An Optimized Electronic Device for Solar Power Harvesting Dedicated to Wireless Sensor Networks

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ABSTRACT

For economics as for practical reasons, this last decade, the use and dissemination of wireless sensor networks (WSN) became obvious; particularly in structural heath monitoring (SHM) use-cases where distances between sensors could be long and access to the structure quite difficult.

Even if efforts are leaded to design small components and RF modules that ask for low-power, the need of an external source is often necessary.

After have acquired knowledge in solar cells as in batteries technologies and methods to control charge/discharge phases as in optimizing algorithms, IFSTTAR laboratory has designed an electronic device that integrates those progress.

This electronic device has a quite generic mission: for a panel of batteries chemistry (Lithium, NiMh) and a panel of solar cells sources (frome mW to some W), the system acts as an improved battery charger whatever the load ask for power.

The system applies control algorithms based on battery capacity and chemistry profile. It also applies the MPPT (Maximum Power Point Tracking) algorithm.

At any time, battery State Of Charge (SOC) can be requested via I2C bus as well as a warning signal is output when SOC becomes critical.

Through standard pin connectors and a simple I2C interface, the system can be used by many wireless devices (sensors) that have to run autonomously. After the presentation of this system, a focus on its application on a real use-case will be given.

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INTRODUCTION

The origin of those works is leaded by previous developments or qualifications of wireless sensor networks (WSN) at IFSTTAR laboratory where most of use-cases are dedicated to Civil Engineering monitoring situations [1].

As introduced by abstract, even if strong optimizations in embedded electronic offer to electrical engineers wider possibilities to design WSN, when its energy source is limited to the one of a battery, many limitations have to be faced: battery lifespan, battery replacement (how to access the monitored structure ?), reduce of sensors computational abilities, reduce of radio frequency communications (frequency, rate, distance), etc. [2].

Thus, the bet of related works consists in designing a generic Power Manager daughter board that extract energy from solar cells as far as most SHM applications runs outdoor. That power-board should be able to ensure energy autonomy when coupled to various wireless sensor networks platforms: various voltages, various power levels, etc [1].

But the design of such a system requires to reconsider traditional electronic methods where, for example, battery charges/discharge algorithms were based on infinite DC source. Variable external sources such as photovoltaic cells or kinetic transducers, battery chemistry complexity (charge/discharges laws) have to be took into account. The result is a complex systems that has to mix many control algorithms.

POWER MANAGER BOARD DESIGN

Power Manager environment

First, the requirements for the design of the Power Manager board have been specified by identifying the context and describing the interacting entities as resumed by figure 1.

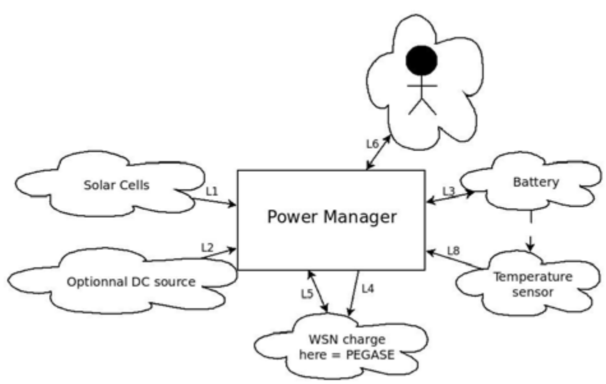

Figure 1. Power Management Board context.

Three main entities interact with Power Manager board and have to be took into account by its control algorithms: the variable input energy source, the battery, the WSN that acts as an electrical load as well as a communication item (battery level, critical threshold...).

Energy sources considerations

When expecting to make a WSN running for hours and days with an energy harvesting feature, different kinds of energy sources could be evaluated. This effervescent topic, since 10 years, is source of exponential works [3].

IFSTTAR laboratory asset some bibliography in that domain and, as many others lab, retained the photovoltaic source. Following table 1 summarizes the reasons of that choice:

Table 1. External energy sources characteristics.

Source	Characteristics
Photovoltaic	Outdoor only, enough good efficiency (~1000 W.h/m²/year in France), 30 years lifespan, cheap technology, good deterministic source
Wind turbine	Outdoor only, very good efficiency ($P = 1.18 * r^2 * s^3$ where r = ray, s = wind speed), long lifespan, big dimensions, few deterministic source, very dependent on turbine location
Kinetic transducers	Out/indoor, poor efficiency and low-power level (some mW / cm²), not a real mature technology (for WSN), very dependent on location, designed for specific spectrum of vibration frequencies
Seebeck effect transducers	Out/indoor, poor efficiency and low level power (some mW / 10°c gradient), not a real mature technology (for WSN), very dependent on location where a temperature gradient must be maintained

Choice of photovoltaic source lead to the question of solar cells dimensioning. Some abacus or free international databases can help WSN designers to envisage the size of solar cells (Example: ISPRA Joint Research Center). The parameters to input those databases typically are: location (latitude, longitude), slope angle (rad), solar cells dimensions (m²), solar cells technology that involves its efficiency (monocrystalline: 15%, polycrystalline: 11% or amorphus: 6%).

Dimensioning of solar cells is a crucial point if performed from the only static point of view: optimizations process (e.g. control algorithms and some hardware implementations carried out by the Power Manager Board) have to be added to the source to ensure charge (e.g. WSN) autonomy; solar cells cannot be plugged directly.

Energy storage considerations

The same qualification and bibliographic works have been carried out for battery technology choice [4]. The characteristics that differentiate a specific battery technology from another are well known and are directly linked to their chemistries and industrial process design. Those main characteristics are: price, energy density, auto-discharge, memory effect, temperature sensitivity, charge/discharge management (maximum current, charge speed).

The most known and spread battery technologies are: Lead, Ni-cd (Nickel Cadmium), Nimh (Nickel Metal Hybride), Li-Ion (Lithium-Ion) or Lipo (Lithium-Polymer) often found in GSM phones.

Following criteria have decided battery choice while keeping in mind the SHM outdoor conditions: wide temperature range, no memory effect, good energy density. Those criteria should avoid or minimize periodic battery replacement. Price is supposed to be compensated by the gain of wireless sensors topology.

Thus Power Manager board is specified able to control charge/discharge of NiMh and mostly LiPo batteries that are most qualified for SHM applications.

The consequence of that choice, especially for LiPo technology, is a very strict implementation charge/discharge control algorithm [4].

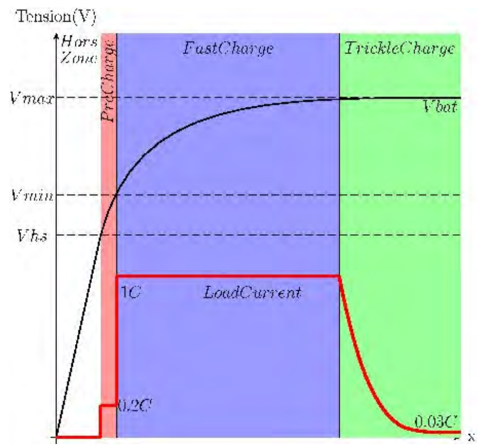

Figure 2. Charge law of Lithium-Polymer battery.

As illustrated in figure 2, contrary to NiMh chemistry [4], LiPo charge law (as discharge) that has to be controlled isn't linear. Moreover, that law depends and temperature (that shifts that curve) and LiPo battery should never over charged nor discharged; if not the destruction of internal battery elements occurs.

Control algorithms and hardware implementation

Above considerations are inputs to the specification and implementation tasks of Power Manager board project. The control solutions must take into account:

- variation of solar cells energy (day / night, during the day, during the year)
- optimization of that source (direct coupling on load is inefficient)
- NiMh and LiPo dis/charge laws
- temperature variation (that modifies dis/charge laws)

The solution consists in hardware and software implementations that are summarized below.

Hardware solution

Traditional approaches could lead to a dual hardware circuit where a boost circuit raises up voltage from solar cells and a second circuit controls battery loading. Battery law control conduct to raise or to reduce its charge power (voltage and current) depending in the State Of Charge (SOC) from Pre-Charge phase to Trickle-Charge phase (refer to Figure 2). SEPIC (Single Ended Primary Inductor Converter) circuit [5] are well suited to such process where battery voltage can be above and below that of the regulator's intended output. Well designed and dimensioned, SEPIC involves the need of a boost converter applied to solar cells and the need of a buck boost converter to control battery charging. The entire SEPIC circuit is controlled by the duty cycle of only one control transistor on which a PWM (Pulse Width Modulation) is applied like illustrated in Figure 3.

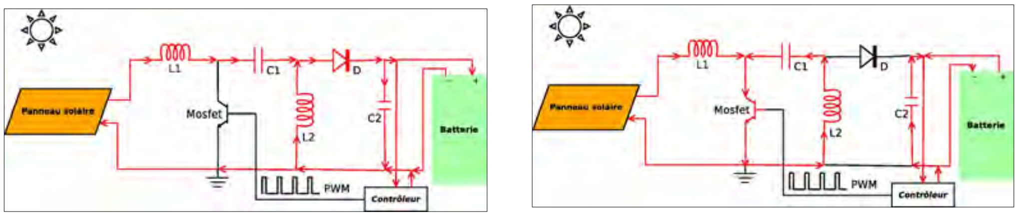

Figure 3. Synoptic of a SEPIC PWM controlled circuit.

The hardware solution also involves an external temperature sampling measure to adjust dis/charge LiPo law control.

Software solution

In addition to the hardware solution, a global control algorithm running in a very integrated small processor ensure the whole mission of the Power Management board. The algorithm is implemented in C language using automation approach; its inputs are battery law, temperature, battery SOC and state (pre-charge, fast-charge, trickle-charge). According to those values, the PWM of the SEPIC is adjusted at 180 kHz in order to set the battery state in the maximum charging mode while keeping full respect of its electrical characteristics. For example, the MPPT [5] algorithm is fully applied when battery SOC is in its Fast-charge phase.

RESULTS

The result is the designed of a Printed Circuit Board (PCB) using an Atmega168 as very low-power processor as illustrated by figure 4. It offers 8 ten bits analog to digital converters (ADC) to sample: voltage and current that input/output from battery, voltage and current that outputs from solar cells and temperature. Processor also drives the PWM that control the SEPIC circuit and hosts two debug leds.

The whole Power Management Board ask for a continuous 17 mW power and is able to manage:

- Amorphus solar cells in [0 – 24 V] range, 300 mA maximum
- Polycrystalline solar cells in [0 – 24 V] range, 350 mA maximum
- NiMh battery : 12 elements of 1.2V (14.4 V). Maximum SEPIC charge of 16.92V
- LiPo battery : 4 elements of 3.7V (14.8 V). Maximum SEPIC charge of 16.8V

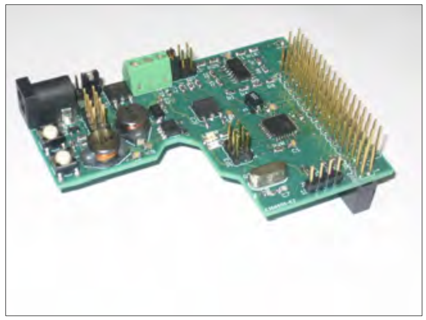

Figure 4. Power Management board designed.

Solar cells and battery dimensioning task should take into account WSN and Power Manager intrinsic power consumptions. In any SHM use-case, if possible, WSN power improvement should be brought as proposed by many methods [6].

Other specific behaviors

As an evidence, the Power Manager board has not only the mission to ensure battery charging from solar cells devices but also to provide enough energy for a specific load (e.g. a specific wireless sensor).

In order to provide the most generic propensity to be coupled to a wide variety of WSN, Power Management Board provides useful functionalities:

- by a simple set of electronic jumpers, user easily select battery mode: static NiMh configuration (14.4 V / 3200 mA.h), static LiPo configuration (14.8 V / 4200 mA.h) or dynamic configuration (parameters are received via I2C bus)
- outputs a flag that warms hosted device that critical battery SOC is exceeded
- through a standardized I2C bus and a simple protocol, wireless connected device can dynamically ask for: new power configuration, battery SOC, number of dis/charge cycles, etc.

Use of those relevant functionalities could be a source of improvements for WSN behaviors. For example, in case of battery critical SOC, it can decide to differ its wireless transmission or going in deep sleep mode, etc.

Coupling to PEGASE load, application on a real SHM use-case

In order to illustrate ideas brought by this article, the use case of PEGASE and its results are given. PEGASE is an high level wireless and generic platform specified and designed by IFSTTAR [1].

Its major hight performances are the following: use of a DSP as core processor, runs a µCLinux as embedded OS, use of a GPS module to ensure localization and UTC time-base up to some µS, implement Tcp/Ip/802.11.b wireless protocol.

Its generics attributes are: an open-source C library that cover all peripherals drivers, a plug and play concept where a simple and inexpensive daughter board is designed for specific use-case (e.g. to read a temperature sensor, an accelerometer,...).

Since 2009, PEGASE is marketed and sold through A3IP French company [7] in hundreds of samples. From customers, PEGASE can be seen as a solution device as well as a wireless development board for fast-prototyping.

IFSTTAR designed the Power Management board as an add-on daughter board that allows fully long term wireless monitoring use-cases.

As a first illustration, an industrial application can be cited : PEGASE coupled to the Power Management board and a specific daughter board that involves 6 displacement sensors was used to monitor fissure on a bridge deck. On that specific bridge illustrated in figure 5, no external energy was available and long term monitoring is wished.

The whole integration provides a useful and cheap WSN system that allows long term SHM of the above bridge near Strasbourg (France).

Figure 5. Power Management Board used with PEGASE WSN in a real SHM application.

CONCLUSION AND ROADMAP

A quite generic Power Management board has been designed by IFSTTAR laboratory and has joined the panoply of PEGASE mother and daughter wireless boards actually marketed by A3IP company [7]. Its generic behaviour allows to connect loads (e.g Wireless Sensors) that ask from some 10^{th} of mW to 0.5 W and to choose battery and solar cells characteristics (chemistry, power,...) adapted to the SHM use-case needs with reasonable dimensions.

The whole system is actually validated on a specific bridge deck monitoring but has to be qualified under other SHM conditions.

Future works should lead IFSTTAR to a new very integrated version of Power Management board as far as the very up-to-date electronic developments tend to proposed such system on chip (SOC) whose functionalities should converge to Power Management ones [8]. Related works are subject to quick evolutions as well as wireless sensors evolution tends to drastic gain in power consumption; the consequence in SHM use-cases applied to civil engineering situations should be a rapid convergence to integrated systems standardization that ensure energy harvesting, battery charging and WSN power management.

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