Smart Power Unit with Ultra Low Power Radio Trigger Capabilities for Wireless Sensor Networks

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Abstract— **This paper presents the design, implementation and characterization of an energy–efficient smart power unit for a wireless sensor network with a versatile nano-Watt wake up radio receiver. A novel Smart Power Unit has been developed featuring multi-source energy harvesting, multi-storage adaptive recharging, electrochemical fuel cell integration, radio wake-up capability and embedded intelligence. An ultra low power on board microcontroller performs maximum power point tracking (MPPT) and optimized charging of supercapacitor or Li-Ion battery at the maximum efficiency. The power unit can communicate with the supplied node via serial interface (I2C or SPI) to provide status of resources or dynamically adapt its operational parameters. The architecture is very flexible: it can host different types of harvesters (solar, wind, vibration, etc.). Also, it can be configured and controlled by using the wake-up radio to enable the design of very efficient power management techniques on the power unit or on the supplied node. Experimental results on the developed prototype demonstrate ultra-low power consumption of the power unit using the wake-up radio. In addition, the power transfer efficiency of the multi-harvester and fuel cell matches the state-of-the-art for Wireless Sensor Networks.**

Keywords: Power management circuits, Maximum Power Point, Multi energy harvesters, Solar harvester, Wind harvester, Wake-up Receiver, Radio trigger, Wireless sensor network .

I. INTRODUCTION

The developments in wireless sensor networks (WSN) technology have enabled a wider range of applications in recent years ranging from surveillance and security to structural health monitoring. The clear advantages of using WSNs which include greater safety, and reduced maintenance cost have increased the demand for even more pervasive and sophisticated monitoring tools. However, the vast majority of sensor nodes are powered by batteries with limited capacity. Even though there are great advancements in the low power electronic circuit design (including data acquisition, signal processing and data communication), high energy density storage devices and optimized power-aware network protocols are still desirable and badly needed.

Since wireless sensor nodes, are mostly used in outdoor settings, the energy can be harvested from environmental sources such as sunlight, wind, vibration, water flow, etc. This characteristic can be exploited to increase the network lifetime. Harvesting this energy efficiently is important to reduce the node form factor and reduce the cost of deployment and maintenance. For this reason maximum power point tracking (MPPT) [1] and power management is a key feature of the sensor node power unit. Finally, the opportunity to take energy from a high density storage such as Fuel Cells (FC) [4] may be exploited. FC is an electrochemical device that uses fuel (i.e. Hydrogen) to generate electrical power. This is a novel option for recharging the other storage units when they are depleted and environmental energy is not readily available.

At the same time, the usage of the low duty cycle data acquisition and sleep-wake up protocol can considerably increase the lifetime of a node [2][3]. As a sensor node can be supplied for only few hours at 100% duty cycle, these optimisation techniques are essential. An option is to use an adaptive duty cycle to increase the acquisition rate only if there is some interesting event, such as value is over, or under a given threshold [2]. The wake-up radio receiver circuit can efficiently wake up the node when such a request is sent from a remote host. Ultra low power radio wake up receiver can reduce the power consumption of the system while still keeping its response time low. Another role of the wake-up radio is that based on network intelligence to select a specific harvester unit to be used at a given time in order to maximize efficiency.

Therefore, flexible, energy efficient multi-harvesters and power management techniques are the key ingredients to increase the lifetime of the node and hence the network to prolonged durations (more than a year time), and ultimately, to achieve the energy sustainability. In addition, many other system design issues require the consideration of small form factor, output voltage level monitoring, capacity of the energy storage, cost efficiency and *plug and play* functionality.

In this paper we present the design and implementation of a novel multi-harvester power unit with radio-trigger capabilities that addresses the above mentioned features. The power unit has been designed to be energy efficient and flexible by using different energy sources and power management policies. Another novel feature is the possibility to exchange information such as power resources and radio trigger address and command with the supplied node to extend the power management capabilities. To achieve that, we

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designed the power unit around the ultra low power microcontroller MSP430 from Texas Instruments (TI), which is enabled to control and monitor the multi harvesting units, the radio trigger, fuel cells and the storage units. Moreover, the microcontroller provides an advanced interface to communicate with the supplied sensor platform.

Since the power unit has a dedicated microcontroller, it can perform MPPT, power management and monitoring of the energy resources directly on board without waking up the main processor. This approach can increase the lifetime of the platform and the power efficiency in the WSN scenario where the main node spends most of time in the sleep mode.

Finally, since the power unit is a stand-alone smart unit (due to the on-board microcontroller), the power unit can be connected as ‘plug and play'. Therefore, the sensors without the power management algorithms can be powered efficiently, without the need for reprogramming or modification of the hardware.

The rest of paper is organized as follows. Section II describes the related work. Section III presents the power unit architecture. Experimental results are shown in section IV. Finally Section V makes concluding remarks.

II. RELATED WORK

Since the vast majority of current WSN platforms are energy constrained, where batteries are the energy supply, the research work on power unit with energy harvesters and techniques for reduction of power consumption is becoming very popular [2][3][5]. Many examples exist, where renewable energy harvesting from the ambient environment is used to extend the lifetime of miniature low power wireless sensor nodes/network (WSN). However, to the best of our knowledge, the power units with radio trigger capabilities are still not reported in the literature.

The literature related to power supply for wireless sensor networks concerns the use of energy harvesters and various storage devices such as batteries (commonly Li-ion, rechargeable) and super-capacitors [3]. Energy harvesting (EH) systems can be categorized by energy storage devices and the types of ambient power sources.

Considering various ambient power sources, the most commonly used harvesters are photovoltaic, wind turbines or mechanical energy harvesting from vibrations or strain [3][5][6][7][8][9]. It is to notice that very few projects have incorporated multiple energy sources in a single power unit, or platform. The system in [8] describes a reconfigurable energy subsystem for WSN, inclusive of solar and vibration energy scavenging with Li-ion rechargeable batteries and super-capacitor for storage. One of its main features is the flexibility and the option to select and fit the node *in* situ, in a Plug-and-Play manner.

The Ambimax system [6] is a viable alternative, combining energy harvesting from wind and solar sources, again using batteries and super capacitors for storage. This system has the added value of being able to perform maximum power point tracking (MPPT). In [9], Kheng and Panda present a hybrid device with indoor light and thermal energy harvesting. This architecture is very similar to our power unit which has the additional MSP430 to perform MPPT. However, in [12], there is no possibility to recharge Li-ion batteries or use the fuel cell. In addition, the system only supplies the nodes without any means to exchange status information such as the power unit presented in this paper. Finally, in [7] the authors present a power unit with three energy scavengers used to recharge NiMh batteries. The limitation here is that the storage pack cannot be changed and the power unit provides very little information relating to the status of its constituent components.

Further to the aforementioned storage mechanisms, electro-chemical fuel cell (FC) technologies, that use fuel (i.e. hydrogen) to generate electrical power, are being considered due to their higher energy densities (comparable with batteries). In [4], the authors describe a fuel cell and a battery hybrid (FC-Bh) system for use in portable microelectronic systems, also characterizing and analyzing the performance of the system.

The basic need for a wake up receiver is to have a dedicated circuit that can continuously listen to a wireless channel and trigger events without any latency, consuming significantly less power than the regular transceiver. This increases network flexibility and reduces the overall power consumption. Some advantages of wake up radio were presented in [13] where it was estimated that a specialized radio interface could consume as little energy as 1μW. Our radio design [18] is a fully featured wake-up receiver with only 300nW (@3.3V) power consumption. The receiver has an address and command capabilities and is connected to the power unit through the SPI interface.

III. SMART POWER UNIT ARCHITECTURE

We present a first prototype of a smart power unit which hosts energy harvesters, fuel cells, microcontroller and a nano-Watt radio wake up receiver (Figure 1).

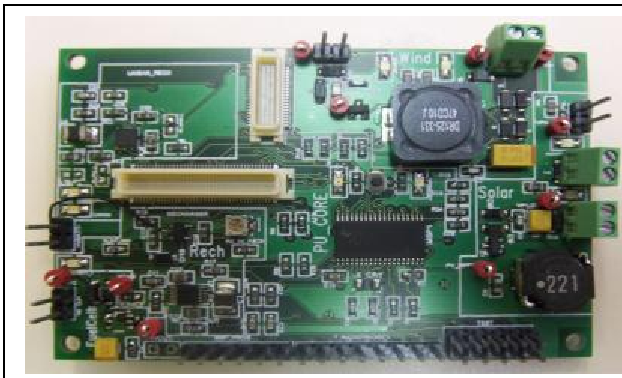

Figure 1 Prototype of power unit and radio trigger board.

The prototype has been developed to be the energy controller and supplier system with the wake up subsystem connected through an SPI interface [19]. Moreover, a common interface to the node provides the supply energy, GPIOs, SPI and I^2C (Figure 2). Due to this interface, in addition to get the required energy, the main node can communicate with the power unit in order to increase the battery life performing power management policies such as changing the duty cycle parameters or sleep/wake up techniques or selectively choosing the harvester unit based on the network's intelligence.

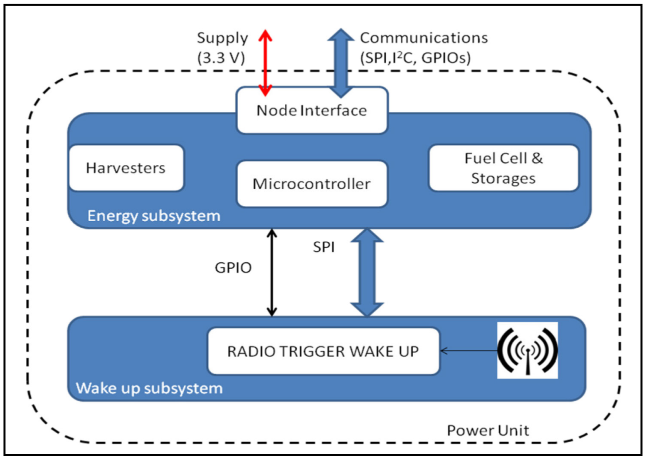

Figure 2 Block diagram of the power unit. The wake up subsystem can receive the events to wake up the power unit microcontroller. The Energy subsystem is based on a MSP430 MCU, capable of providing real-time power information, enabling true energy awareness.

The power unit is described as "smart" because it has been designed to provide advanced features, and the possibility to control and optimize operating parameters in the field. In particular it is possible to monitor the current state of the harvesters, batteries and micro fuel-cells. Furthermore, it is possible to change the operating frequency used by internal DC/DC converters and chargers. Moreover the major advantage of the radio trigger wake up receiver in our approach is that the on board microcontroller can directly control the data and wake up the main node only if when is needed.

The detailed architecture of the two subsystems is described in the two following subsections.

A. Multi harvester power unit

Figure 3 illustrates the architecture of the Energy subsystem and the interfaces. It is capable of hosting various environmental sources and storage (1/2 batteries, 1/2 supercapacitors and FC) and a nano-power radio wake up receiver. The power unit uses the TI MSP430F2274 microcontroller, a 16-bit ultra-low power microcontroller, with 32KB flash, 1KB RAM, 10-bit ADC, 2 op-amp and 2 Universal serial communicator interfaces. This device is chosen due to its ultra-low power consumption, it has the necessary ADC and peripherals for the microcontroller. It can select the adequate power resources to guarantee the best power efficiency and can interact with the supplied devices to improve the power management on both sides (power unit and supplied platform). The MCU executes programmable power management policies, and provides the required flexibility and energy awareness, considering the node may be deployed in various locations with varying environmental power availability. The SPI port and GPIO is used to connect the wake up receiver unit. The Smart Power Unit provides the following features:

- *Wake up radio trigger*. The microcontroller uses the GPIO connected to the wake up radio as an external wake up trigger, and the SPI port to read data from the radio. This capability can reduce the power consumption by waking up the main node with false alarms.
- *Dynamic Maximum Power Point Tracking (MPPT)*. The power unit can decide to disable or to activate this feature. The presence of such a circuit is justified only if the power consumed to perform a Tracking of the Maximum power point is significantly less than the gained by MPPT on the energy transducer.

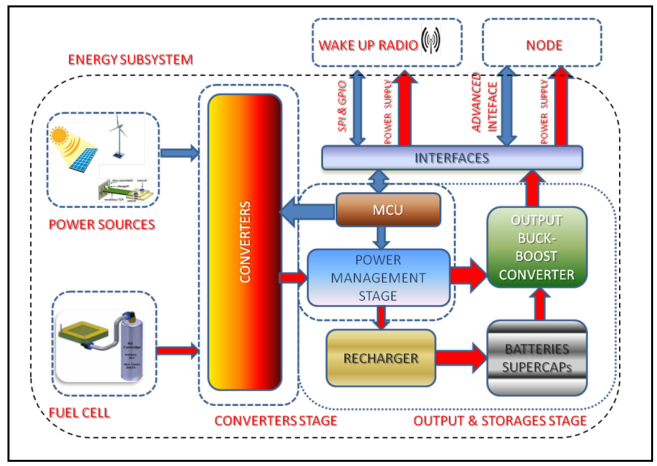

Figure 3 Energy subsystem architecture –The subsytem supply node and wake up unit with 3.3Voltage. In addiction the interface to the radio trigger is done using SPI and GPIO. The node has I^{2}C and two GPIO to enable communication and interrupts, respectively.)

- *Dynamic selection of the energy source used to recharge the reservoirs and supply the node.*
- *Dynamic alteration of the operating frequency and duty cycle.* This capability serves to increase the energy conversion efficiency of the power unit.
- *Dynamic selection of storage*. In order to increase the efficiency of the power unit and extend the lifetime of the batteries, which are usually limited to a few hundred charge cycles, the power unit can host two batteries and select one for discharging and one for charging, alternatively selecting the super capacitor. The selection depends on storage and the policy implemented for the specific application.

1) Harvesters

Although there are different types of energy harvesters, solar energy is the most efficient natural energy source available for sensor networks in outdoor applications. At 12.00am on a sunny day, the incident light on the Earth's surface has a power density of approximately 100 mW/cm^2. Other sources are mechanical (vibration or wind) and thermal energy. Since our typical deployment scenario is outdoors, we developed the prototype with solar and wind harvesters.

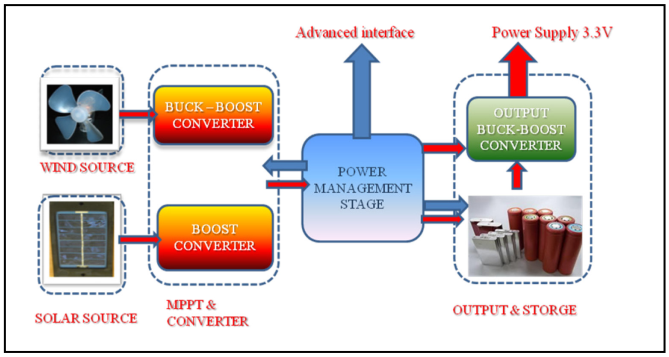

Figure 4 Harvester architecture – Photovoltaic and wind harvesters are hosted on the prototype

The block diagram of a harvester is presented in Figure 4. Although this model presents two transducers, the figure shows the modularity of the architecture. It allows an array of transducers (in this case a photovoltaic cell and a micro wind turbine). In our prototype we used the same architecture of our older work with solar and wind energy [10][12]. The novelty in this work is of having both harvesters on the same board together with a dedicated microcontroller. Each transducer is associated to the relative conversion and the MPPT circuit that powers the output and energy-storing stage through a suitable switching policy between the sources. As the figure shows, there are four main blocks: the transducers (solar and wind sources), the converter MPPT stage, the output/storage stage and finally the power management stage. The transducers harvest the energy from the environment converting it to electrical power. The MPPT and the converters use this energy to recharge batteries or supply the devices. Finally, the power management stage controlled by a microcontroller changes the parameters (i.e. MPPT) of the other stages to optimize the use of incoming energy. Moreover, this stage provides information about the status of monitored parameters (i.e. battery level).

2) Storage

An energy storage system is an energy reservoir which can store energy and supply it when necessary. Energy reservoirs are defined by two key parameters: the energy density and the power density. The energy density is a term used for the amount of energy stored in a given system or region of space per unit volume. The power density is the amount of power (time rate of energy transfer) per unit volume. Ideally an energy reservoir should offer both a high energy and a high power density. A typical energy reservoir, such as a battery, features high energy density, but a limited power density, whereas new components, such as super capacitors, offer low energy and high power density. Novel kind of storage for WSNs is presented in form of thin film lithium-ion batteries. As the energy reservoirs are concerned, it is clear that Li-Ion batteries and super capacitors (at a micro- or macro-scale) remain the dominant technology in wireless sensor networks. Our power unit hosts both of them.

3) Fuel cell(FC)

FC is an electrochemical device that uses fuel (i.e. Hydrogen) to generate electrical power. FC has a very high energy density, compared to batteries. However the FC cannot respond to sudden changes in the load. Therefore, a system powered solely by the FC is not viable. For this problem, a hybrid system, where the FC is used to recharge conventional batteries or a super capacitor, is a solution. In our power unit, we use the fuel cell as the ultimate energy source to recharge the battery and supply the system when the environmental sources are not sufficient and the battery level is low.

The activation of the fuel cell is driven from the microcontroller, which can switch it on depending on the implemented policy. As shown in Figure 5, the fuel cell output is connected to the recharger and the output stage. The choice to use the fuel cell just as ultimate energy source is because the FC cannot be recharged automatically, like the batteries. For the FC, the fuel has to be manually recharged. However we take the advantage of very high energy density of fuel cell and use it only when it is absolutely necessary. Although the power unit will be designed and tuned to be autonomous with the energy harvested from environmental source, the fuel cell is used for critical situations when the shortage of environmental energy is longer than expected.

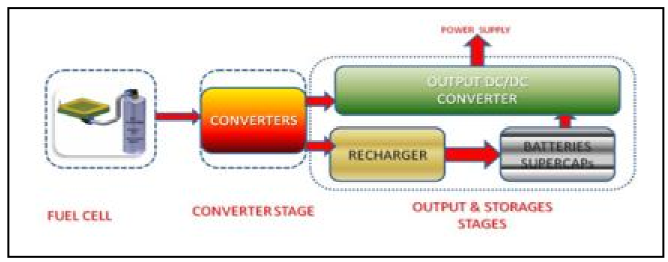

Figure 5 Fuel cell architecture. The activation of fuel cell is driven from microcontroller

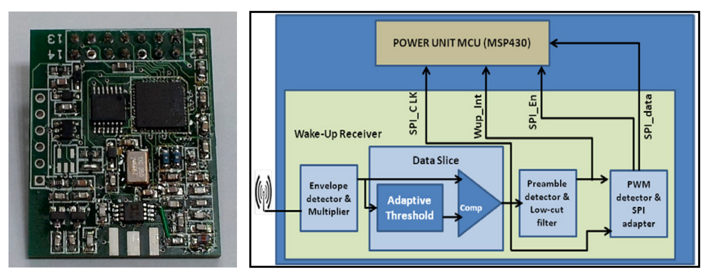

Figure 6 Radio wake up reciever, PCB and archietecture with power unit MCU SPI connection

B. Radio Trigger

In order to increase the flexibility and introduce the possibility to remotely control the advanced power management policies, we included in the design of our power unit a nano-Watt wake up receiver [18]. The wake up radio (WUR) is directly connected to the on board MCU through an SPI interface. The MCU can evaluate the event and adapt itself or send the wake up to the main node. This approach on one hand can reduce the false alarms and consequently, the power consumption due to unnecessary wake-ups of the main node. On the other hand, the network can use the ultra low power radio receiver to control and/or configure the power unit in an asynchronous fashion.

Figure 6 shows the architecture of the wake up receiver and the connection to the power unit microcontroller. The WUR detects the preamble (wake up signal), generates the interrupt (WUp-Int) which then wakes up the MSP430 from power down mode (LPM4.5) to Low Power Mode 3 (LPM3), to read the demodulated wake up packet as a digital stream on the SPI. Once the correct address is decoded, the power unit is woken up.

IV. Experimental results

In order to evaluate the performance of the approach the prototyped platform has been evaluated experimentally with respect to operational power consumption and the energy efficiency.

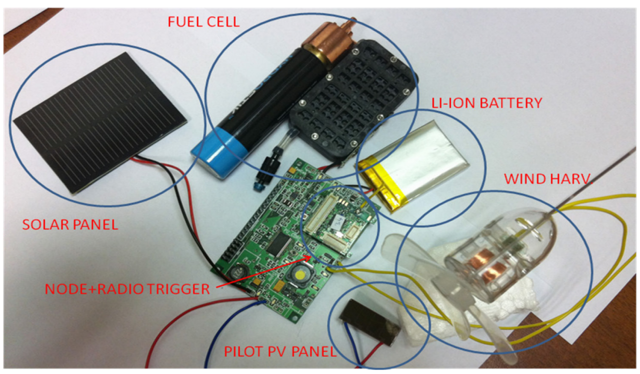

Figure 7 Fully integrated prototype with solar and pilot panel, wind harvester and fuel cell

TABLE I. Power consumption

Devices	Consumption (3.3V)	
	Active	Sleep
Wake up radio	300nW	300nW
MCU SPU (1Mhz)	1.29mW	5uW

Power consumption. The MCU of smart power unit was clocked at 1Mhz.

TABLE I. shows the power consumption of the on-board microcontroller and the wake up radio. The active time of MCU depends on the power management policy and firmware implemented. However the power consumption is very low both in active mode and in sleep mode. The time needed to perform the MPPT of both wind and solar harvesters is only a few milliseconds. For this reason in the typical scenario the MCU spends most of time sleeping and is woken up by internal clock or an external event (i.e. through the wake up radio).

To evaluate the performance of solar harvesting, a 112cm^2 PV module (max 450mW) was used, with an irradiation that forces the solar cell to produce about 50mW. A measure of the board efficiency with MPPT recharging both a super capacitor and Li-Ion batteries was taken.

A plastic four-bladed horizontal-axis wind turbine, with a diameter of 6.3cm with a max 10mW output has been used as wind generator. To evaluate the performance the same assumption as in previous work was used [10].

TABLE II. Energy Sources

Sources	Performance	
	Max Power	Efficiency
Solar (Li-Ion Battery)	450mW	82%
Solar (SuperCap)	450mW	75%
Wind (SuperCap)	10mW	85%
FC (Li-Ion Battery)	1W (recharging limit @ 200mA)	80%

Performance of harvesters and Fuel cell. The efficiency was evaluated measuring the power (V*I) of the input source and the power transferred to the energy storage. Thus the efficiency counts both energy lost by converter stages and by SPU MCU.

Although the power unit provides the possibility to recharge batteries from wind sources, the measurement recharging only a 50F super capacitor was performed due to the small output.

Finally, to evaluate the performance of recharging batteries from the fuel cell, the industrial MiniPAK from Horizon was used [11]. The output of this device is 2W (5V, 400mA). This device can host a solid state hydrogen cartridge, called HYDROSTICK, which provides about 12Wh of energy. Measurements have been performed, setting 200mA as max recharging current, because it is a correct trade-off between stability of the FC and time to recharge the battery (about 3 hours for 800mAh). In this case, the efficiency is calculated as the ratio of the power discharged by the MiniPAK over the power supplied to the battery.

TABLE II details the power provided from different sources. The energy lost through converter circuits is considered, and included in the efficiency of single harvesting. The efficiency is evaluated by measuring the power (V*I) of source at the input of the power unit and the power transferred to the energy storage. Therefore, the efficiency accounts for both the energy lost from converter stages and the energy lost from SPU MCU. In order to measure the current generated by harvesting sources (Solar, Wind) and FC, as well as the current supplied (battery and super capacitor), we used a 0.25ohm shunt resistor and measured the voltage drop across the shunt. We acquired and stored the data using LabVIEW from National Instruments and the DAQ NI-USB-6210 acquisition board. Finally, we used MATLAB to plot the voltage, current, power data and elaborate the average efficiency. Figure 8 shows an example recharging the Li-Ion battery with the Fuel cell.

V. Conclusions

In this paper we presented the design and implementation of a smart and versatile power unit that is able to harvest energy from different sources and fuel cells. The smart power unit stores energy in both super capacitors and Li-Ion battery. The power unit considers the flexibility of multi harvesting and the MCU on board the power unit has ultra low power radio wake up capabilities. These features allow the board to perform MPPT to improve the efficiency of the energy harvesting process and increase the possibility to use power management policy by using the communication with the node and using the radio wake up receiver. The power unit allows novel research directions to be undertaken in terms of energy-aware protocol design, and opportunistic sampling and networking for WSN, among others.

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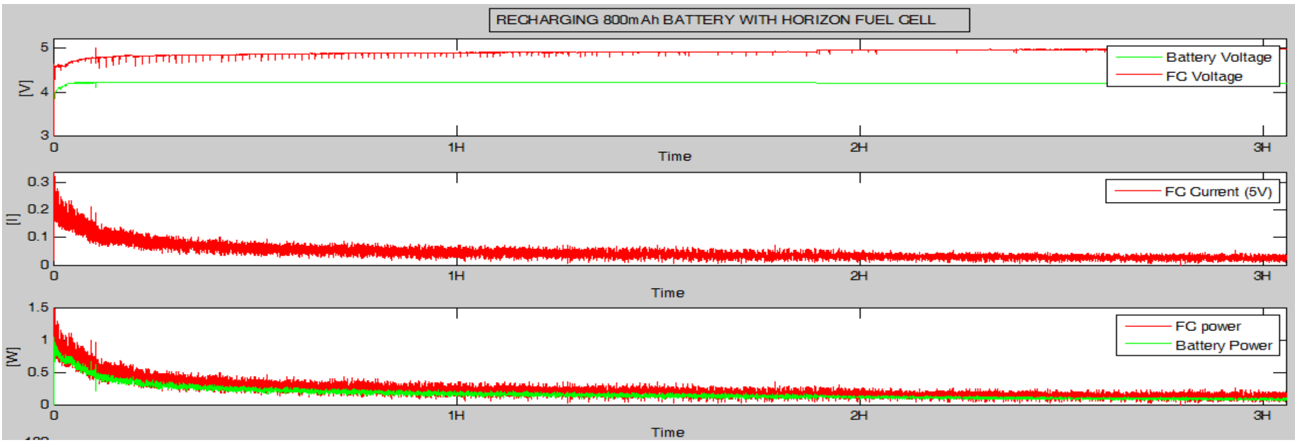

Figure 8 Voltage, Current and Power in time recharging a 800mHA Li-Ion battery with the fuel cell.

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