DEMAG

Project number: COOP-CT-2004-512811

Project acronym: DEMAG

Project title: Domestic EMergency Advanced Generator

Instrument: Cooperative Research

Thematic priority: 6.1 – "Sustainable Energy Systems"

Publishable final activity report

Period covered: from M1 to M30		Date of preparation:	20/11/2007
Start date of the project	15/01/2005	Duration:	30 months
Project coordinator name	Alfredo PICANO		
Project coordinator organisation name	LABOR Srl	Revision	0

SECTION 1 Project execution

1.1 Project objectives

The future reliability of centralised energy supply is questioned by energy experts, authorities and final users. In current large scale interconnected supply grids a problem in any portion of the massive generation, transmission and distribution chain can leave customers in a wide geographic area without power and vulnerable.

Weaknesses can affect electricity distribution from several origins (costs of fossil fuels, need to reduce greenhouse emissions, reduced water availability due to global warming, lack of maintenance of electricity grids, etc.), all factors which are supposed to have an increasing impact in the future.

An **Emergency Power Supply**[1] (EPS) with a rated capacity of at least 10 kWh based upon existing accumulator technologies is clearly unfeasible and impracticable for weight and size reasons; keeping such an amount of chemical batteries in a house would be a non-sense.

DEMAG intends to investigate the indoor domestic application of advanced hydrogen technologies to life saving emergency energy generators, and deliver an **Emergency Power Supply**, rated 10 kWh, based on the integration of a PEM fuel cell with ultracapacitors and with a metal hydrates container for hydrogen storage: the FC is expected to provide a basic power output, whereas ultracapacitors can supply temporary peak loads.

The **tangible outcomes** of the DEMAG project will be:

- 10 kWh **Emergency Power Supply**, able to supply 1 kW during 10 hours
- 220 Volt @ 50 Hz power output
- Power generation by means of a 1 kW PEM Fuel Cell
- Weight < 100 Kg (including hydrogen storage, energy generation by PEMFC, controllers, auxiliaries and ancillaries)
- Volume < 12 litres (including hydrogen storage, energy generation by PEMFC, controllers, auxiliaries and ancillaries)
- Safe energy storage through a state-of-the-art metal hydrates $LaNi_5$ hydrogen tank, operating at 2 bar and room temperature
- automatic start-up during black-out and shut-down on grid reconnection
- flexible and easy installation both for **new installations** and **retrofit**
- Able to supply a load exceeding the rated power for a limited time, thanks to the integration with ultracapacitors, (e.g. start-up of the compressor of a refrigerator, the inductive starter of a fluorescent lamp, or the charge of a capacitor in a switch power supply), while the system alerts the users by means of a warning sound; if the extra load persists, DEMAG will interrupt the supply for some seconds, allowing the users to remove the extra loads.

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[1] the target of the project is not an UPS (Uninterruptible Power Supply), rather is an EPS (Emergency Power Supply), because:

1. an UPS is designed to provide **the full operation** of the sub-grid connected (typically one or more devices), in the absence of the electricity of the grid, and starts operating immediately after the black-out, providing continuity in the electricity supply
2. an EPS similarly starts autonomously after the black out, but is designed to support some **limited essential functions of the sub-grid connected**, according to its rated power; this means that the system does not properly match the total nominal power of the sub-grid connected, but is able to supply part of it, typically devices providing safety related functions

- Usable also as a portable power generator, powered by a small size lighter hydrogen tank

1.2 Contractors involved

Participant role	Participant type	Participant No.	Participant short name	Country	Date enter project	Date exit project
CO	RTD	7	LABOR	I	Month 1	Month 30
CR	SMEP	1	AGT	I	Month 1	Month 30
CR	SMEP	2	SEIRA	I	Month 1	Month 30
CR	SMEP	3	ENERTRON	D	Month 1	Month 12
CR	SMEP	4	SZWED	PL	Month 1	Month 30
CR	SMEP	5	PIU’	I	Month 10	Month 30
CR	SMEP	10	Enertronix	D	Month 14	Month 30
CR	OTH	6	IDEATEL	ES	Month 1	Month 30
CR	RTD	8	UNITORV	I	Month 1	Month 30
CR	RTD	9	TUG	A	Month 1	Month 30

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1.3 Work performed

The work performed in the project was split in the following Workpackages:

1. **WP1 EPS operative specifications**
   a) A test bed for direct measurement of domestic load profiles have been designed and prototyped. This experimental data acquisition layout have been used to measure load profile absorption, both in transient and steady regime, of several critical and non-critical domestic devices
   b) Domestic loads have been categorized in four priority classes. This information are used by the controller to implement the load management strategy and to disconnect selectively different loads

2. WP2 Design of hydrogen storage tank

a) The adsorption/desorption reaction of hydrogen in metal hydrides has been studied so as to define the storage module dimensions (weight and volume) needed for DEMAG project and the mass and energy fluxes needed for its operation.

b) A market survey, to identify off the shelf metal hydride tanks, has been performed and a suitable device for hydrogen storage has been selected.

2. WP3 Design of the central unit

a) A Central Unit, able to produce up to 10kWh of electrical energy has been designed on the basis of a PEM Fuel cell, and a metal hydride commercial storage tank.

b) An intelligent DC-DC converter, able to coordinate the power contributions coming from the fuel cell and the supercapacitors pack has been designed

c) An electronic controller, integrating the communication with peripheral units, and allowing the correct implementation of start-up and shut-down of the DEMAG system and the load management strategy, has been designed

3. WP4 Design of peripheral units

a) An intelligent Master Switch Interface has been designed in order to disconnect the domestic environment from the power grid in case of blackout, and to reconnect safely when the main power is back.

b) An Automatic Disconnection Module, with the twofold objective of providing remote disconnection ability to the central unit and monitoring power demand has been designed.

4. WP5 EPS prototyping

The DEMAG EPS has been prototyped, and it is installed for testing in Labor's laboratories.

5. WP6 Testing

a) DEMAG EPS has been thoroughly tested, and several improvements have been identified and/or implemented to optimize its efficiency and improve its behaviour.

b) Results have been widely assessed among the partners. The technological feasibility of the DEMAG concept is accepted, while there are still concerns for what regards the economic

6. WP7 Safety assessment

A thorough report, addressing the normative framework in the fuel cell and hydrogen related technologies has been issued, with focus on the components used in DEMAG.

7. WP8 Dissemination and exploitation

a) Exploitation and marketing strategy were defined, along with the routes for future research and development activities

a) The dissemination measures carried out in the second year of the project include:

- Fairs, workshops and meetings
- A Web page for the dissemination of the aims and results to the wide public
- Contacts with potential customers

1.4 Final Results

The main results achieved by the FEMAG project are herewith reported:

1.4.1 Definition of load profiles

Understanding domestic loads power requirement was the first step to design the accessories integrated to the FC and to prototype the DEMAG system. To fulfil this objective, estimating the power profiles required by loads, in terms of peak power and total starting energy, a test bench for 220-VAC acquisition has been integrated.

Typical domestic loads have been monitored, acquired and analysed. As a result of this activity and of the design philosophy of the DEMAG, as it was conceived at the beginning of the project, the complete system would not have been able to supply mean power in excess of 1kW. This consideration has led to the definition of several priority classes, which has been used in the implementation of a load management strategy.

Moreover technical specifications of the DEMAG system have been outlined, and an assessment of the directives and norms for CE compliance certification have been performed.

1.4.2 Design of hydrogen storage tank

The objectives of this WP has been completely fulfilled, and the results are herewith summarized:

1. The adsorption/desorption reaction of hydrogen in metal hydrides has been studied so as to define the storage module dimensions (weight and volume) needed for DEMAG project, and mass and energy fluxes needed for the operation of the tank, during charging and discharging phases.
2. A literature review has been performed in order to define a reasonably accurate zero-dimensional model of hydrogen adsorption/desorption kinetics. This model allows to predict the dynamic behaviour of the tank.
3. A complete test-bench layout have been designed for the characterization of metal hydride parameters included in the model. Moreover a complete testing protocol for static and dynamic experiments have been defined.
4. A market survey, to identify off the shelf metal hydride tanks, has been performed and a suitable device for hydrogen storage has been selected.

The results of this activity confirm from various points of view such as inherent safety, low volume utilization and acceptable gravimetric density (compared with batteries), that the metal hydrides represents a very good compromise for deployment in static applications like DEMAG.

1.4.3 Design of Central Unit

The design of the Central Unit (CU) has been fully accomplished. The CU can be split in three major sections, that are herewith briefly described:

- Energy storage and PEM Fuel cell: the energy architecture of the CU is based on a FC made by Ballard, a well-known Canadian manufacturer, which is thermally integrated with the release of hydrogen from the metal hydride storage tank defined previous activities. Other energy and power buffers (ultra-capacitors) have been foreseen in order to avoid overload of the FC, and at the same time to allow it to work at near fix point.

- Intelligent DC-DC converter: this component has been developed by the Consortium, and is critical for the successful implementation of a FC based system. Its main function is to manage automatically contributions coming from fuel cell and ultra-capacitors, allowing the fuel cell stack to supply a quasi- stationary power, improving remarkably its own lifetime.
- Electronic controller: the DEMAG system controller is in charge of supervising the energy management, starting and stopping the FC, the intelligent converter (described in the previous paragraph) and the inverter.

  Other important functions relates to the management of peripheral units, used for the implementation of loads priority classes, and for a safe connection-disconnection to the main grid.

  Moreover the DEMAG CU controller provides a visual HMI (Human Machine Interface) with touch screen capabilities, allowing users to monitor the status of the system, to analyse the communication network and to modify the priority assignment of peripheral units.

1.4.4 Design of peripheral units

One of the focal point of the DEMAG system has been to provide the central unit with the capability to communicate with peripheral units. A complete communication system, based on ZigBee technology, have been designed as a framework to enable an intelligent management of the DEMAG system.

Two kind of devices, with different purposes, have been designed:

- A so-called Master Switch Interface (MSI), to be installed serial to the master switch of the domestic electrical plant, which provides the CU with the ability to detect the blackout condition, and to reconnect safely to the external grid when the main power is back.
- Automatic Disconnection Modules (ADMs), which is able to provide the CU with information about the load connected, and the ability to exclude them selectively based on their priority class. This module consist of a low-cost plug-in adapter and can be used for each and every appliance in the domestic environment, which is relevant for the end user.

1.4.5 DEMAG Prototyping

According to the results of the previous design activities, the DEMAG complete system has been prototyped and is available for demonstration at LABOR laboratories. Details and pictures of the different subsection are provided in the following paragraphs.

Tank prototyping

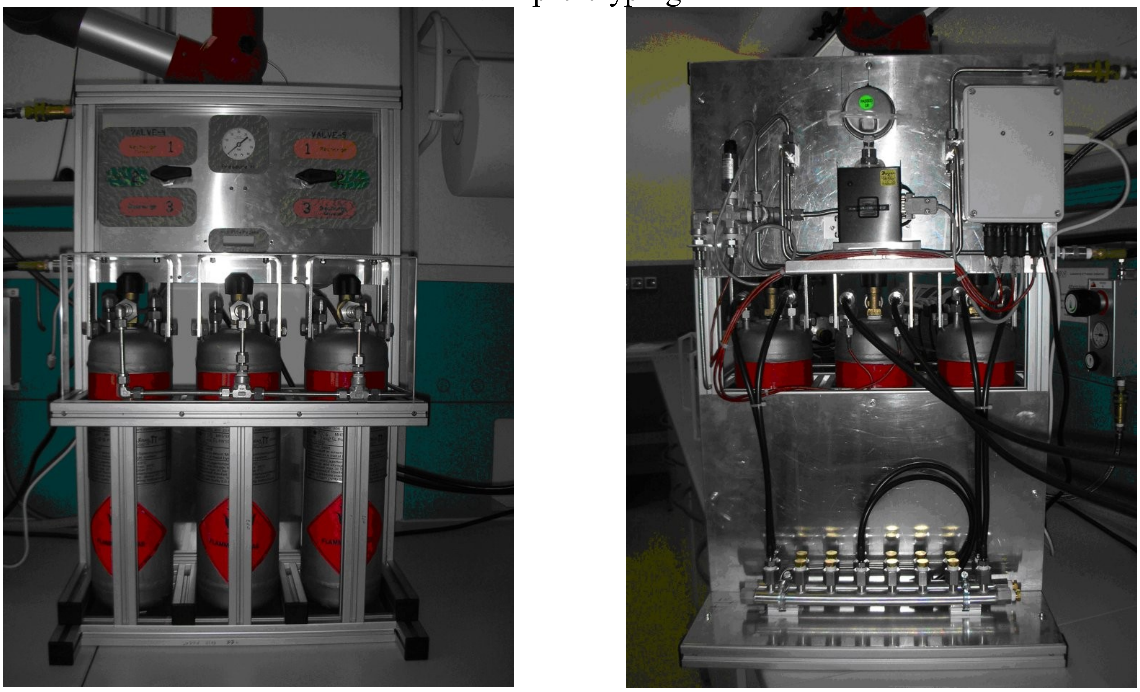

Figure 1: Installation of the metal hydride storage cylinders in the test bench

An experimental test of the charging performance was carried out. First, the canister was allowed to reach thermal equilibrium with the cooling water which flowed at 12 l/min. Its temperature was set in the thermostatic bath at 15 °C. Then, hydrogen was allowed to flow into the canister, supplied at 25 bar by means of the external reservoir and of the pressure regulators.

The results of the test are shown in figure 2 and 3. It can be seen that, under the abovementioned conditions, the charging operation of one canister (which could contain 1 Nm^3 of hydrogen, i.e. approximately 90 g) required almost 8 minutes. In order to get faster charging operation, it is however possible to increase the supply pressure (up to 35 bar) and to decrease the cooling water inlet temperature (down to 5-10 °C), so that it is conceivable to obtain an overall refilling time of 30-35 minutes for the 7 canisters required by the DEMAG system.

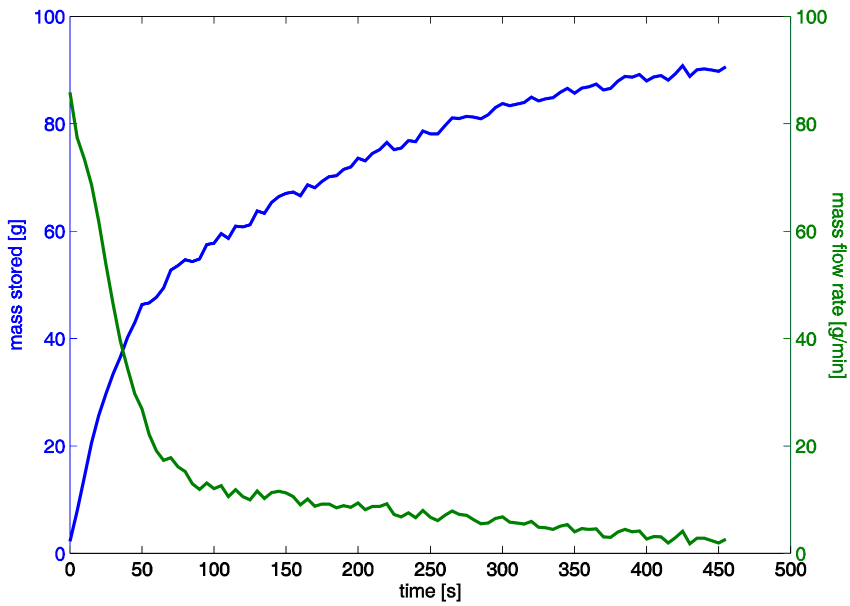

Figure 2: cumulative hydrogen mass stored in one canister (blue, left) and hydrogen mass flow rate (green, right) during charging operation

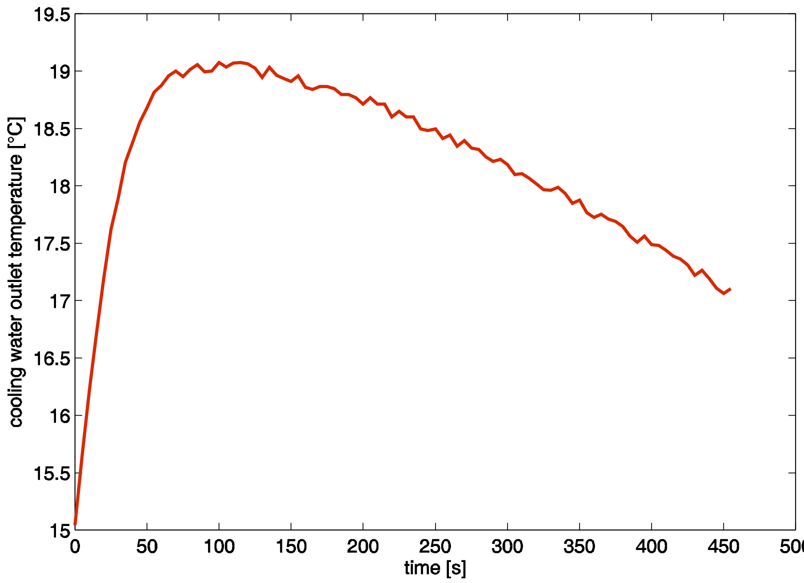

Figure 3: cooling water outlet temperature during charging operation

Further tests were carried out for different discharging conditions, by connecting the storage canisters to the fuel cell and then regulating the power output of the fuel cell at various levels, therefore effectively regulating the hydrogen reaction rate in the metal hydride within a short range (for a constant power output the fuel cell needs an almost constant hydrogen flow rate; variations in the flow rate may occur if the efficiency varies due to different operating conditions, such as supply pressure and coolant temperature, but these variations are usually quite small).

All the tests performed has shown that the storage canisters were able to supply the required hydrogen flow rate at pressures compatible with the fuel cell needs, and for the required time.

Figure 4 and 5 show the results obtained during one of such tests. The power output from the fuel cell was set at 0,8 kW, and therefore the required hydrogen flow rate was approximately 1 g/min, as a result from the simple calculation $m = P/(\eta \cdot LHV)$ (the efficiency of the whole power train η, including converters and auxiliaries, was approximately 40%).

The discharge process could go on uninterrupted until the canister was near empty, since the hydrogen pressure was always higher than the minimum required for the correct operation of the fuel cell (approximately 0,8 bar).

Since the canister could contain almost 90 g of hydrogen, it could supply hydrogen for as long as 90 minutes. This proved that the storage system, which is composed of 7 canisters, was able to meet the DEMAG system specifications (average output 1 kW for 10 h), together with other energy storage systems, such as the battery pack, included in the DEMAG architecture.

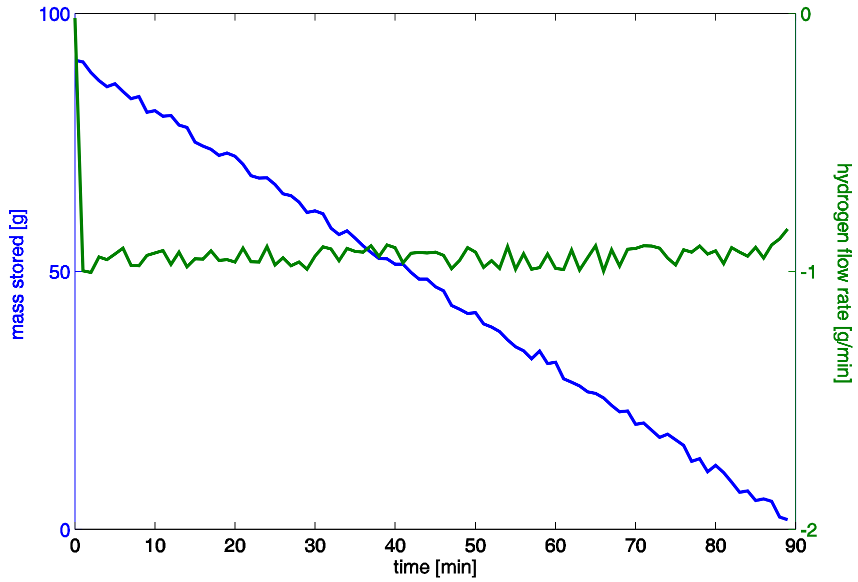

Figure 4: hydrogen mass stored and hydrogen flow rate during discharging operation at constant power output

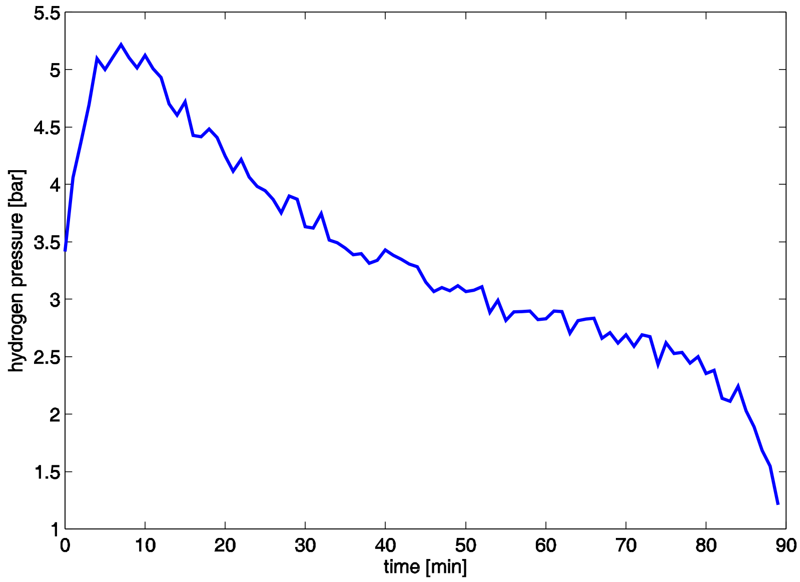

Figure 5: hydrogen pressure at the canister outlet during discharging operation at constant power output

Central Unit Prototyping

The central unit has been prototype in laboratory environment, and shown in the following picture

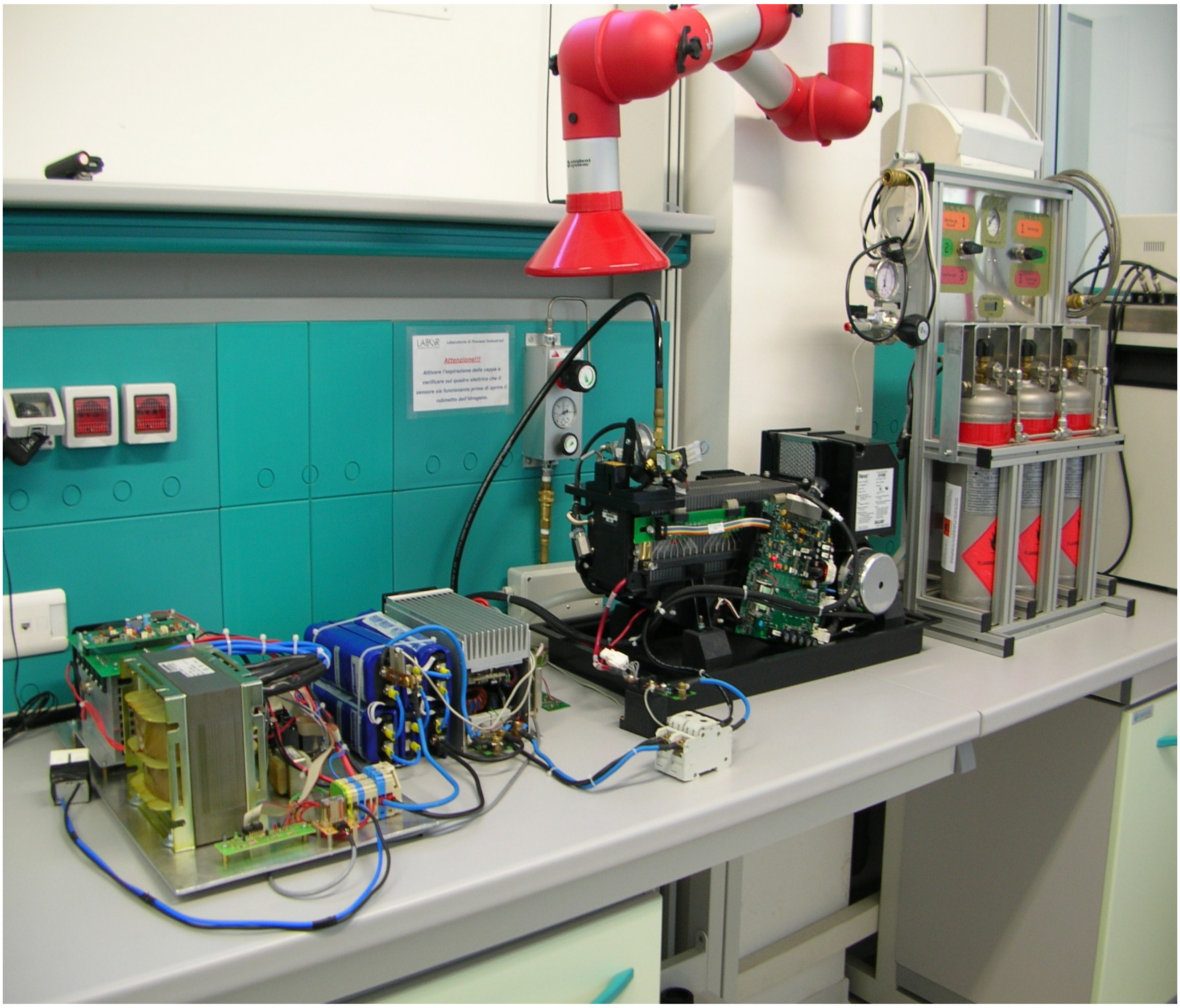

Figure 6: Central Unit assembled in laboratory

Peripheral units prototyping

In the following pictures the master switch unit (MSI and external power supply) and the Automatic Disconnection Modules are shown:

Figure 7: Overall view of the master switch unit (MSI + power supply)

Figure 8: Overall view of the ADM prototype

1.4.6 Testing

A complete experimental test phase has been performed in LABOR's laboratory on the global EPS DEMAG prototype.

It has been decided to divide the experiments in two parts: firstly, the behaviour of the central unit, i.e. the electronic system controller performance, the intervention priority management between fuel cell stack and super-capacitors pack, the behaviour when the load requirement exceeds the fuel cell stack nominal power, have been tested; then, the behaviour of the DEMAG EPS is assessed when a black-out occurs and when the grid tension comes back, the behaviour of the peripheral units (MSI and ADMs) and the compliance of loads priority classes have been tested.

The following picture shows how the correct management of power contributions coming from fuel cell and ultra-capacitors. The system is able to protect the fuel cell from power spikes, and to change the power demand according to a ramp that can be set via firmware and adapted to the dynamic behaviour of the fuel cell.

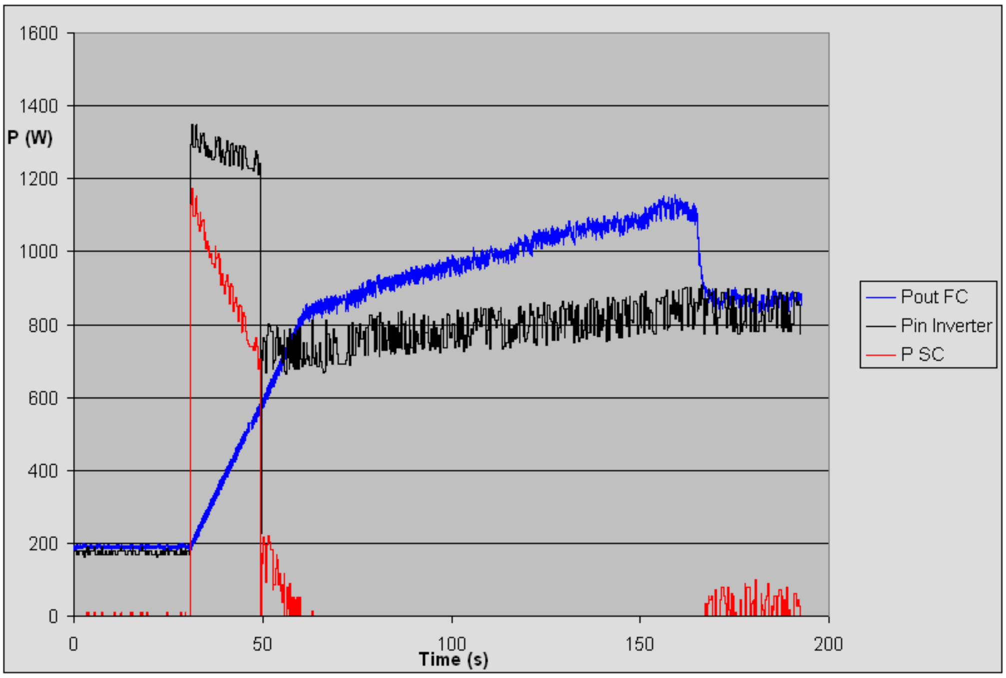

Figure 9: Fuel cell and ultra-capacitors outlet power - Inverter inlet power

The correct behaviour of the DEMAG system has been tested in laboratory through several, connecting and disconnecting test, with different conditions, and the robustness of both the architecture of the control system and its firmware implementation, has been fully demonstrated.

SECTION 2 Dissemination and use

The main publishable results and their possible exploitation are described:

2.1 Overview table

Exploitable Knowledge (description)	**Exploitable product(s) or measure(s)**	**Sector(s) of application**	**Timetable for commercial use**	**Patents or other IPR protection**	**Owner & Other Partners Involved**
Wireless communication for load management	Wireless devices for load insertion and disconnection	Consumer electronics, domotics	2008		AGT, LABOR
Hybrid system design	DEMAG generator	FC OEM integration Power and control electronics	2009		AGT, LABOR

2.2 Description of exploitable results

DEMAG wireless communication devices

2.2.1.1 Result description

A complete communication system, based on ZigBee technology, have been designed as a framework to enable an intelligent management of the DEMAG system.

The Central Unit (CU) is therefore able to communicate with peripheral units to detect device failure, mains blackout, load power absorption for each device; moreover the CU is able to interact actively with peripheral units to implement an intelligent selection of the loads to be supplied, based on their priority, and to provide secure reconnection when the main grid is back.

The DEMAG modular architecture, consisting of a central supervising unit and peripheral devices incorporating different functionalities, could be exploited in traditional backup systems, with the following advantages:

- It allows to design the size of the backup power for emergency loads and not for the nominal power of the domestic grid, since it provides the capability to disconnect unnecessary loads.
- It allows to place the Central Unit detached from the main switch.
- Is ideal both for new installation and for retrofit of existing grids.

2.2.1.2 Possible market applications

As outlined in previous paragraphs, the wireless communicating devices have a lot of functionalities, that could be interesting in the design of backup systems. In principle a module providing such auto-diagnostics and communication capability with a master supervising unit, can be used, for example in hospital or emergency centers, to exclude non-critical loads from the power grid, when the emergency backup power is used.

The DEMAG devices have been designed to read the current drawn from the power grid, but they could be modified with the aim of hosting several kind of sensors like temperature, humidity, acceleration, or anti-intrusion, and they could be much effective in implementing a central monitoring system over remote environment.

Refinement of the prototype will be evaluated in the future, as well as the incorporation of different sensing technology.

2.2.1.3 Stage of development

Industrial demonstrator. Prototypes of peripheral devices and central supervising unit have been actually built, and are available for technology demonstration.

2.2.1.4 Collaboration sought or offered

Possible collaboration may arise, on this topic, with companies active in commercialization of traditional power backup system.

2.2.1.5 Intellectual property rights granted or published

No IPR has been granted

2.2.1.6 Contact details

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2.2.2 DEMAG generator design

2.2.2.1 Result description

Fuel cells are universally deemed as a disruptive technology, i.e. a breakthrough development destined to enter massively in everyday technology thanks to undiscussed potential advantages respect to competing standard technologies such as batteries.

The Consortium of the DEMAG project has designed and developed a hybrid power generator based on the integration of PEM Fuel cells, supplied with hydrogen from metal hydrides tanks, and electric power buffer ancillaries (like batteries and super-capacitors).

The DEMAG generator is used to supply power to the domestic grid, in case of blackout, through any outlet of the electrical system, and the main characteristic of the power train deployed in this application is to avoid the Fuel Cell to be forced to sustain highly dynamic load, and peaks over the nominal power of the FC, since the variable power supply is one of the main reasons of the stack lifetime reduction.

Indeed the architecture of the DEMAG generator is able to convert power spikes, typical of load insertion into domestic grid outlet, in quasi-stationary variations of FC power demand, using super-capacitors as ancillary power storage system. An intelligent DC/DC converter manages intervention priority of power components.

Moreover a supervisor is able to interact with the peripheral units providing the DEMAG system with the intelligence needed to manage the interaction between loads and the generator.

A prototype of the overall DEMAG system has been built and is available for demonstration runs.

2.2.2.2 Possible market applications

The main market application of the knowledge generated under the DEMAG project is the design and production of FC-based domestic solutions for replacing traditional battery in non-critical backup power applications, i.e. when the continuity of power supply is not required.

2.2.2.3 Stage of development

Laboratory prototype.

2.2.2.4 Collaboration sought or offered

Possible collaborations offered are:

- Fuel cell application feasibility
- Fuel cell system and product design
- Fuel cell system engineering and prototyping
- Fuel cell system deployment in domestic environment

2.2.2.5 Intellectual property rights granted or published

No IPR has been issued.

2.2.2.6 Contact details

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