

An Effective Multi-Source Energy Harvester for Low Power Applications

Davide Carli^{*}, Davide Brunelli[†], Luca Benini[‡] and Massimiliano Ruggeri[§]

^{*}ENDIF, University of Ferrara, via Saragat 1, Ferrara, Italy. Email: davide.carli@unife.it

[†]DISI, University of Trento, via Sommarive 14, Povo, Trento, Italy. Email: davide.brunelli@disi.unitn.it

[‡]DEIS, University of Bologna, viale Risorgimento 2, Bologna, Italy. Email: luca.benini@unibo.it

[§]IMAMOTER, National Research Council, via Canal Bianco 28, Ferrara, Italy. Email: m.ruggeri@imamoter.cnr.it

Abstract—Small autonomous embedded systems powered by means of energy harvesting techniques, have gained momentum in industry and research. This paper presents a simple, yet effective and complete energy harvesting solution which permits the exploitation of an arbitrary number of ambient energy sources. The proposed modular architecture collects energy from each of the connected harvesting subsystems in a concurrent and independent way. The possibility of connecting a lithium-ion or nickel-metal hydride rechargeable battery protects the system against long periods of ambient energy shortage and improves its overall dependability. The simple, fully analogue design of the power management and battery monitoring circuits minimizes the component count and the parasitic consumption of the harvester. The numerical simulation of the system behavior allows an in-depth analysis of its operation under different environmental conditions and validates the effectiveness of the design.

I. INTRODUCTION

The increasing attractiveness of computing and sensing solutions able to operate on-the-go (portable) or scattered across a certain area (spatially distributed), has fostered research activity on the issues related to power supply and autonomy. At the present time, batteries are the most widespread powering strategy for this kind of devices. However, this solution has some limitations, as it requires the periodic recharge or replacement of the batteries due to their leakage and aging. In some applications, such as monitoring using wireless sensor nodes deployed in hard to reach locations, maintenance can be rather difficult and expensive.

Among the solutions proposed to limit the impact of these battery-related issues or to completely overcome them, the idea of getting the energy needed to power the desired device directly from its operating environment has been regarded as one of the most promising. Over the last years an increasing number of researches have worked in this direction. This innovative powering strategy, commonly known as *energy harvesting*, intends to convert different forms of energy available in the environment (e.g. solar radiation, vibrations, etc.) to electrical energy, and to use it to fully or partially supply a low-power electronic system.

An energy harvester can be considered as an interface between one or several energy suppliers (the renewable ambient

energy sources) and one or several energy consumers or loads, i.e. the systems to be powered. The real challenge in the design of energy harvesting systems is to provide a continuous and stable power supply to the load in spite of the adverse availability characteristics of the energy sources (often uneven and unpredictable [1]), while keeping at the same time the harvester size and cost as low as possible.

The key design goals which should be considered to implement an effective energy harvester are principally two:

1) it should perform the end-to-end power transfer (from the energy sources to the load) with the maximum possible efficiency, i.e. losing the least possible amount of energy along the path. This requirement poses the following issues: (a) each device performing the conversion of a certain kind of ambient energy to electrical energy should be always kept operating at its maximum conversion efficiency, with the aid of an expressly designed maximum-power-point tracking (MPPT) circuit, (b) the circuits which convey the power from a section of the system to another one (e.g. DC/DC converters) should lose the least possible amount of energy during the transfer, and (c) the power consumption of the harvester control circuitry should be negligible when compared to the power delivered to the load;

2) it should act as a buffer between the variable power consumption of the final system and the wide dynamic range of the ambient sources. This requires the harvester to store the collected energy in devices working as energy reservoirs, to be filled as much as possible when the ambient sources are available and to be slowly emptied to power the load when they are not. Supercapacitors and rechargeable batteries are usually used for this purpose. The absence of predefined charge and discharge profiles and thus their higher power density, the possibility of precisely estimating the state-of-charge from the voltage across them, and their high maximum recharging cycle life time, make the supercapacitors the best choice for this task [2]. However, when compared to batteries, they still provide a much lower energy density: this can be a limiting factor if the harvester is expected to continue powering the load even during long periods of ambient energy shortage.

This paper presents a multi-source, multi-storage energy harvesting architecture expressly designed to achieve autonomous operation and to constitute a dependable power source for low power applications (< 100 mW). The proposed

The work presented in this paper has been supported by the ArtistDesign Network of Excellence (IST-2007-214373) and by the GENESI Project (Grant agreement n. 257916) funded by the EU 7th Framework Programme.

architecture is highly modular, supercapacitor-based and supports an arbitrary number of energy harvesting subsystems which can also be hot-plugged. The exploitation of several ambient energy sources in a concurrent and autonomous way improves the system reliability by reducing its dependence on the availability changes of each energy source. During sustained periods of ambient energy shortage, the system operativeness is guaranteed by the presence of a nickel-metal hydride (NiMH) or lithium-ion (Li-ion) rechargeable battery. The power management circuit is designed to protect both battery types from overcharging and undercharging conditions, and when the battery intervention is required its energy is drawn in a pulsed way: a strategy that helps prolonging the battery autonomy [3]. Besides its flexibility and dependability, the implementation is fully analogue and requires relatively few ultra-low-power components: this minimizes the power consumption of the harvesting system itself, as well as its cost. An energy harvester implementing the proposed architecture will be presented as well. It is targeted at stationary outdoor applications, and thus features two harvesting subsystems which collect the energy provided by wind flow and solar radiation. To simulate the system behaviour and to plan its deployment in a particular site, a useful design framework has been implemented in Matlab simulation environment: the results of a simulation are discussed at the end of the paper.

II. RELATED WORKS

While energy harvesting from a single energy source has been often investigated (see [4] for a comprehensive and up-to-date survey), there are fewer works dealing with the issue of energy collection from several sources at the same time and aimed at powering an electronic system with small average power requirements (around 100 mW or below).

A well-known multi-source energy harvester is Ambi-max [5]. It is targeted to power a wireless sensor network (WSN) node in an outdoor environment, and relies on solar radiation and wind flow to collect the needed energy. As in our case, the system architecture is rather modular, thanks to a diode-based power ORing strategy. It includes a Li-ion battery as well, performing as backup energy reservoir: however, the continuous connection of the battery to the load during long periods of ambient energy shortage is not optimal, because a pulsed absorption from the battery (like the one implemented in our system) helps prolonging the battery autonomy [3].

Another work addressing WSN nodes in an outdoor environment is [6]. Both solar radiation and wind flow are exploited by this system too, but also the energy coming from water flow is harvested. The energy flow from each energy harvesting subsystem to the battery is controlled by a microcontroller: this brings some advantages, like the possibility of performing periodically a complete charge-discharge cycle to recover the battery after a high number of incomplete ones, but has a negative impact on the system modularity. To add another energy harvesting subsystem, for example, the software run by the microcontroller needs to be updated, and additional control signals must be available.

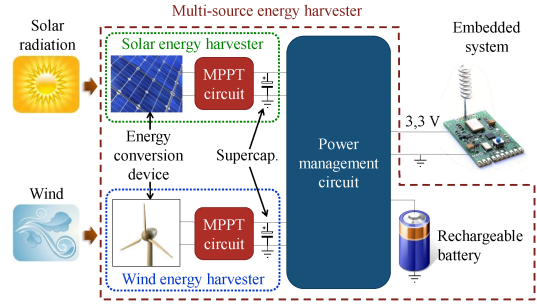


Figure 1. Architecture of the multi-source energy harvester.

With regard to the architecture of the power management subsystem, two more works are worth to mention. The first one is presented in [7]: it is still at an early development stage, but contains an interesting idea. The authors of this work propose a multi-source, multi-storage and multi-load energy harvesting architecture based on a single multiple-input and multiple-output DC/DC converter, which automatically collects the energy from the sources and redistributes it among the storage devices and the loads. From a theoretical point of view the system is promising, however the only implementation by the authors relies on an externally powered FPGA: this setup prevents the identification of any possible implementation issue and an analysis on the actual power consumption due to the harvesting system itself.

The second one is the work presented in [8]. Although this harvester relies only on the energy coming from the solar radiation, its storage subsystem features three supercapacitors, to improve the system reliability during the cold booting phase. Here the power path is dynamically managed by a set of MOSFETs, driven by a microcontroller-based control circuit. The MOSFET-based power ORing solution ensures the minimization of the parasitic power consumption along the power path. However, the whole system is quite complex and features also redundant blocks (like four DC/DC converters) which affect considerably power consumption and cost.

Finally, we report the existence of a commercial multi-source energy harvester, the EH-LinkTM by MicroStrain, Inc. [9]. It is able to interface with several types of electrical generators (e.g. from vibrations, temperature differences, etc.), but the technical information disclosed by the manufacturer are too few to enable a fair comparison with the works mentioned above. However, at the moment the number of inputs is limited to three, and cannot be extended; besides, it does not seem possible to use the harvesting capabilities of the system for purposes different from the powering of the wireless node integrated in the system.

III. SYSTEM ARCHITECTURE

The architecture of the proposed multi-source energy harvesting system is depicted in Fig. 1.

A. Energy harvesting subsystems

The energy harvesters at the first stage of the system provide the capability to convert certain kinds of ambient energy to

electrical energy, and to store it temporarily for future usage. Although Fig. 1 shows just two energy harvesting subsystems, the proposed architecture supports an arbitrary number of energy harvesters, which can all be connected to the power management circuit in a very straightforward manner, which will be detailed in the following sections.

Each harvester can usually be modeled with the following components: (1) a device performing the conversion from a particular kind of energy (kinetic, electromagnetic, thermal, etc.) to electrical energy; (2) a circuit which adjusts dynamically the operational parameters of the conversion device in response to the variations of the available energy level, in order to let it convert the maximum possible amount of power in every condition; (3) a device which stores the collected electrical energy.

With regard to stationary outdoor applications, the ones we are interested in, the energy sources most suited to be harnessed are solar radiation and wind, because of their wide availability and high power density [10]. These two sources, besides their property of being renewable, are also complementary to some extent: strong winds occur more frequently during night-time or when the weather is bad, than in sunny days [11]. For these reason, we have chosen to exploit these two ambient energy sources: this choice is in line with works [5], [6] already recalled in Section II.

For the design, the development and the subsequent numerical simulation of the system we considered as reference energy harvesters the two systems presented in [12] and [13]. The first one is a highly optimized solar energy harvester. It relies on a small size photovoltaic (PV) panel with an area of just 112 cm^2 . The PV panel conversion efficiency is kept as high as possible at any time by a clever MPPT circuit (thoroughly addressed in [14]), which is self-powered by a pilot cell: this allows the harvester to cold boot, i.e. to start working even when the output supercapacitor is empty. The second one is a tiny wind energy harvester, with an overall volume below 300 cm^3 . The wind flow kinetic energy is converted to electrical energy by means of a horizontal-axis wind turbine with a diameter of 6.3 cm . The DC/DC which transfers the energy from the wind generator to the output supercapacitor is expressly driven so that its input resistance remains equal to the value which maximizes the wind generator conversion efficiency. The fully analogue control circuitry powers itself off during the periods of wind absence, keeping the harvester static consumption as low as possible.

B. Power management circuit

Through a simple diode-based power ORing strategy, the energy harvesting subsystems operate independently of each other: this also permits to hot-plug additional harvesting subsystems without the need of reconfiguring anything. Still, they can contribute at the same time, all together, to the replenishment of the system energy reservoirs. The main reservoir is a supercapacitor, while the second, optional, is a rechargeable battery. Both NiMH and Li-ion batteries are supported by the overcharge and undercharge protection cir-

cuits: however, the charge-discharge profile of NiMH batteries is best suited to the proposed battery control circuit. When the ambient sources provide more power than required by the load, part of the energy stored in the main reservoir is used to recharge the battery. The battery energy is used only when the charge of the main reservoir falls below an adjustable threshold. The embedded system is powered by a buck-boost DC/DC converter, providing a stable output voltage of 3.3 V . The input of the DC/DC is directly connected to the main reservoir. To protect the battery from reaching an undercharging condition, the final DC/DC converter and thus the system are shutdown when the battery voltage falls below an adjustable threshold.

IV. POWER MANAGEMENT POLICY

A functional scheme of the power management circuit is shown in Fig. 2. It should be noted that this diagram is a simplified version of the actual schematic of the circuit: as indicated in the lower part of the figure, many of the used symbols represent the functionality of more complex sub-circuits. This choice has been made to simplify the comprehension of the high level operation of the circuit, without diverting the reader's attention with negligible implementation details. The sub-circuits U_1 , U_2 , U_3 , and U_4 are based on an ultra-low-power comparator, the LTC1440 by Linear Technology; the reference included in this device has been employed to generate the desired threshold voltages V_{oc} , V_{uc} , and V_i , as well as to adjust the hysteresis of the comparator circuit. The logic functions performed by U_5 and U_6 have been implemented through low power, CMOS-based logic gates: in the context of Fig. 2, they both operate as AND gates. The symbol associated to U_7 and U_8 represents a circuit operating as a monostable multivibrator. Finally, the switch S_1 has been implemented with an integrated programmable current-limiting switch, while a properly sized, low on-resistance MOSFET implements S_2 .

The supercapacitor C_0 plays a key role in the proposed architecture: it works as the energy buffer from which the final DC/DC U_9 draws the energy to power the load. Every energy flow present inside the whole energy harvester, goes through this supercapacitor: (i) the one coming from the connected harvesting subsystems, (ii) the one coming from the battery when the environment does not provide a sufficient amount of energy, (iii) the one recharging the battery when the environment provides overabundant power, and finally (iv) the one which actually supplies the load, through the buck-boost converter U_9 .

A. Interface with the harvesting subsystems

The power management circuit interfaces to the several energy harvesting subsystems with the diode-based power ORing solution shown on the left of Fig. 2. This kind of connection ensures that C_0 is always charged by the harvesting subsystem with the highest output voltage and the presence of a diode on each line prevents the exchange of energy between different harvesting subsystems, and makes each of them completely independent from the others.

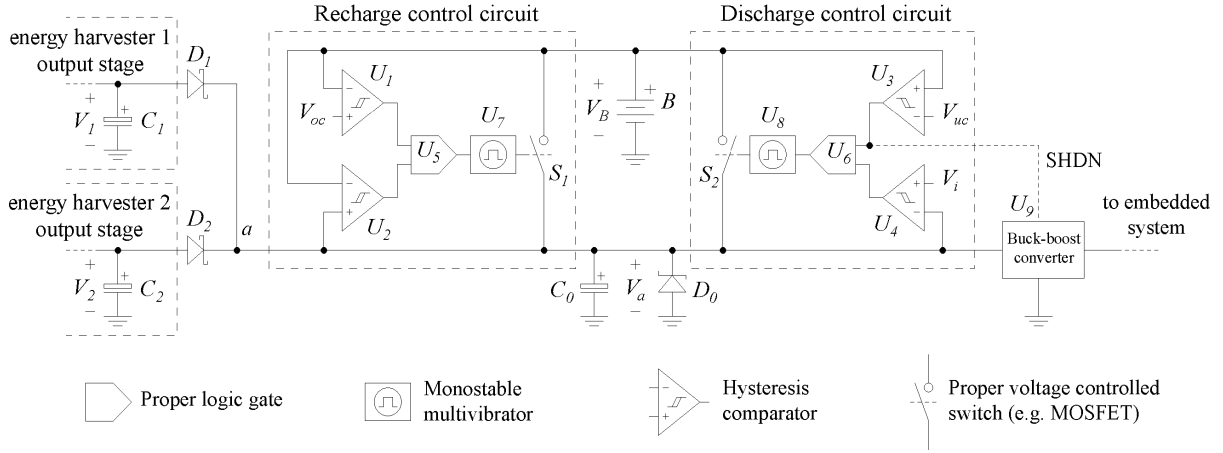


Figure 2. Functional scheme of the power management subsystem.

With respect to other possible MOSFET-based power ORing solutions [15], the only drawback of the diode-based one is the parasitic power consumption caused by the forward voltage drop on the diode, when the current flows from a harvesting subsystem to C_0 . To minimize this unwanted power consumption, we use very low forward voltage Schottky diodes to implement the power ORing connection. Considering the low current levels through these diodes (below tens of milliamperes), the power overhead is comparable or below the one determined by a MOSFET-based ORing solution, which requires an additional driving circuit as well. Besides, the diode-based solution provides additional advantages, in terms of self-synchronization, low complexity and cost.

A proper sizing of the harvesting subsystem output supercapacitors (C_1 , C_2 , ...) is required to ensure that each of them equally contributes on average to replenish C_0 . For example, considering an architecture with just two energy sources, the value of C_1 and C_2 should satisfy the relationship $P_1/C_1 = P_2/C_2$, where P_1 (or P_2) is the average power generated by the first (or second) harvesting subsystem.

B. Battery control

The battery can connect to supercapacitor C_0 , the main energy reservoir, through one of the switches S_1 or S_2 . While S_1 allows C_0 to recharge the battery, S_2 allows the battery to recharge C_0 : thus, in each switch, the current always flows in just one direction. As the battery cannot be recharged with a current greater than a certain value, S_1 is current limited with an adjustable limit value, while S_2 is not.

The recharge process is supervised by the *recharge control circuit*, and it starts when the following two conditions are satisfied: (1) the battery voltage V_B is lower than the overcharge threshold voltage V_{oc} , and (2) the voltage across the main reservoir V_a is greater than $V_B + 100$ mV. The comparator circuits U_1 and U_2 respectively determine the satisfaction of these conditions: both are configured to have a 100 mV hysteresis, but while in U_1 the hysteresis is symmetrical, in U_2 it is shifted by a quantity slightly greater than the width of the hysteresis itself. This ensures that the output of U_2 is

never asserted when V_a is lower than V_B , otherwise the battery would recharge the supercapacitor. When both conditions are met, also the output of U_5 becomes asserted: this triggers the monostable circuit U_7 , which maintains S_1 closed for an adjustable time interval of some seconds.

The role of U_7 is to keep S_1 closed for a time interval long enough to allow the completion of the charge redistribution transient involving C_0 and the battery: indeed, if U_5 drove S_1 directly, the transient would be interrupted too early, because U_5 output remains asserted for a very short time. This behaviour is caused by the significant internal parasitic resistance of the supercapacitor, which makes V_a increase steeply when S_1 becomes closed, and this condition leads to the immediate deassertion of U_2 output.

If the overcharge condition is reached, U_1 prevents the battery to charge further. This means that, if the harvested power continues exceeding the power needed by the load, V_a is free to increase proportionally. To avoid V_a reaching the maximum voltage rating of C_0 , a Zener diode D_0 is placed in parallel to C_0 : when V_a reaches the Zener voltage (around 5 V), it cannot increase further, so the energy in excess coming from the harvesting subsystems is dissipated by D_0 . The capacity and the maximum voltage rating of C_0 should be selected to make the reaching of this stage very rare.

The discharge process works very similarly to the recharge one: when (1) the battery voltage V_B is greater than the undercharge threshold voltage V_{uc} and (2) V_a falls below the discharge start threshold V_i , then S_2 remains active for a certain, adjustable time interval. V_i should be set to a level above the minimum input voltage supported by U_9 , to ensure its continuous operation. To avoid deep discharging the battery, the output of U_3 is connected directly to the shutdown pin of U_9 : if V_B falls below V_{uc} the power going to the load is cut off until the harvester collects enough ambient energy to recharge the battery over the level set by U_3 hysteresis.

V. SIMULATION RESULTS

The prototype shown in Fig. 3 implements the proposed system. Both solar and wind energy harvesting subsystems

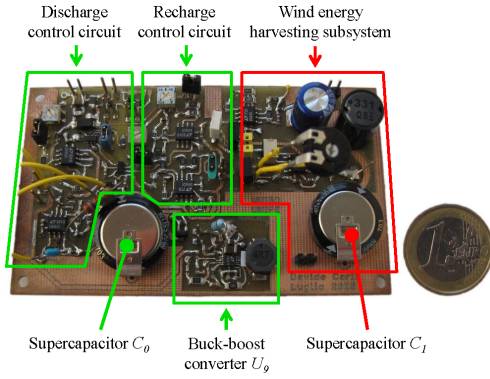


Figure 3. Prototype of the multi-source energy harvester.

have been fully characterized, as reported in [12] and [13]. The functionality of the power management circuit described in the previous section has been experimentally tested as well.

To assess the overall harvesting capabilities of the whole multi-source energy harvester, and to verify whether it would be suited to a certain low power application before actually deploying the devices, we have developed a Matlab simulation framework to numerically evaluate the behaviour of the harvester. The simulator allows the user to specify the time sequence of the data regarding the environmental variables relevant to the harvesting subsystems (e.g. solar radiation, wind speed, etc.) measured in a certain time interval in the site of interest, as well as the expected power consumption profile of the load system (e.g. a system which periodically becomes active, with a known duty cycle). On the basis of these input data and of the operating parameters specified for the harvesting system (like voltage thresholds, device parameters, etc.), the framework determines the system behaviour together with the current and voltage waveforms in the most relevant nodes of the circuit.

The program is very useful to plan the actual deployment of the harvesting system and it is able to anticipate the harvester performance in a particular operating environment with adequate accuracy, along with the dependencies on system parameters (e.g. the capacity of the supercapacitors, the voltage thresholds in the battery management sub-circuits, the connection of an additional harvesting subsystem, etc.).

To aid the reader in understanding the system behaviour detailed in the previous section and to report an example of the simulator capabilities, we used the simulation script described above to generate the plots shown in Fig. 4.

The meteorological data considered for this simulation have actually been gathered on October 24, 2007 at the Grand-St-Bernard pass, at 2400 m above sea level between Italy and Switzerland. These data and the system parameters have been expressly set to make the simulated system perform the highest possible number of transitions, to highlight its operation. As shown in Fig. 4a and Fig. 4d, the selected day was quite windy and cloudy. To further reduce the impact of the solar harvesting subsystem, the PV panel size has been lowered to just 60 cm². The starting voltage across the supercapacitors

at the output of the wind harvesting subsystem ($C_1 = 1$ F) and of the solar harvesting subsystem ($C_2 = 50$ F) have been set to unlikely values, i.e. rather lower than the voltage across C_0 (see the left of Fig. 4e). V_i has been set to 2 V, while the system to be powered consumes 100 mW for 1 s every 30 s, and has a standby power of 0.1 mW.

The waveforms on Fig. 4e permit to distinguish the changes in the harvester operation. At the start of the simulation, during T_1 , C_1 and C_2 are quite discharged with respect to C_0 , so they cannot provide any energy to the main reservoir. This causes the battery to activate, and to sustain alone the power consumption of the load: a steady current flows outside the battery (Fig. 4c), and the battery discharges linearly (Fig. 4f).

At the end of T_1 the wind appears, and C_1 recharges until when it can provide some energy to C_0 . During T_2 only the power coming from the wind harvesting subsystem is present, but it is not enough to sustain alone the whole power needs of the load (indeed in Fig. 4b the harvested power remains on average below the average output power level). So the battery intervention is still required and the battery continues discharging.

Before the end of T_2 , the sun appears and C_2 starts charging. However, even if the total harvested power exceeds the output power, just a part of it can be relayed to C_0 , because C_2 has not reached the level of C_0 yet. So, before the end of T_2 , the harvested power going to C_0 is still coming from the wind subsystem only, and this determines the spike observable in Fig. 4e around the 9th hour. During T_3 , V_a increases because of significant wind flow: the wind energy is sufficient to keep V_a above V_i , so the battery stops delivering current. V_a continues increasing thanks to the wind flow until it reaches $V_B + 100$ mV: the recharge process starts and during T_4 , C_0 keeps recharging the battery in a pulsed way. However, the average recharge current is low, because the energy excess provided by the wind subsystem is quite low.

When C_2 reaches the level of C_0 , both harvesters contribute to recharging the battery, during T_5 . At the end of T_5 , the battery is fully charged, and the overcharge protection circuit U_1 prevents the battery from further charging. For this reason, during T_6 , V_a is free to increase above the battery level. At the start of T_7 , V_a reaches the Zener diode threshold, so the energy in excess coming from the harvesting subsystems is wasted on D_0 . Finally, during T_8 , input and the output power levels are very similar, thus V_a remains quite steady.

VI. CONCLUSION

In this paper we have presented an effective multi-source, multi-storage energy harvesting architecture. Its straightforward, fully analogue design based on ultra-low-power components makes it a very efficient and cost-effective solution to enable the autonomous operation of low power applications. Its modular design and power ORing strategy permits to harvest ambient energy from an arbitrary number of different sources through hot-pluggable harvesting subsystems. The possibility of collecting energy from a high number of different generators improves the system reliability by reducing the impact of

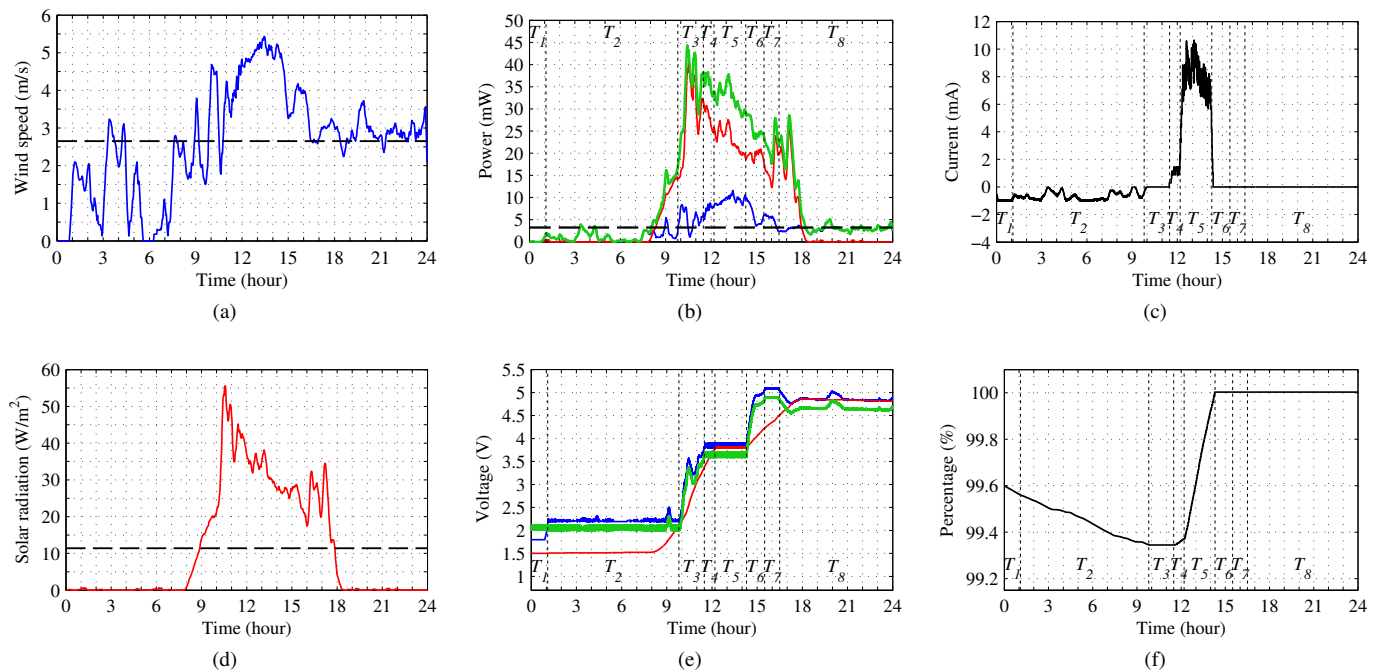


Figure 4. Plots resulting from the system simulation in Matlab. (a) Wind speed data collected on October 24, 2007 at the Grand-St-Bernard pass [16] (dashed: average value). (d) Solar radiation data collected on October 24, 2007 at the Grand-St-Bernard pass [16] (dashed: average value). (b) Power harvested by each of the two energy harvesting subsystem (blue: wind - red: solar), their sum giving the total harvested power (green), and the average output power consumed by the load (dashed). (e) Waveforms of the voltages across the supercapacitors present in the system (blue: across C_1 , wind - red: across C_2 , solar - green: across C_0). (c) Current flowing inside (outside) the battery, when positive (negative). (f) Battery charge, in percentage.

the availability variations affecting each energy source. The system, based on supercapacitor, can also accommodate a rechargeable battery, to ensure a continuous power supply to the load system even during long periods of ambient energy shortage. The battery is protected from overcharges and undercharges, and is recharged when the operating environment provides more power than required by the load.

The implemented harvesting system has been presented along with an expressly developed simulation framework. It enables the designer to assess the harvester suitability to a certain application through simulating the system behaviour in realistic operating conditions, specified for example by meteorological data or by the power profile of the system to be powered. Finally, this tool is also useful to evaluate the effects of different system parameters on the system overall performance.

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