Smart battery management systems: towards an efficient integration of electrical energy storage in smart regions

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ABSTRACT: Electrical energy storage systems for electric vehicles or stationary applications will be important actors in Smart Region’s energy scenarios, strongly contributing to increase the efficient and sustainable use of available resources. However, massive integration of such systems still poses many problems, requiring enhancements in batteries’ life time, autonomy, reliability and cost. The development of new smart and accurate battery management systems able to communicate with a broad range of smart devices and energy management systems, to account with users’ needs and smart grid management directives, are essential to operate such battery based energy storage systems, improving their overall performance. The paper discusses some of the technological developments needed in this domain and the requirements of smart battery management systems to comply with, presenting a modular hardware platform, developed at LNEG, as an example of the required structure and functionalities, relevant both in electrical mobility and decentralized smart-grid energy storage systems.

1 INTRODUCTION

New Smart Region’s and Smart Building development scenarios are closely related with the efficient, sustainable and integrated use of available energy resources, considering that energy is increasingly scarcer and can´t be misused or wasted. Recent data shows that the built environment, mainly in cities or developed regions, has a relevant share of the global energy consumption and in the production of gases with climate impact, representing about 40% of the energy world-wide total consumption. This shows the necessity of thinking new ways to optimize the regions built environment energy usage, as a key contribution to decrease the global energy consumption and improve energy efficiency, both as consumers and producers (Meeus, 2010).

With new coming smart-grid architectures, energy storage systems are being pointed out as important technologies to help solving many of the current issues with the increasing grid’s integration of renewable sources of energy, like wind or photovoltaic systems, contributing for their more efficient use and for more efficient and flexible management of energy demand (Ruester, 2012) (EASE/EERA, 2012) (Espinar, 2011).

This paper discusses the role, technologies and contributions of energy storage systems, namely those based on electrical batteries, in the context of Smart Regions and Sustainable Buildings, focusing the analysis in two main applications domains: electric vehicles (EV’s) and decentralized stationary electric energy storage systems (SEES) for buildings or final users. In these contexts, new smart battery interface and management systems (Smart BMS) are considered to be the key enabling systems to the mass deployment and integration of these energy storage devices into smart grids and micro-grids. The development of a modular hardware platform, currently undertaken at LNEG, will be presented as an example of a development tool leading to future smart BMS’s, using this hardware/software infrastructure to obtain the required devices with advanced functionalities to be applied both in electrical mobility and decentralized smart-grid energy storage systems.

2 ENERGY STORAGE SYSTEMS IN SMART REGIONS CONTEXTS

Public policies have been leading to an increasing penetration of non-fossil energy sources into the distribution grids. Nevertheless there are still some drawbacks to overcome with the proficient usage of these energy sources, mainly concerning the variability and intermittence of their availability, which causes significant mismatches between the more intensive energy demand phases and the periods when these kinds of energy are available. So, this integration requires a flexible and efficient balance of energy production and demand, regarding demand peak shaving, load shifting, and renewable resources variability compensation (Meeus, 2010).

Short term energy variability, mainly due to fluctuations of natural resources but also resulting from unpredictable small scale demand changes, are already addressed, in some extent, by energy producers and operators of distribution grids, by installing electric energy storage systems in energy plants or substations, in order to supply the missing power during short periods of time (Eurelectric, 2012) (Ruester, 2012) (Espinar, 2011) (Rastler, 2010).

However, medium term grid’s stability and efficiency can also profit from the gradual penetration and adoption of local electrical storage systems, at several other levels (cities, small communities, buildings, etc.), decreasing the need of other expensive investments at the grid level (with high environmental impacts) and also lowering integration risks and costs.

For smart regions and smart buildings, the goal of achieving almost null energy balances is generally done by introducing local production based on renewable energy sources. This compensates or balances the energy consumption from the grid over a considered period of time (generally during one year), but requires solving new challenges in the design, construction and operation of these kinds of buildings. It also requires innovative energy management systems, namely including some kind of integration of local energy storage devices and EV’s batteries as well as distributed stationary electric energy storage systems, which have been pointed out as being key technologies for this purpose (Ruester, 2012).

In the case of electric mobility, there is a progressively increasing variety of vehicles, from small 4 or 2 wheeled ones till private or public transportation vehicles. It is aimed that these vehicles can supply a large amount of energy stored in their batteries using Vehicle-to-Grid (V2G) integration solutions and technologies, allowing a more flexible management of the energy production and demand from the grid distribution point of view.

On the stationary side, applications can also be scaled from smart cities or communities, to buildings or down to the final energy consumers. Local electrical energy storage devices can store energy when it is not needed (from local generation or from grid at lower rates, taking profit, directly, from energy tariff differentiation offered by utilities) and discharge it when necessary. If their costs are affordable, they will support individual customers to reduce energy bills, constituting an important tool to modify energy consumption profiles and to manage consumption and eventual local production, at a domestic level.

Both stationary batteries and electrical vehicles, fully integrated within local Home Intelligent Energy Management Systems, will be determinant to enhance the environmental performance of buildings and communities (Figure 1).

Nowadays, there is a strong effort of research and technology development of electric energy storage systems, mainly focused in electrochemical devices but also in super capacitors, based on new materials allowing higher power and energy densities.

Lithium-ion (Li-ion) multi-cell batteries, offering high energy and power density, have become, in the recent years, the most important electrical storage technology, mostly due to its applications in the areas of portable and mobile applications (laptops, cell phones, small electric vehicles, etc.). However, these batteries can also be modular and scalable, making them suitable both for mobility applications, with different kinds of electrical vehicles with different energy supply needs, and for the stationary cases, with different levels of energy storage capacity needs, from the distribution level to the end-user (Fuchs, 2012).

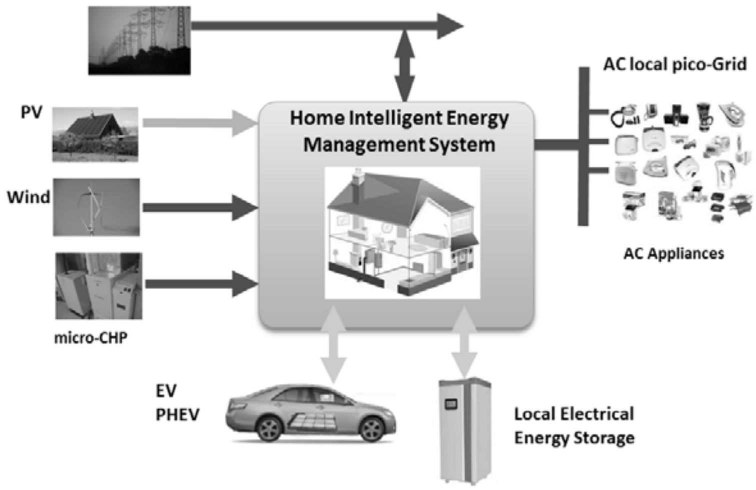

Figure 1. Energy storage systems within smart energy sustainable buildings.

Presently, the massive market penetration of EV's is very much dependent on the confidence of users on the battery systems performance, regarding its autonomy, life cycle and costs. From the electrical grid point of view, there are also constrains that should be considered to prevent grid's congestions faults and power strengthening needs, in order to accommodate the predicted increase in energy demand, caused by EV's charging. Concepts like "smart charging" (grid controlled) and V2G can help the electric vehicles to cope with the grid operation, but these strategies may collide with the best use of EV's batteries, forcing them to charge/discharge frequently in a partial way, causing its early aging.

In stationary applications the concept of smart charging still applies but V2G turns now into Battery-to-Grid (B2G), with benefits in terms of the range of selectable batteries and related algorithms and systems to control their operations. SEES can also accomplish all the roles intended for EV's, regarding grid's variability compensation and energetic efficiency, presenting advantages in terms of optimization of load management /demand response and peak shaving.

3 MAIN REQUIREMENTS OF SMART BATERY MANAGEMENT SYSTEMS

For electrical energy storage systems being largely spread, either for mobility or stationary applications especially in the context of smart charging in V2G or B2G environments, there is a strong need of innovative and flexible management systems and electronic interfaces, which could offer these storage systems the proper functionalities, accuracy and communication capabilities at a reasonable cost.

Complex multi-cell battery electrical storage systems require electronic Battery Management Systems (BMS) which monitors and controls the charge and discharge processes of the several cells or modules within the battery pack. These management and control systems are vital to ensure the safe operation of the battery packs and to extend its life cycles (Lu, 2013).

Nowadays there is some offer of on-the-shelf BMS and some battery's manufacturers integrate such OEM devices into their products. Despite that, development and research in new real-time battery's state-of-charge (SoC) and state-of-health (SoH) optimized estimation methods and algorithms and cells' active charge balancing hardware topologies and algorithms are still needed (Zhang, 2011). These subjects require advanced and accurate data acquisition modules and easily configurable data processing and control embedded systems. Either for EV or stationary applications, BMS for batteries working in smart environments require significant processing, memory and communication resources to fulfill, in real-time, a set of battery storage specifications and functionalities, which include (Lu, 2013):

- precise measurement of physical variables (cell voltages, currents and temperatures) to better estimate battery state and control the charge/discharge cycles;

- more accurate real-time algorithms to estimate the battery's state and to improve cells' charge balancing;
- supervision of charge/discharge operations, detecting and acting in emergency situations, to guarantee battery security and protection;
- advanced communications capabilities, to interconnect with other external devices and equipment (as smart chargers, local user's interfaces, vehicle's subsystems, energy management systems).

Flexible management systems, with affordable costs, must then be developed using modular and distributed multiprocessing architectures, profiting from a low cost but powerful processors range, available at the market.

Regarding communications, it will be vital to offer a range of different communication and networking technologies and various standard protocols will be required to interconnect these energy storage batteries to other systems and peripherals under different application scenarios. This will allow an easier system integration in the EV's local control environments, in smart energy management and supply infrastructures or to interface with the end users, for instance in smart buildings (Figure 2).

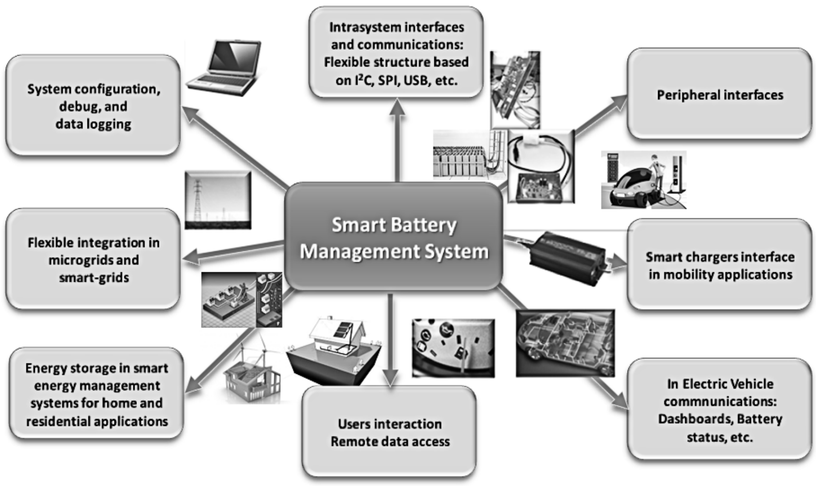

Figure 2. Smart Battery Management Systems communications interactions.

Another functionality these management systems must include is the local capability to control the charge balancing and equalization between cells of the battery pack. In multi-cell batteries, namely those with several Li-ion cells connected in series, the charge imbalance between cells is a relevant issue that can degrade the expected battery number of charge/discharge cycles (Einhorn, 2012) (Mizuno, 2012) (Zhang, 2011). Generally, the increasing number of charging/discharging cycles and ageing will intensify the cells' charge imbalance in a series-connected battery string and will decrease the total storage capacity and number of running cycles of the battery pack. So, keeping cells' charges at an equalized level is a very important issue for enhancing battery life which, itself, is an important concern for the end-users. Then, to optimize the overall pack running life, charge balance among cells, either in discharge or charge cycles, must be assured.

Several balancing or charge equalizer methods have been presented during the last years, both passive with charge dissipation and active using local charge re-distribution and balancing. Presently, there is a strong research effort in this domain, both to improve the algorithms and strategies of active methods and to lower equalization time and the costs of driving circuits. Another important aspect is to understand their consequences regarding battery life, as they imply additional charges and discharges, even if small, at cells' level. The efficient management of multi-cell batteries' charge and discharge cycles is also strongly dependent on the knowledge's accuracy of its cell's internal states, such as SoC, SoH and Depth-of-Discharge (DoD), which cannot be measured directly, during normal battery operation. Estimated values have to be used, determined by algorithms based on dynamic cell models, experimental data specific to the battery cell's type and on physical quantities measured from the battery pack (cell's voltages, currents, temperatures, etc.) (Rahimi, 2012) (He, 2012) (Tsai, 2012).

The majority of the existing cell models are mainly suited for simulation studies or for experimental offline testing, supported by powerful processing and memory resources, provided by up-to-date computational equipment. However, EV's and SEES' applications must rely on real time embedded electronic systems, which have more limited computational resources, to keep their costs at a low level. Besides that, the common existing models have not been developed having in mind the interactions that the battery based energy storage systems should stand in normal operation. In these systems, energy flow can change frequently in repetitive charge/discharge operations, causing partial charging-discharging cycles, with consequences on the performance and life time of batteries. Due to these new application scenarios, real-time estimation of batteries' internal states is nowadays a domain of competitive research, where the goal is to achieve lower complexity real-time embedded algorithms, without affecting accuracy and batteries information reliability. Available commercial BMS use proprietary algorithms, either for charge balancing or parameters estimation, making it difficult to embed new ones. Smart BMS must offer the possibility to include custom real-time estimation algorithms allowing reconfiguration and programmability to accommodate application dependent requirements.

4 MODULAR HARDWARE PLATFORM AND DEVELOPMENT FRAMEWORK FOR THE IMPLEMENTATION OF CUSTOM SMART BATTERY MANAGEMENT SYSTEMS

The previous considerations led to the development of a modular hardware platform, currently being implemented at LNEG, for the custom development of smart electronic microsystems for managing batteries operations, including the above mentioned structures and functionalities (Gano, 2012). This highly configurable and programmable structure supports the design of custom optimized real-time algorithms for cells' state estimation and for energy efficient cells' charge balancing subsystems, as well as flexible hardware/software integration. It is designed for battery packs with different Li-ion cell types and for different management infrastructures and devices, offering several hardware expansion possibilities (Figure 3).

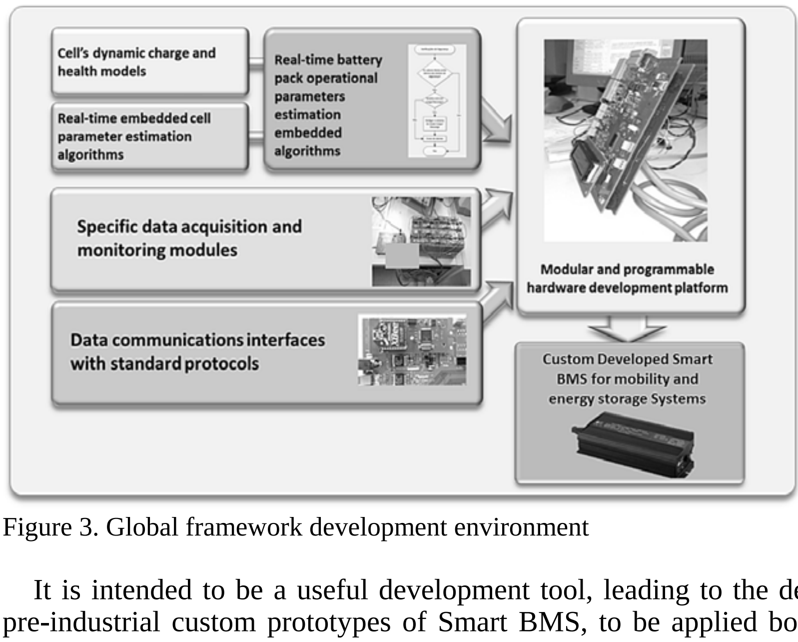

Figure 3. Global framework development environment

It is intended to be a useful development tool, leading to the design and implementation of pre-industrial custom prototypes of Smart BMS, to be applied both in electrical mobility and decentralized smart-grid energy storage systems, in the contexts of smart-grid integration and smart home energy management systems usage.

4.1 *System architecture*

The platform is based on two main subsystems with complementary functionalities: the cells' monitoring and balancing subsystem (with multiple modules) and the battery control and management subsystem for global data processing, local control and external interface (Figure 4).

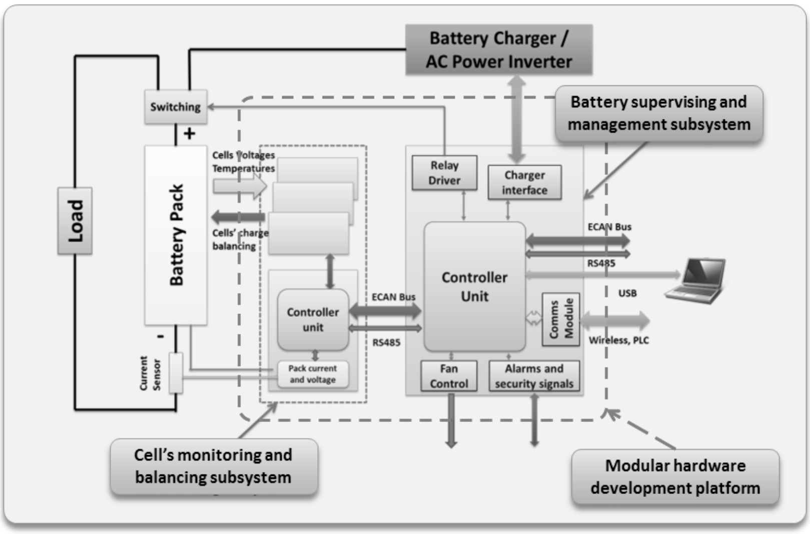

Figure 4. Global framework hardware architecture.

Each subsystem has a flexible configuration, allowing several interface and custom signal acquisition modules to be used for monitoring several battery physical variables. They include local control and actuation capabilities for processing both analogue and digital signals, using auto-ranging measuring circuits and calibration methods for improved accuracy.

The cells' monitoring and balancing subsystem is designed for real-time monitoring of each one of the pack individual cells' voltages, the battery pack distributed internal temperatures, the flowing current and the battery terminal's voltage. It is also able to control the individual cells' charge balancing process, including the possibility of using several charge balancing strategies, based on different electronic driving modules that are also under development. This will allow the test and evaluation of the actual performance of several balancing methods with respective driving circuits.

Currently, this subsystem can accommodate a maximum of 32 cells' monitoring modules, giving a maximum of a 192 Li-ion cells within the battery pack, each one with a nominal voltage between 1 and 5V. It has also its own local data processing unit, based on a 32 bit microcontroller, with local processing power for real-time estimation of main cells' functional parameters, like SoC and SoH. This subsystem can use different selectable methods to measure the battery pack flowing current using precision resistive shunts or Hall-effect sensors. The current measurement can range between 10 to 500A full scale, using programmable measuring ranges to optimize the resolution and the related measuring error. The total battery pack terminal's voltage is also measured using a resistive voltage divider, with programmable taps to optimize the accuracy for several measuring voltage ranges. There are 8 selectable voltage ranges between 10 and 1000V, to be selected accordingly to the total number and the nominal voltage of each cell within the respective battery pack.

The interface between the two hardware subsystems is made using the ECAN-Bus standard communications protocol, having an RS-485 serial port as an option. This interface has a galvanic isolation between both subsystems.

The other subsystem is responsible for the battery system's global management and control during charge and discharge phases. It controls the adequate battery connections' switching with external systems, making possible the battery pack isolation from external circuits in emergency cases or during stand-by, in addition to the battery's switching during the normal charging/discharging cycles. It also includes supplementary temperature measurement capabilities and driving electronics for battery global pack thermal monitoring and management, using specific fan controllers for preventing system thermal runaway.

This subsystem offers several standard interfaces and communication protocols to data interchange with external systems. As referred before, the development of smart battery management systems with enhanced communication capabilities is of major relevance in smart-grid application and integration contexts. This platform, offering several data communication ports with different communication technologies and standard protocols, will make it easier to interconnect the final developed smart battery management systems with other systems, within the smart-grid integration and the electrical mobility contexts. The main onboard external interfaces are again two ECAN-Bus 2.0 and serial RS485 ports, but one USB port is also available for direct interface with a host computer for system configuration, programming and data logging. Besides the above mentioned onboard communication ports, an expansion port for additional communication modules is available, giving the possibility of using wireless protocols (Bluetooth, ZigBee IP, WiFi, etc.) or Powerline Communications (PLC) standards, like the HomePlug Green PHY new standard. These expansion modules should have its own coprocessor for communication protocol stack handling and the local interface with the board main processor is made using standard UART, SPI or I^2C serial protocols.

In order to have direct control of the charging process, this subsystem interfaces directly with several types of chargers, using analogue or Pulse Width Modulated (PWM) signals or, in case of ‘smart’ chargers, the above mentioned ECAN Bus digital communications interface. The availability of several I/O expansion ports makes the integration of custom modules also possible, for instance, for electrical isolation monitoring and current leaks detection, improving this way the safety of the battery pack.

A graphical software interface for system configuration and data acquisition is also being developed, allowing an easier framework interface, both in terms of its hardware and firmware.

4.2 *System functionalities*

One of the goals of this development framework is to implement a library of algorithms and procedures for flexible and custom implementation of functionalities in the final smart battery management system, having in mind different applications and different cells’ technologies. As referred before, to fully manage the charge and discharge operations of a battery, a smart BMS needs to real-time measure and monitor several physical quantities in order to estimate some important parameters related with the state of the battery, as SoC and SoH, that cannot be measured directly during its normal operation. So, real time estimation of these variables can be a rather complex task, demanding configurable data processing resources and accurate algorithms which are still object of worldwide research efforts. Presently, most part of the existing commercial BMS systems don´t offer configuration or programming capabilities to test or integrate new developments or adaptations to these algorithms, paying attention to specific cells’ type or applications. However, this ability is one of the advantages to be offered by the present development framework, that can be used either to support experimental studies of cells and batteries models, in order to either develop and tune future algorithms, or to test and validate such algorithms to embed them in the system’s final firmware, having in mind specific mobility or stationary storage applications.

5 CONCLUSIONS

In smart cities and regions, sustainable strategies in the energy domain require a flexible and efficient balance of energy production and demand, regarding demand peak shaving, load shifting, and renewable resources variability compensation. This imposes a number of challenges in the design, construction and operation of buildings, demanding local advanced energy management systems with the integration of some kind of local energy storage devices.

Within these new energy management scenarios, electric vehicles and decentralized stationary energy storage are considered to be growing application areas for advanced batteries, mainly those based on Li-ion multi-cell packs, as electrical energy storage devices. For these systems being largely spread, either for mobility or stationary applications, innovative, flexible powerful embedded processing systems and electronic interfaces are required, offering these storage systems the proper functionalities, accuracy and communication capabilities at a reasonable cost, requested by smart environments.

The platform framework being implemented at LNEG, owns a set of characteristics (modular hardware/software architecture, multiprocessing, advanced communications, firmware libraries, etc.) which entitles it to be a powerful tool to support the design and development of such systems, leading to pre-industrial prototypes for a broad range of applications in the domain of EV or decentralized SEES. Its configurability, both in software and hardware, and programmability, will also allow to embed new software algorithms for management and control of batteries' operations, specifically developed and tuned for custom smart BMS.

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