15 A efficiency curve of the 110 V/220 V version converter, where the power is from high voltage side to low voltage side, and ambient temperature is 25°C ~ 30°C.

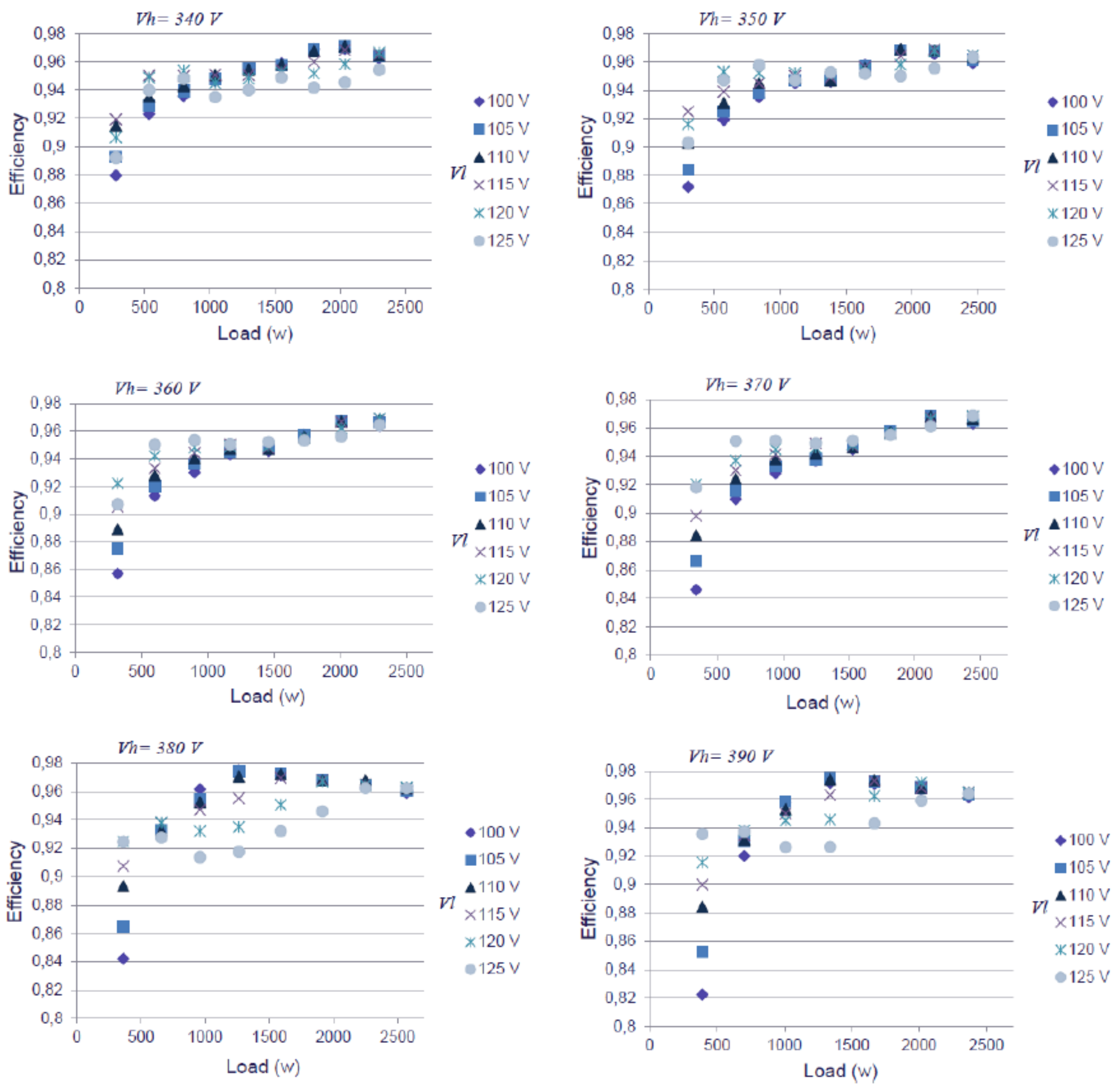


Figure 16 A efficiency curve of the 110 V/220 V version converter, where the power is from low voltage side to high voltage side, and ambient temperature is 25 ˚C ~ 30 ˚C.

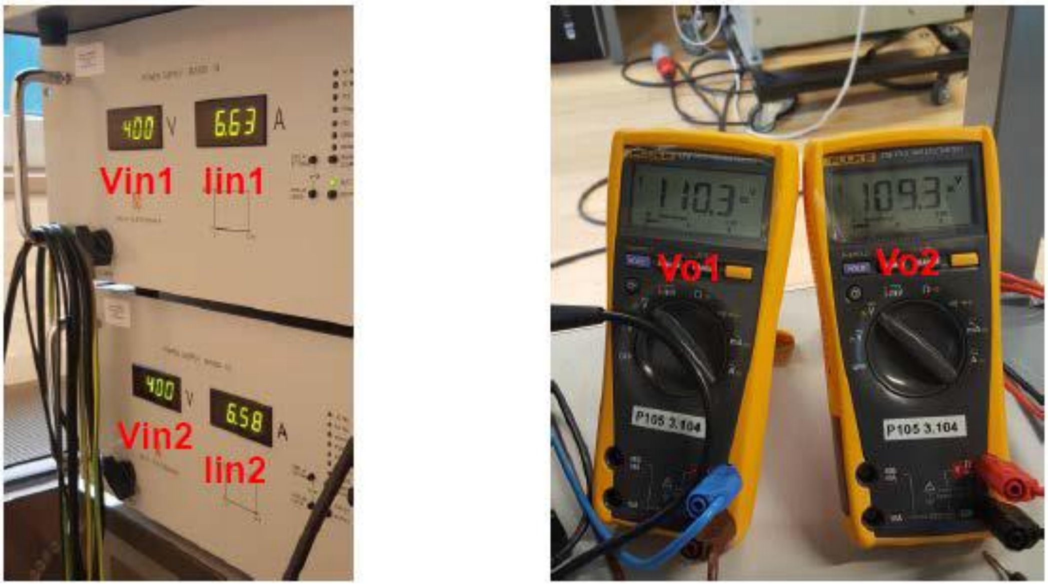


Figure 17 The low voltage side voltage balancing of the 110 V/220 V version converter.

1.5.6 WP 6 System prototypes (BPSE, LE)

The objectives of WP& were:
- To build three prototype systems that can serve as
- Objects for system level testing and learning
- Attractive demonstration units for dissemination purposes
- A deliverable unit for a specific site (one unit).

Prototype systems:

BPSE have built a prototype system where the master controller was connected. In Figure 18, the system is being tested in the BPSE lab. The system test was done with two FCgen®-H2PM 5.0 kW units connected to the master controller. The system was connected to two battery banks to simulate the configuration intended in the LeanEco system.

Fuel cell tests

- 2x5kW + Master controller with batteries on the output
- DCDC and stack Redundancy in case of error = robustness

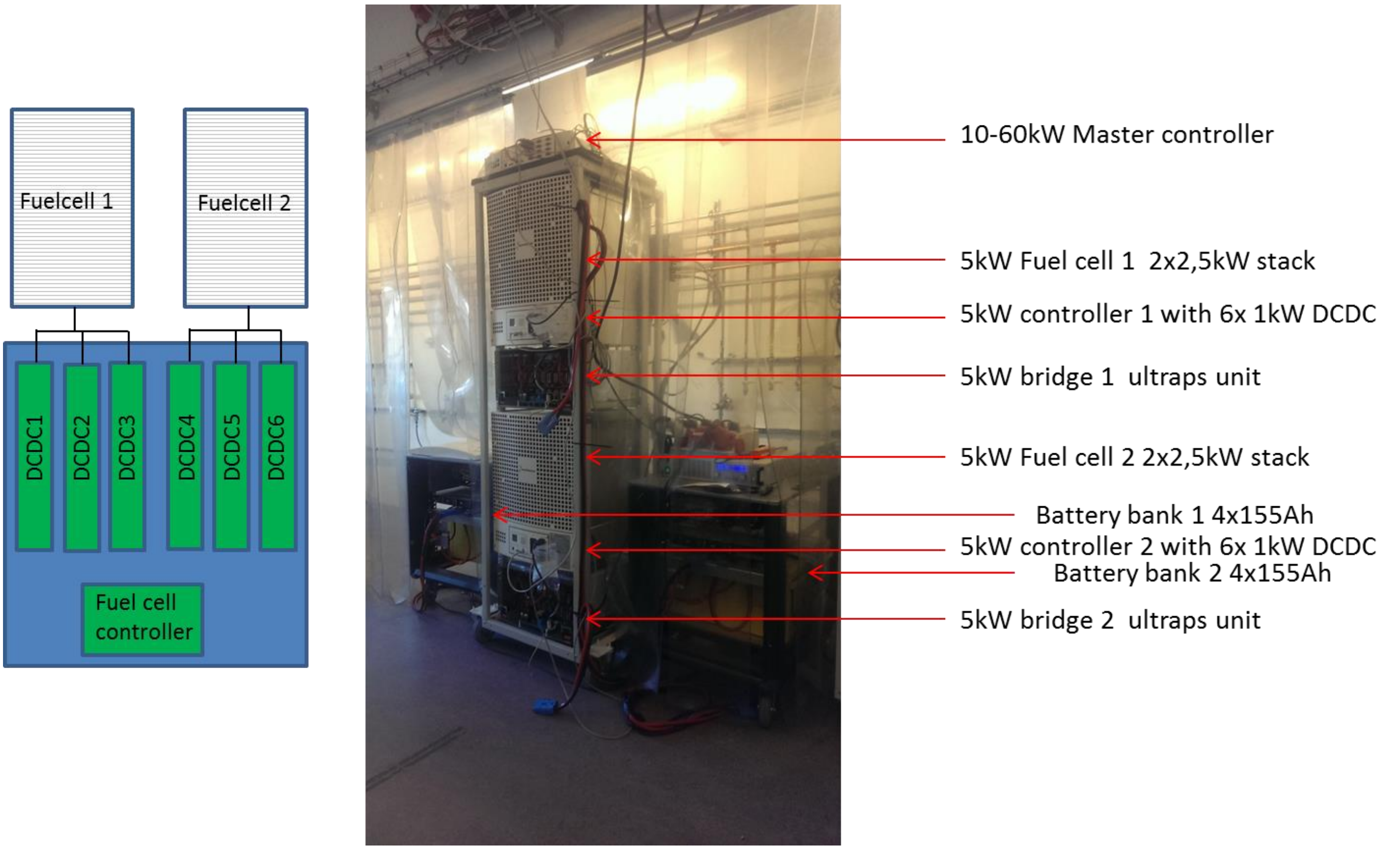


Figure 18 FCgen®-H2PM 5.0 kW prototype

1.5.7 WP 7 Demonstration (STOFA)

The objectives of the WP7 were:

- To install and operate the new UPS/backup system at a realistic environment and under realistic conditions and use.
- The site should be a good representative for the target applications/markets such that any learning and feedback has maximum value.
- To review the project achievements in the light of the actual application/market.
- To gather as much learning and feedback as possible for the product development to follow.

This work package was not completed. LeanEco did not get their system ready within the project period. After several project extensions LeanEco was declared bankrupt.

Aalborg university delivered a working version of the DCDC Bi-directonal converter. But LeanEco didn't manufacture it for a complete system integration.

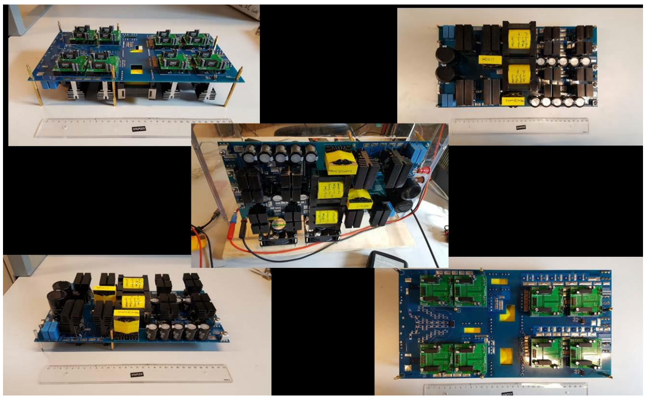


Figure 19 A prototype of the 110 V/220 V version

Ballard Power Systems Europe developed and produced the master controller for the fuel cell systems. The controller and fuel cell system were ready to be tested together with the LeanEco system.
BPSE have had success installing fuel cell system with the master controller outside this project, where it has proven to be a success when installing more than 5 kW of fuel cell power.

Figure 20 2 x FCgen®-H2PM 5.0 kW system (10kW) with master controller in top of the rack.

1.5.8 WP 8 Dissemination

The aims of the dissemination activities in Crossroads were:
- To emphasize that a break-through has been achieved in the field of fuel cell for UPS/backup power
solutions.
- To highlight that a new and unique UPS solution has been born to be used for railroads, fibre network hubs and mobile network base stations.
To make it easy to use the project results for general marketing activities.
To create a project environment where
- The risk of conflicts in the field of marketing and communication becomes very low
- Dissemination gets priority.

The main dissemination activity types performed were:

Participation in conferences

Articles
1. Project presentation, energiteknologi.dk: https://energiteknologi.dk/da/projects/detail?program=All&teknologi=64&lokalitet=All&start=&slut=&field_status_value=All&keyword=&field_company_nid=All&page=15
2. Project presentation, biopress.dk: http://www.biopress.dk/PDF/170-millioner-til-bioenergi-brint-og-braendselsceller

Academic publications
1. Zian Qin, Ying Pang, Huai Wang, Frede Blaabjerg, "A component-reduced Zero-Voltage Switching three-level DC-DC converter," in Proc. of IEEE-IECON'2016, pp. 2439-2444, 2016.
2. Zian Qin, Yanfeng Shen, Huai Wang, Frede Blaabjerg, "A voltage doubler circuit to extend the soft-switching range of dual active bridge converters," in Proc. of IEEE-APEC' 2017, pp. 300-306, 2017.
3. Zian Qin, Zhan Shen, Frede Blaabjerg, "Modelling and analysis of the transformer current resonance in dual active bridge converters," in Proc. of IEEE-ECCE' 2017, pp. 4520-4524, 2017.
4. Zian Qin, Yanfeng Shen, Poh Chiang Loh, Huai Wang, Frede Blaabjerg, "A dual active bridge converter with an extended high-efficiency range by DC blocking capacitor voltage control," IEEE Transactions on Power Electronics, vol. 33, no. 7, pp. 5949-5966, 2018.

1.5.9 WP 9 Technology study – Integration opportunities

The objective of the WP9 was:

- To establish key specification for integration of uninterruptable power supplies in critical points in communication networks.

Through corporation with communication network specialist, the aim was to study customer needs for application of fuel cell uninterruptable power supplies at critical notes in different network configurations. The technology study should focus on clarifying the product specification that will satisfy the network operator’s needs. This will help us to specify new products that will bring higher value to the customers in critical network notes where the customers need alternatives to battery.

The study should enable a united project environment across partners and subsystems in order to identify and pursue innovative opportunities created by merging end users, experts, applications and new technology.

During the project period, a new task was added to the project, called **Remote SOH data retrieval system implementation and testing**.

In the process of finding the best remote access solution, Ballard has looked at a Napto solution.

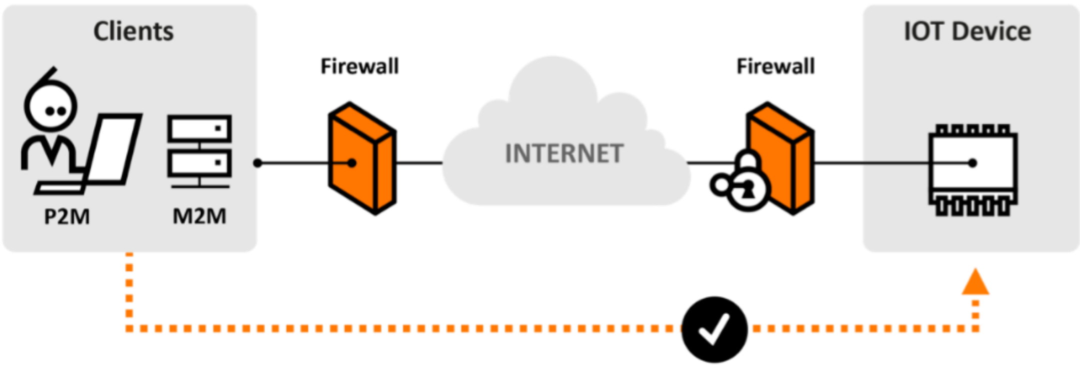


Figure 21 Napto solution

We have had meetings with Napto about implementation and how Napto could work in 5kW FCC.

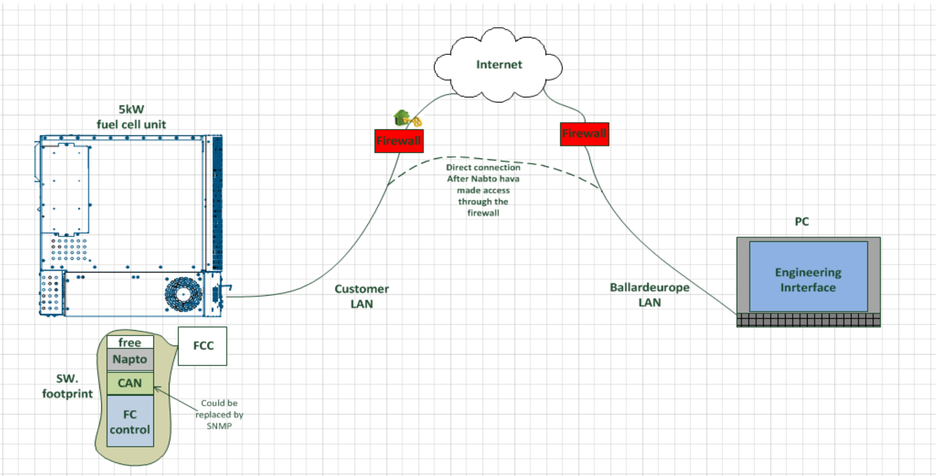


Figure 22 Napto solution in BPSE fuel cell product

An analysis of the implementation cost has been made.
The implementation of Nato requires implementing Napto software into the Fuel cell controller (FCC). The controller is already on the limits of it capacity. The implementation would require other features to be disabled.
Access to the customers network were still needed, and this has proven to be difficult to get on all locations. Some operators allow BPSE to connect to the system through VPN and some don't allow any access through their network.

The implementation cost, requirement on FCC and the need of access through the customer's network is the reason for the Napto solution was put on hold.
When the next generation of Fuel cell Controller is developed, the Napto solution might get implemented.

Alternative solution:
A second solution from a company called Secomea has been investigated and implemented on some sites.
The solution connects the device, in this case the fuel cell, to a site manger device from Secomea (Figure 23). The device can be connected to the onsite internet or to a mobile network device.
This allows BPSE to connect to the system without having access to the costumers network.
The solution requires no software implementation in or FCC. The site manager is a small box connected to the ethernet in the fuel cell. The solution is more expensive than the Napto solution in the long run, but along as the remote access isn't a requested from more of our customers the Secomea solution is the best alternative.

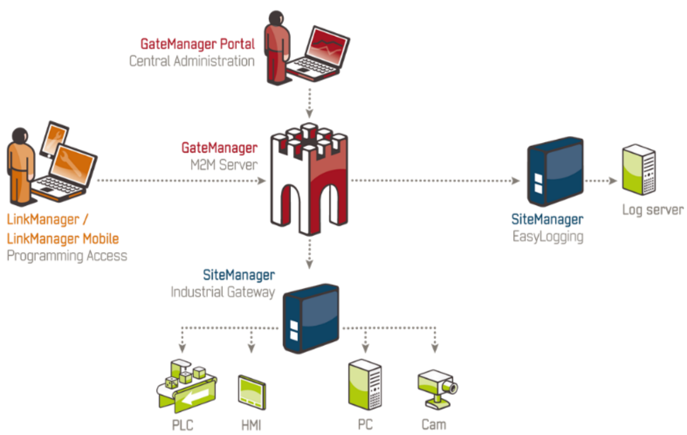


Figure 23 Secomea solution diagram

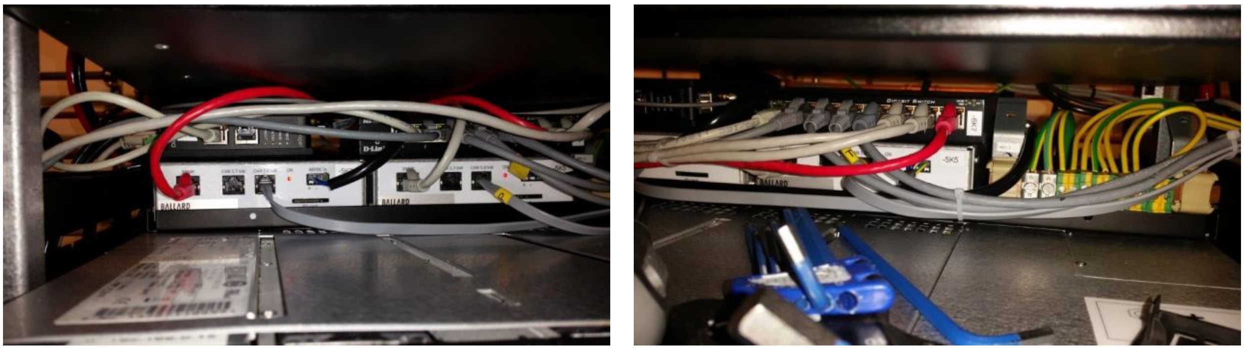


Figure 24 Secomea solution integrated into a 10-kW fuel cell backup system

Figure 24 shows the Secomea solution currently being tested on a site in Sweden.

1.6 Utilization of project results

Looing on the expected project results, the following conclusions can be drawn:

- *Initial cost and total-cost-of-ownership must be competitive vs. classic solutions*

It is not of BPSE knowledge that a calculation of the complete system has been made.

- *Installation must be simpler, more elegant and less costly than traditional solutions*

No installation has been made in the project period. The design would have been simple to install. Everything was designed to be integrated in 19 " racks. The grid and customer supply would have been the only connections to the UPS system. The fuel cell system needs to have exhaust to the outside and hydrogen bottles stored outside in a cabinet.

- *Reliability must be substantially higher than classic solutions – and well proven. The experience is that even minor faults may be considered to disqualify a new technology – despite the fact that traditional solutions can be far from reliable e.g. due to the use of lead acid batteries and diesel engines similarly, maintenance efforts must be visibly less and also less complicated than for classic*

- *Solutions*

Individual components where developed.
DCDC bidirectional converter (AAU)
Master controller (BPSE)
But the complete solution was never built or tested. The learnings from the project have been utilized in the many publications made by AAU. And the master controller developed has been installed in many fuel cell systems.

- *The solutions must be robust in order to sustain odd use, misunderstandings or even faults when installing and using the systems*

The Omni system was designed to be a robust system with many alternative ways of distributing power in the case of faults etc. The multiple backup function with battery and fuel cell technology where one of the robustness implementations.

The bidirectional converter should also have helped with the robustness by enabling many different output voltages on both sides depending on the need.
Unfortunately, these functions were never tested in a complete system.

- *Fuel solutions and logistics must be easy to understand, elegant to implement – and scalable. (A new and different fuel is often considered to be a challenge, despite the fact that is takes exactly the same handling and care as a traditional type of fuel).*

Ballard Power Systems Europe (BPSE) haas successfully developed and implemented the master controller in the system. By implementing this, we create an easy, scalable system. The Fuel cell systems are installed in 19” rack with 48 VDC output. They can be connected to existing UPS systems or configured by BPSE as a complete UPS unit with 48 VDC and 230/400 AC output.

The project’s goal was to create this complete UPS system together with LeanEcos Omni system. LeanEco did not built their system in time to be integrated with the fuel cell system, but all functions needed to connect to the fuel cell system to the Omni system were developed.

1.7 Project conclusion and perspective

The project partner Aalborg University has successfully designed, built and tested several prototypes of the bidirectional converter that should have been integrated into LeanEcos Omni system.

Ballard Power Systems Europe has successfully developed the master controller. This was not tested together with the Omni system, but have been installed in several fuel cell systems at customers with great success.

Figure 25 Master controller design

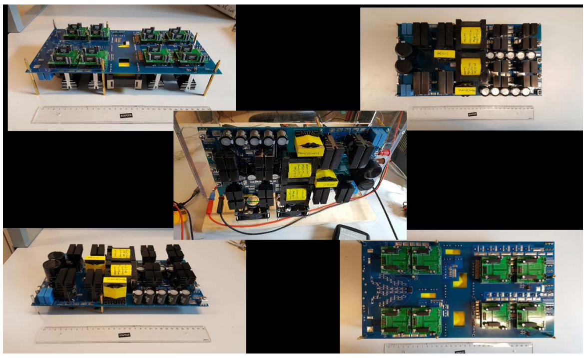


Figure 26 A prototype of the 110 V/220 V ver-