MULTIFUNCTIONAL MODULE LITHIUM-ION STORAGE AND PHOTOVOLTAIC CONVERSION OF SOLAR ENERGY

J.F. Reynaud[1], C. Alonso[1], P. Aloïsi[1], C. Cabal[1], B. Estibals[1], G. Rigobert[2], G. Sarre[2], H. Rouault[3], D. Mourzagh[3], F. Mattera[4], S. Geniès[4]
[1]CNRS, Laboratory for Analysis and Architecture of Systems (LAAS), France
[2]SAFT, France
[3]CEA-LITEN, Laboratory for Energy Compounds (LCE), France
[4]INES-RDI/CEA-LITEN, Laboratory for Solar Systems (L2S), France

ABSTRACT

A large part of photovoltaic research is dedicated to developing innovative integration technology for the module. Now the use of a storage function in such intermittent power supply systems is crucial in order to get better adequacy between the peaks of energetic consumption and production. The integration degree of photovoltaic systems will be improved if all the components: panel, battery, converters, electronic control unit, cablings can be combined in a compact single unit. Different battery technologies are currently used with photovoltaic systems along with some of the charging and discharging techniques that are available. Lithium-ion technology appears to be the best candidate because of its high energetic efficiency, high specific energy density, deep discharge ability, its long cycling life and its possible different shapes (cylindrical or prismatic styles) to obtain an integrated design. To optimize the battery performance, different conditions are required and achieved by control sub-systems, integrated into battery and module construction. The electronic management system presented in this paper aims to optimize the use of the battery making the overall system more reliable and cost effective. On the one hand, a research algorithm of the optimal power to charge and discharge an advanced lithium-ion battery for photovoltaic application is necessary to obtain an optimum electronic management system. On the other hand, a Maximum Power Point Tracking is also incorporated into the electronic control unit, to optimize the solar array production under varying atmospheric conditions. This paper will describe a new concept of an integrated multifunctional module using lithium-ion batteries and new control algorithms.

INTRODUCTION

The context of our research is a new national project named Module LiPV constituted by a consortium of two laboratories specializing in solar energy, material of energy storage and architecture systems, and one industry experts in batteries. This project depends on the French National Research Agency (ANR). The objective of our work is to demonstrate the feasibility of a new concept of a multifunctional photovoltaic system.

Today, photovoltaic (PV) energy has a high threshold of technical viability and constitutes a serious solution to respond to the total energy consumption. Registered in a fast-growing context, photovoltaic power systems could be designed for different applications. This paper presents a multifunctional module, noted M_{LiPV}, where all the components, panel, battery, converters, electronic control unit and cablings are combined in a compact single unit. This module offers different possibility of configurations with their advantages:

1. Stand-alone configuration, direct current: saving of space inside a mobile home, easy to use (even for a non expert user), no need for a specific place for the batteries, easier to install and to replace, and no need to modify the existing systems.

2. Stand-alone configuration, alternative current: saving of space (no technical room), easier to install, easier to transport on the site, and flexibility to adapt the system to the expectation of users.

3. Grid connected configuration: easier to integrate thanks to the compactness of the module, easier to install, and flexibility to adapt the system to the expectation of users.

Fig. 1 shows the multifunctional module integrated in a full photovoltaic power system with its different configurations.

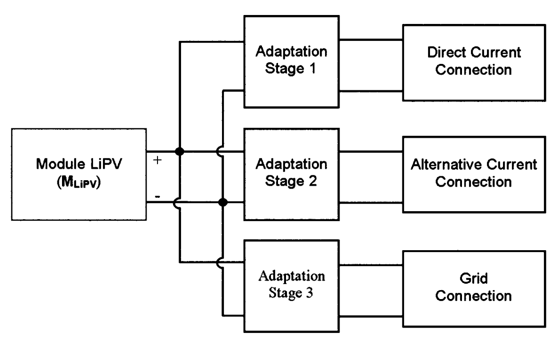

Fig. 1. Descriptive of the full photovoltaic power system.

The high degree of integration of this module involves new designs and technologies for all inserted components. Today, lead–acid batteries are the most commonly used technology for photovoltaic energy

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storage due to their low cost and their great availability [1]. However, the battery is the component which most strongly influences the photovoltaic system cost and reliability. There are three possible reasons which could explain this situation:

- Photovoltaic systems impose specific operating conditions.
- The battery and cell characteristics (life time, efficiency) are different from one to another.
- The battery management is often not appropriate to the battery technology.

To square up these difficulties, conventional photovoltaic power and storage systems must be reviewed and improved to be efficient during charge and discharge without degrading the life time of the battery. A new concept of energy management and storage system is presented in this paper to smooth the intermittent energy production from the PV generator to the load.

DESCRIPTION OF THE MULTIFUNCTIONAL MODULE

The elementary architecture studied in this paper includes a PV generator, a storage system and an optimal conversion chain including MPPT and electronic management system with different electrical functions to be connected to a load with a maximum security. Fig. 2 shows the integrated design of the multifunctional module which has been presented in the 22nd European Photovoltaic Solar Energy Conference in Milan (September 2007).

Fig. 3 describes the functional architecture of the multifunctional module M_{LiPV} with all sub-systems included.

The principal function of this architecture is to transfer the maximum power from a PV panel and store or restore the energy to the load. For that, the electronic management system will be designed and implemented on a microprocessor to control all sub-systems described below.

The PV generator of the module delivers the maximum energy of one panel. To satisfy the power value defined by the application, several modules M_{LiPV} could be associated in parallel. The power of the PV panel in this project can be between 75W and 200W depending on PV cell technology.

The dc-to-dc converter connected to the PV generator is associated with a Maximum Power Point Tracking (MPPT) optimizing the research of the Maximum Power delivered by the PV generator. The non-reversibility of this static converter will protect the panel from a possible battery discharge of electrical current.

The battery, elemental component of the multifunctional module, will be a lithium-ion battery. Electronic management system and charge/discharge regulator will ensure the management of the battery, protection and control system included in the dc-to-dc converter. Control algorithms would be adapted to the lithium-ion electrochemistry used (i.e. nickel oxide or iron phosphate).

The module "Panel / Converter / Li-ion Battery", noted M_{LiPV}, could work in two cases as follows:

- M_{LiPV} working alone,
- M_{LiPV} working in parallel with different equivalent modules.

Parallel association of n M_{LiPV} modules allow higher power on the order of n*M_{LiPV} depending on the application. The number of n modules M_{LiPV} is equal to the number of PV panels necessary to supply one load.

The system is sized to ensure the continuity of the supply energy for four days with random meteorological conditions. The system is not, at this stage, bi-directional and does not accept energy injection from the grid.

The developed operating system takes into consideration the various characteristics of the individual battery cells and manages depending on the load profile, how the energy flow has to be controlled.

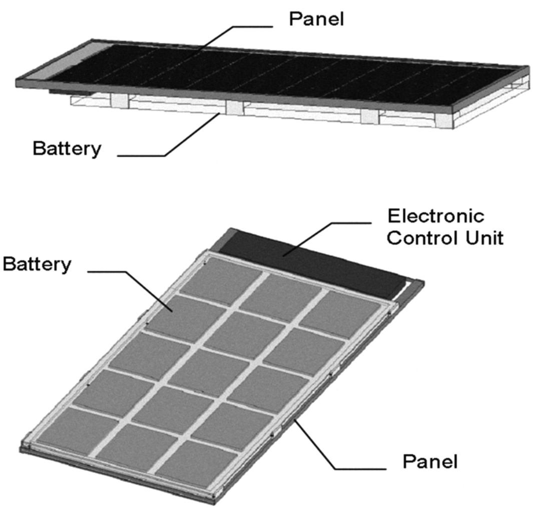

Fig. 2. Design of the multifunctional lithium-ion module, (PVSEC Milan, September 2007).

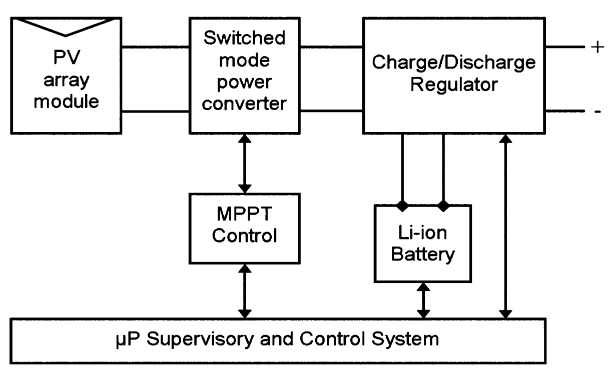

Fig. 3. Functional architecture of the multifunctional module M_{LiPV}.

A. Maximum Power Point Tracking

To maximize the photovoltaic module efficiency, it is necessary to have the operating point between the PV generator and the load very close to the MPP of the PV source. However, as the MPP changes with radiation and seasons, it is difficult to track it at all radiations. To overcome this problem, a solution consists in introducing an adaptation stage (a static converter) between the PV source and the load associated with the Maximum Power Point Tracking (MPPT) working as an impedance adaptation.

Different types of MPPT exist. Their differences depend on the type of implementation, the theoretical control principle and the acquisition parameters. Indeed, the existing tracking methods reach the MPP more or less successfully.

In our case, the multifunctional module uses an MPPT controller created by the Laboratory for Analysis and Architecture of Systems (LAAS-CNRS). Indeed, in this laboratory, different MPPT algorithms have been developed for photovoltaic applications since 1997. The conversion chain of M_{LiPV} will use the recent optimal MPPT, which has demonstrated excellent behaviors [2,3]. For example, in steady state the MPPT efficiency is about 99.6 %, and during brutal radiation variations, the recovery of the new maximum power point is inferior to 5 ms. Fig. 5 shows an experimental result of a boost converter associated with a MPPT controller. All these performances will be integrated in the multifunctional module.

B. Energy Storage System

Electricity production systems based on renewable energy and, in particular, photovoltaic systems need an energy storage system because of the intermittent energy source. Nowadays, photovoltaic systems often use energy storage systems based on lead-acid batteries due to economic and industrial availability reasons. But these conventional technologies of battery have environmental drawbacks and limits that can reduce the development of systems by random life time leading to a high possession cost. Today, storage system represents sixty percent of the cost of the full system. That would be reduced to thirty percent with new technologies used in this project [4]. Due to their characteristics and their high potential of evolution, lithium-ion batteries are showing possibilities to run over the actual limitations in photovoltaic systems. Lithium-ion technology has remarkable energy efficiency (97%) [4] and higher than conventional technologies (an average of 80% for lead-acid batteries) given the fact that there are not parasitic reactions in cycle.

Actual active materials for lithium-ion batteries present excellent properties of cyclability and life time estimated at twenty years. In this project, active materials work at a range of temperatures higher than classical operation conditions. So, researches will be based on the storage system adaptation to improve efficiency and reduce the cost of the multifunctional module. Firstly, SAFT will study a conventional couple of electrodes, Lithium Nickel Oxide ($LiNiO_2$) for the positive electrode and natural graphite for the negative electrode. Secondly, an emergent couple of electrodes, natural graphite (LiC_6) for the negative electrode and iron phosphate for the positive electrode ($LiFePO_4$), will be studied and integrated to the multifunctional module by the Atomic Energy Commission (CEA). $LiFePO_4$ has been investigated intensively as potential positive material for lithium-ion batteries because of its high stability (even at high state of charge) and moderate cost and toxicity. The couple $LiFePO_4/FePO_4$ operates at 3.45 V vs. Li^+/Li, which makes it stable in almost all electrolytes commonly used in lithium batteries. In other words, $LiFePO_4$ becomes today one of the most attractive material for automotive and stationary applications.

So far, $LiFePO_4/C$ shows excellent performances in term of specific capacity, power, energy density and safety towards electrolyte but has to demonstrate long life capability. High density prototypes are under testing at CEA-LITEN.

C. Electronic Management System (EMS)

The basic task of an electronic management system is to ensure that optimum use is made of the energy inside the battery and that the risk of damage inflicted upon the battery is minimized [5]. This is achieved by monitoring and controlling the battery's charging and discharging. Battery management, power management and energy management define the full electronic management system. Battery management involves implementing functions that ensure optimum use of the battery. Power management involves the implementation of functions that ensure a proper distribution of power through the system and minimum power consumption by each system part. Energy management involves implementing functions that ensure that energy conversions in a system are made as efficient as possible.

Management of cell batteries and conversion chains requires the monitoring of the state of the system in maintaining healthy operational condition. For this reason an electronic management system will be implemented to reduce the continuous expense of energy storage with improvements in storage lifetime and reliability.

Due to the influence of internal battery parameters (material, design, dimension, and technology) and external battery parameters (charging and discharge rates, temperature) on the lifetime of the battery [5], an equalizing circuit on each battery cell has to be designed. Improvements of the lifetime of the battery will be observed. A protection circuit will be implemented in the battery management to overcome all security problems.

Power management will be included in the design to optimize the power consumption of the multifunctional module. The research is aimed at finding an optimum method of adequately powering all sub-systems integrated in the module.

Energy management will be designed to regulate the energy flow from the PV generator to the battery and to the load, and from the battery to the load. A charge/discharge regulator has to be placed in the module to regulate operations and improve energy management by running the battery temporarily independent of the load profile and cutting the battery off from the remaining stand-alone system.

SPECIFICATIONS OF THE MULTIFUNCTIONAL MODULE

To respond to the energy consumption in housing and other applications, the module takes into account different characteristics. The mass of the multifunctional module can not exceed 15kg (storage included) and its dimensions are equal to those of the panel. The reliability of the system should be a minimum of 15 years. The mechanical resistance of the module has to respect European standard NF EN 61646 and the robustness of the interfaces and the mechanical load should be high. Linked to climatic stress, the module should comply with the European standard NF EN 61215. Table 1 shows operating temperatures for the components.

°C	T_{Max}	$T_{Average}$	T_{Min}
Panel	+ 85	< 40	- 40
Battery	+ 60	< 30	-20
Electronic	+ 85	< 40	-40

Table 1. Operating temperature of the multifunctional module.

The objective is to obtain results complying with quality standards and predefined performances and least cost. All these specifications will be respected and will have an impact on the electronic and storage design.

SIMULATION RESULTS

The operation of the complete system is quite complex and the analysis, regarding the number of sub-systems, is a real challenge. The development and design of the system can be done by the use of modeling and simulations.

Fig. 4 gives the P_{PV} (V_{PV}) simulated characteristics of the PV generator model function of solar irradiations. Oscillations around the maximum power point validate the behavior of the simulated model.

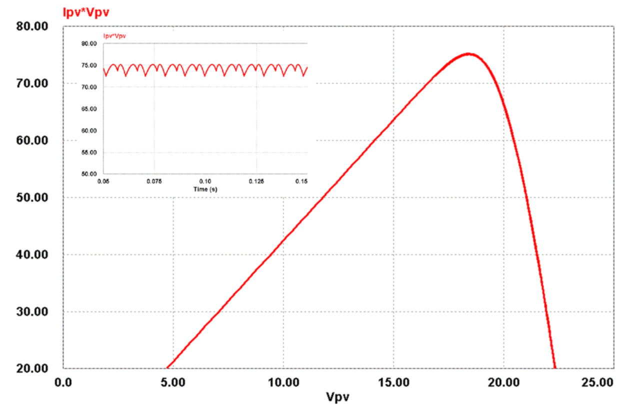

Fig. 4. Panel Characteristic $P_{PV}(V_{PV})$ and delivered power by the panel P_{PV}.

EXPERIMENTAL RESULTS

This section is focused on different examples of experimental results. Tests were realised with a prototype of a boost converter associated with a MPPT controller.

Fig. 5 presents an experimental result of the research of the maximum power point, in steady-state, when the system is submitted at a constant irradiation level, high power in this case, for a MPPT designed by LAAS.

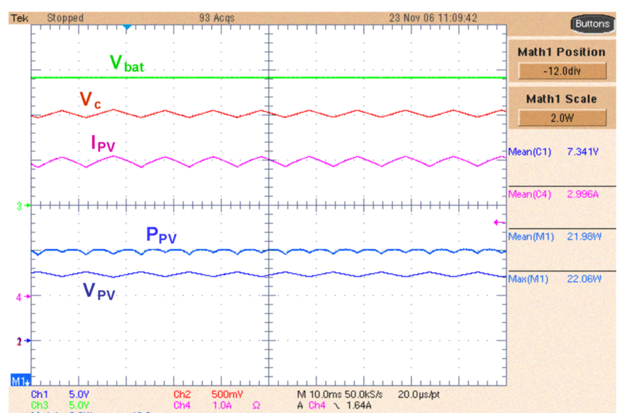

Fig. 5. Steady state behavior of PV array variables and dc-dc converter.

Fig. 6 shows the behaviour of the PV electrical variables when occurs a brutal increasing of the sun radiation. In this type of change, the PV current increases immediately. The PV voltage remains practically unchanged and then the duty cycle remains identical allowing instantaneously a new recover of the MPP. The phenomenon is the same when the PV current decreases (low sun radiation). In this type of MPPT control, the losses of efficiency are minimised during transitory.

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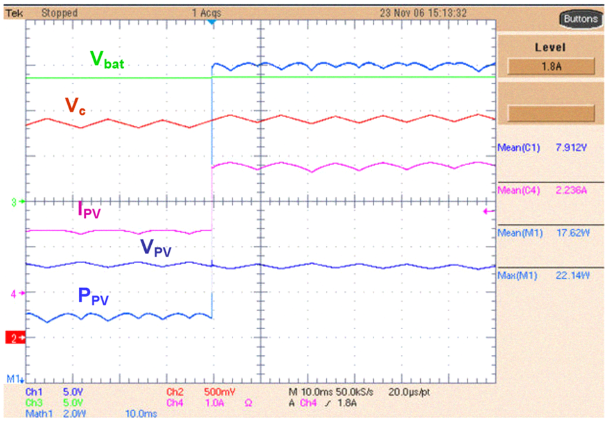

Fig. 6. Response of the system submitted to brutal increasing of solar radiation.

Finally, Fig. 7 shows a discharge characteristic of a high energy type lithium-ion battery, designed by SAFT, with different rates of discharge values. Characterization of the multifunctional module can be made using simulation and experimental results of each sub-system.

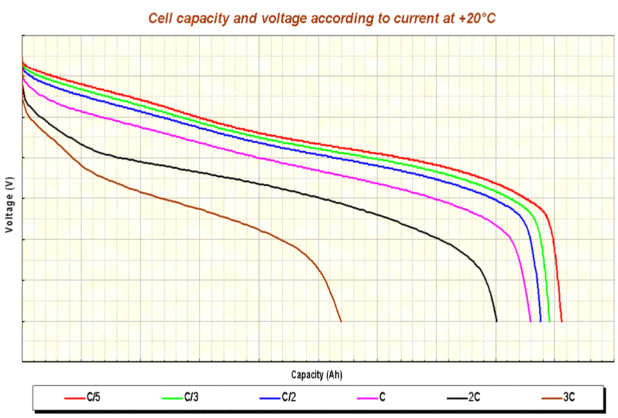

Fig. 7. Discharge voltages at different constant current and +20°C.

CONCLUSION

The overall cost of a stand-alone PV system can be reduced with new battery technologies and new control algorithms which achieve high battery lifetime and reliability, under continuously varying atmospheric conditions, which give rise to intermittent PV energy production. In this paper, a new concept of a multifunctional module has been presented, consisting of the integration of all components in one structure. Advantages of the proposed module are: (a) the MPPT controller employed in the conversion chain ensures maximum of the energy is transferred to the battery, and thus better exploitation of the PV generator is achieved; (b) the battery lifetime is increased because of the utilization of lithium-ion technology; (c) the operating management strategy is a significant approach to increase the system reliability; (d) the possibility of adapting the power easily by putting the modules in parallel.

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REFERENCES

[1] R. Kaiser, “Optimized battery-management system to improve storage lifetime in renewable energy systems”, *Journal of Power Sources* 168 (2007) 58-65.

[2] R. Leyva, C. Alonso, and A. Cid-Pastor, “MPPT of photovoltaic System using Extremum-Seeking Control,” *IEEE Aerospace and Electronic Systems*, *vol,* **42**, Jan. 2006, pp. 249-258.

[3] Cabal C., Alonso C., Cid-Pastor A., Estibals B., Seguier L., Leyva R., Schweitz G., Alzieu J., “Adaptive digital MPPT control for photovoltaic applications”, *International Symposium on Industrial Electronics (ISIE07),* June 2007 pp. 2414 – 2419.

[4] F. Mattera, “Confidential report of the Multifunctional Module Lithium-Ion project”, 2007.

[5] Johnson. A. Asumadu, M. Haque, H. Vogel, C. Willards, “Precision Battery Management System”, *Instrumentation and Measurement Technology Conference (IMTC05),* May 2005.

[6] M. Glavin, W.G.Hurley, “Battery Management System for Solar Energy Applications”, *Universities Power Engineering Conference, 2006. UPEC '06. Proceedings of the 41st International, Vol.* **1**, pp. 79-83.

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