An Efficient Solar Energy Harvester for Wireless Sensor Nodes

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Abstract

Solar harvesting circuits have been recently proposed to increase the autonomy of embedded systems. One key design challenge is how to optimize the efficiency of solar energy collection under non stationary light conditions. This paper proposes a scavenger that exploits miniaturized photovoltaic modules to perform automatic maximum power point tracking at a minimum energy cost. The system adjusts dynamically to the light intensity variations and its measured power consumption is less than 1mW.

Experimental results show increments of global efficiency up to 80%, diverging from ideal situation by less than 10%, and demonstrate the flexibility and the robustness of our approach.

1. Introduction

Although research continues to develop higher energy-density batteries and very low power embedded platforms have recently entered the marketplace, the amount of available energy on board still severely limits the lifespan of distributed battery operated embedded systems. The ultimate goal is to achieve a perpetually powered system without a necessary periodical maintenance for battery replacement or recharging. Wireless sensor networks for outdoor environmental monitoring are a class of systems where exploiting alternative power sources could increase the autonomy of the nodes considerably. Energy harvesting techniques can solve the problem by supplying and converting energy from the surrounding environment and refilling an energy buffer formed by a battery stack or by supercapacitors.

Energy scavengers using small photovoltaic *PV* modules have been recently proposed to enable perpetual operation of WSNs. Unfortunately the low energy budget available does not help to perform an efficient replenishment of the storage devices. Under varying temperature or irradiance conditions the output characteristics of a *PV* module changes non-linearly. Therefore the problem is to automatically find the voltage (and the current) at which it should operate to obtain the maximum output power. An efficient photovoltaic energy harvesting system should track this particular operating point called *Maximum Power Point* (*MPP*). To this purpose many designers have actively investigated techniques for *MPP* tracking (*MPPT*) [1, 2]. So far *MPPT* methods have been roughly classified into two groups: large-scale *PV* power systems, generally based on digital signal processor (DSP) or microcontrollers [3], and small-scale *PV* power systems usually without DSP or any other digital controller. However, with the increased interest in harvesting technology for wireless sensor networks a new class of *MPPT* methods, focused on micro-scale *PV* power systems, has recently emerged. These approaches tackle the development of *MPPT* techniques with power consumption of a few mW. In fact, maximum power point tracking using small-size *PV* modules is practicable only if the power consumed by the tracker is substantially lower than the amount of output power that it gains. The harvester circuit proposed in this paper consumes less that $1\,mW$ and approaches the ideal situation beyond 90%. Since it does not use any microcontroller or DSP for *MPPT*, the embedded system can be shut down when unused to save energy. Moreover it does not require a pre-charged storage device (such as rechargeable batteries), and it works even if the energy buffers are empty. All these features make the proposed solution suitable for low-power systems and in particular for wireless sensor networks.

The remainder of the paper is organized as follows. Related works are reviewed in the next section followed by the list of the contributions and the innovations that our work proposes. A background on problems and characteristics of *MPPT* systems is discussed in Section 4. Section 5 describes the actual implementation of our *PV* harvester. Experimental results and the performance achieved are the focus of Section 6, finally Section 7 concludes the paper.

2. Related Work

Although the experience in exploiting *PV* modules is consolidated, research on solar power scavenging for sensor network is quite recent. Several solutions have been presented in the last years: *Prometheus* [4] and *Heliomote* [5] were probably the first proposals to supply a sensor node with the help of a small *PV* module. Both systems do not perform any *MPPT* and the replenishment of energy buffers is performed by a direct connection between the *PV* panel and the storage device. This solution forces the operating point of the solar cell to the voltage of the capacitor V_{CAP} that is usually far from optimal, reducing drastically the output power of the *PV* module. The adoption of a diode to protect the solar module does not help because the *PV* cell only works when the buffer voltage is lower than the *PV* panel voltage, and the diode is forward biased. As a consequence, the amount of power drawn from the *PV* module also depends on the energy buffer level (V_{BAT} or V_{CAP}).

This also leads to problems in developing power management software for sensor networks. Adding *Energy harvesting aware features* might require the knowledge of the current available energy and the estimation of the future harvested power [6,7] to tune the system behavior. Clearly, if there is a relation between conver-

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sion efficiency and energy buffer level, the energy prediction will require more computing effort and may lose in accuracy.

Ultra-low power systems designed for wearable devices and smart materials equipped with photovoltaic harvester are also presented in [8, 9]. Due to the small size, these architectures are powered with miniaturized batteries and exploit the scavenger only as trickle recharger without any effective tracking of the *MPP*.

In [10] a *MPPT* system that uses only a supercapacitor as energy reservoir is presented. The microcontroller on the node runs a tracking algorithm and drives a pulse width modulator (*PWM*) circuit to control the power converter. The microcontroller is essential for the *MPPT* system which leads to the main drawback of this implementation: the *MPPT* circuit cannot work without microcontroller and exploiting the scavenger on another sensor node requires a revision of the firmware. *Ambimax* [11] is another solution from the same authors of [10]. It is a more refined version and tries to eliminate the overhead caused by an always-running algorithm on the MCU. The control unit is independent from the target embedded system and does not require any programmable device. Although it uses only low power logic components, the *MPPT* system requires the presence of a rechargeable battery as secondary buffer to work when the primary buffer is empty. The sensor used to estimate the position of the peak power point is a photodiode. Unfortunately this component has a not negligible power consumption and it requires also a conditioning circuit for the output signal. However the innovative idea to exploit a low power comparator to generate a *PWM* signal has been adopted also in our work as starting point. We remove some inefficiency and add new features as described in the next section.

3. Contributions

This paper contains the following new results:

- We present a low-energy photovoltaic harvesting circuit for wireless sensor nodes, that is able to track variations of the *MPP* during the day. Differently from [11] which exploits photosensors, our method uses a micro *PV* module as pilot cell. To the best of our knowledge nobody has experimented and implemented this solution in a *MPPT* system, especially in a small-sized energy scavenger for sensor networks. The advantage is that the pilot cell does not require any additional energy, whereas exploiting photosensors consumes power and they do not operate when the energy reservoir is empty;

- Differently from [11], which needs a battery as secondary buffer, our *MPPT* system does not require any reservoir capacitor to operate. Our supply unit chooses automatically the source to power the *MPPT* circuit between the *PV* module or the DC/DC converter used by the sensor node. As a result, the *MPP* can be tracked immediately even with empty energy buffers. This behaviour is desirable since (a) it matches common models used in power management software and (b) it guarantees faster recovery;

- The control circuit of the proposed scavenger is completely independent from the powered system. Therefore it saves more power because it is possible to shut down not only the microcontroller and other on-board components, but also the DC/DC converter that is no more required for the scavenger;

- Even if the average energy consumed by the sensor node is higher than the energy intake from the environment leading to the emptying of the energy reservoir (e.g. it happens in cloudy days, or under scarce irradiance), the scavenger detaches the sensor node increasing the scavenging efficiency, and collects an amount of energy sufficient to perform some basic recovering operations before supplying the node again.

4. The *MPPT* problem

The *I-V* characteristic of a *PV* module, when neglecting the internal shunt resistance, is given by the following equation:

$$I_o = I_g - I_{sat}\left\{e^{\frac{q}{AKT}(V_o+IoR_s)} - 1\right\} \quad (1)$$

where I_g is the generated current, I_{sat} is the reverse saturation current, q is the electronic charge, A is a dimensional factor, K is the Boltzmann constant, T the temperature in degree Kelvin, R_s the series resistance of the cell. The plot of the *PV* module adopted in our solar harvester is shown in Fig. 1. It shows the behavior under two different light conditions.

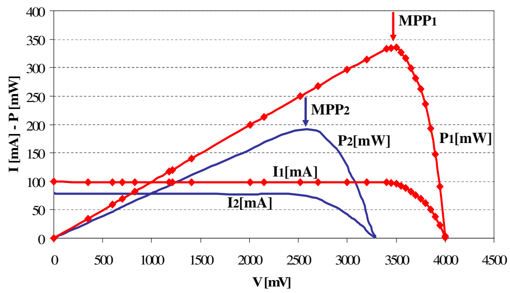

Figure 1. I-V and P-V plots of the used photovoltaic module

The problem considered by *MPPT* is to automatically find the operating point (V_{PV}, I_{PV}) at which a *PV* module should operate to obtain the maximum output power under a given temperature and irradiance, following it when light intensity changes (indicated with arrows in Fig. 1). There are several methods and algorithms to analyze and find the *MPP* [12], certainly the most used are *Hill-Climbing/Perturb and Observe (P&O)* [10] and *Fractional Open-Circuit Voltage (FOC)* [2]. *Hill-Climbing and P&O* methods operate by periodically perturbing the system by a change of the converter duty ratio or a variation of the solar array voltage. If the given perturbation leads to an increase (decrease) in output power, the subsequent perturbation is made in the same (opposite) direction. In this manner, the tracker continuously looks for the maximum power point. Implementations of these methods are commonly used and usually very accurate but require DSPs or microcontrollers that consume non-negligible power. On the other hand, among the simplest methods for *MPP* tracking, Fractional Open-Circuit Voltage is definitely the most used and cost-effective in medium and small-scale *PV* systems. This method exploits the nearly linear proportional relationship between the operating voltage at *MPP* (V_{MPP}) of a *PV* module and the open circuit voltage (V_{OC}).

$$V_{MPP} \approx K_{FOC} \cdot V_{OC} \quad (2)$$

V_{OC} [V]	V_{MPP} [V]	K_{FOC}
3,24	2,50	0,772
3,40	2,52	0,741
3,40	2,44	0,717
3,60	2,80	0,778
3,60	2,60	0,722
3,96	2,92	0,737
4,50	3,50	0,778
4,50	3,30	0,733

Table 1. Fractional Open-Circuit Voltage, Relation between V_{OC} and V_{MPP}

where the proportional constant K_{FOC} belongs to the interval $(0.71, 0.78)$, with a slow increase when the light intensity fades. Table. 1 shows the behavior of the constant (K_{FOC}) of the used solar cell, during different irradiance conditions.

The *MPP* can be approximated by measuring periodically V_{OC} with a temporary disconnection of the *PV* module from the circuit. Clearly it is a disadvantage because of the temporarily drop of power from the panel. To overcome this problem, we employ an additional small *PV* module acting as pilot cell, carefully selected to closely represent the characteristics of the principal *PV* array. We adopt the CPC1824 from Clare, Inc. [13]. It is a monolithic photovoltaic string of solar cells of only 9 mm^2, and it is used as irradiance sensor providing feedback information to the tracker. The operating point of the pilot cell follows almost linearly the behavior of the main *PV* module during light variations. Fig. 2 compares the behavior of the two cells under the same solar intensity variation. The plot displays the operating voltage of the pilot cell ($V_{pilot\ cell}$) over the V_{OC} of the big *PV* module. For clarity we plot also the same V_{OC}, and the V_{MPP} of the main module to verify the similarity of the variations. As shown the behavior is near linear thus it is possible exploiting the voltage of the CPC1824 ($V_{pilot\ cell}$) as a reference signal for tracking the position of the *MPP* (3).

$$V_{MPP} \approx K_{FOC} \cdot V_{OC} \approx K_{FOC} \cdot (K_{pilot} \cdot V_{pilot\ cell}) \qquad (3)$$

Moreover, using a pilot cell leads to much smaller tracking unit and it is no more necessary to provide a power supply for a light irradiance sensor as in [11]. Another point to notice is that the linear relationship is only an approximation, and the *PV* cell technically never operates at the exact *MPP*, but it does not require a DSP or microcontroller and it is low-power consuming and very cheap to implement.

5. System Design

The hardware architecture of the solar scavenger is displayed in Fig. 3. It is realized using COTS parts and it consists of three units: the *MPP Regulator*, the *MPP Tracker* and the *MPP Power supply*. The *MPP Regulator* usually exploited in *MPPT* techniques is a power converter selected within a buck, a boost or a buck/boost configuration. We opted for a buck power converter operating in continuous mode since the maximum capacitor voltage V_{CAP} is lower than the nominal operating voltage of the solar cell. The *MPP Regulator* employs an inductor and two switches (in our case

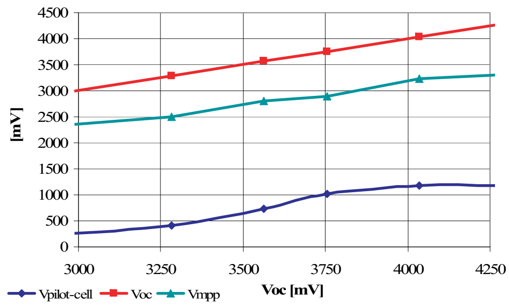

Figure 2. Near linear relation between V_{MPP} and the pilot cell

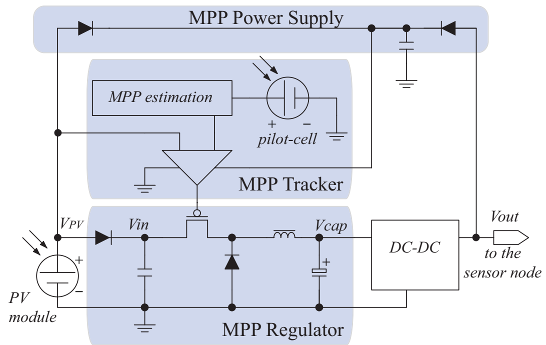

Figure 3. Conceptual diagram of the harvester platform

a MOSFET transistor and a diode) and it alternates between energy storing, connecting the inductor to voltage source, and discharging the inductor to replenish the load.

Accordingly to Fig. 3, the relationship between input and output voltage of the buck power converter can be described by the following equation:

$$\frac{V_{cap}}{V_{in}} = \frac{t_{on}}{T} = D \qquad (4)$$

where D is the duty ratio of the switching cycle and t_{on} is the closed switch interval. Normally a buck converter adjusts the duty ratio of the switch activity to provide a constant output voltage when the input voltage or the drawn output power change due to load variations. In contrast to the normal use, the purpose of the *MPP Regulator* is keeping the input voltage V_{PV} around an imposed value, preferably the maximum power point. Since the input power (V_{PV}, I_{PV}) varies continuously with the atmospheric conditions, the circuit adjusts dynamically the duty cycle (D) to track the *MPP* supported by the small capacitance at the input. In our work narrow pulses with a duty-ratio D are generated by the tracking unit.

The switching frequency, the input capacitance and the inductor value should be selected for the best performance considering conversion efficiency, cost and power consumption. For example, the higher the switching frequency, the lower the inductor and the capacitance size, but also the tracker power consumption and losses are higher. On the other hand, larger capacitances decrease the responsiveness of the harvester to fast variations of environmental irradiance.

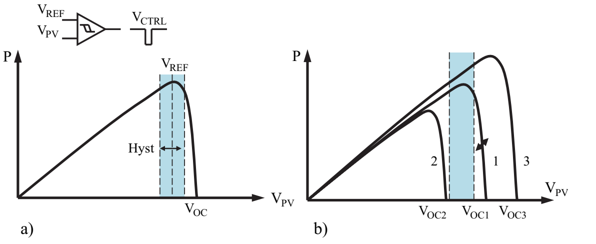

Figure 4. Window around *MPP* and tracking significance

The core of the scavenger is the *MPP Tracker* that attempts to obtain the maximum achievable power from the solar cell. The operating voltage V_{PV} is led to one of the inputs of the adopted ultra-low power comparator (LTC1440 from Linear Technology). It generates the control signal V_{ctrl} comparing this signal to a reference signal V_{REF}. As pointed out in Section 4, the *Fractional Open-circuit* method is exploited by matching V_{REF} to the estimated V_{MPP} using approximation (3) and the pilot cell as input signal. The pilot cell is exposed to the same light conditions as the main solar cell. The adopted ultra-low power comparator consumes less than $100\,\mu W$, and it is capable of adjustable hysteresis between input signals therefore a lower and an upper threshold can be programmed. We exploit this feature to tune the hysteresis window (see Fig. 4a) around V_{REF}, adjusting the size and the position. In this way the actual operating point is not a fixed value, but oscillates around the *MPP*. Narrowing the windows around estimated *MPP* means to operate at higher switching frequencies, with higher conversion efficiency, because the solar cell is confined to a smaller voltage range. This can lead to a higher average output power if the MPP tracker is configured correctly, since the solar cell will spend much more time close to its MPP. On the other hand it requires a faster comparator, which is generally more power consuming. Moreover, tightening the hysteresis band makes the tracking operation critical and requires more accuracy. The maximum allowed difference between upper and lower threshold is $100\,mV$ for the LTC1440, but in the implementation usually a band of $15\,mV$ is exploited.

The importance of a tracking method in this implementation is clearly explained in Fig. 4b. It displays the variation of the *P-V* characteristic of a photovoltaic module under three different irradiance intensities, keeping the window position fixed. A system equipped with a *MPP* regulator without a tracking unit can obtain the maximum efficiency only if the *MPP* is situated inside the band (1). A higher light intensity shifts the curve to the right (3) and causes the *MPP* regulator to operate at a non-optimal power point. The worst and fatal case (2) occurs when the light fades. No point of the curve crosses the control window, therefore no PWM signal V_{ctrl} is generated to the power converter, causing a real disconnection between *PV* source and energy reservoir. The performance in this case is obviously worse than not using *MPPT* at all and connecting the *PV* cell directly to a storage device.

With an empty supercapacitor and the DC/DC converter turned off, the MPP tracker is still able to operate. This feature is guaranteed by the *MPP power supply* unit which powers the harvesting circuit even if the DC/DC is not working. If the solar cell supplies a high enough voltage, the *MPP power supply* unit switches dynamically between the DC/DC output and *PV* module choosing the highest available power source, exploiting a couple of fast diodes. This permits to have the highest control signal V_{ctrl} to switch-off the MOS transistor, suppressing any drain current that could decrease the performance of the power converter.

6. Experimental Results

We investigate the performance of the proposed energy scavenger by measuring the power consumed by the *MPPT* system, measuring the charging efficiency of the energy buffer and estimating the efficiency during the tracking of the *MPP*. Finally we test the sustainability of the scavenger powering a real wireless sensor node. All the measurements have been performed using a $36\,cm^2$ *PV* module with a nominal output power of $300\,mW$ under full outdoor irradiance. For reproducibility of the experimental setup, the solar cell is illuminated by a $100\,W$ bulb lamp using several distances. The maximum light intensity of the lamp enables the solar cell to produce about $50\,mW$.

6.1 Power consumption

The main contribution to power consumption is given by *MPP* regulator during its switching activity. When the switch of the *MPP* regulator is open, the overall circuit consumes less than half a mW. ($P_{switch-off} \approx 300\,\mu W$). Peaks of about $1\,mW$ have been measured when the comparator switches the MOS transistor on ($P_{switch-on}$). The average power can be easily computed using the following equation.

$$P = D \cdot P_{switch-off} + (1 - D) \cdot P_{switch-on} \tag{5}$$

Considering that the duty cycle of the control signal V_{ctrl} is typically higher than 80%, the average power consumed by the whole circuit is below $1\,mW$.

6.2 Scavenging efficiency

Conversion efficiency is usually defined as follows:

$$\eta = \frac{P_{transferred}}{P_{MPP}} \tag{6}$$

$$P_{MPP} = V_{MPP} \cdot I_{MPP} \tag{7}$$

$$P_{transferred} = \frac{1}{2}\frac{C}{T}\left[V^2(t) - V^2(t-T)\right] \tag{8}$$

Where P_{MPP} is the power at the *MPP* and $P_{transferred}$ is the average power transferred to the energy buffer. When supercapacitors are used, $P_{transferred}$ is usually computed as the value necessary to increase the energy level from $E\,(t-T)$ to $E\,(t)$ during a given time interval T. Using this definition only scavengers that work always on the correct *MPP* can achieve efficiency close to 100% and losses are only caused by power dissipation of system components. In our tests, η has been evaluated also considering the DC/DC converter which affects the result with its own intrinsic losses. Fig. 5 shows how efficient the proposed method is in replenishing the supercapacitor over elapsed time. The continuous curve represents the linear charging behavior in case of a direct connection between the *PV* panel and the storage device.

The dashed curve shows the ideal trend: the supercapacitor is constantly refilled with the maximum available power P_{MPP}. The charging behavior using the proposed energy scavenger is plotted as the curve with dots. As shown it approaches closely the ideal curve, with a maximum error less than 10%. Note that other scavenging solutions such as [11], can not perform better since their tracking circuit does not operate with an empty energy reservoir. The curve with triangles has been obtained excluding from the scavenging platform the *MPP power supply* unit and using the DC/DC as only source. The discontinuous shape is due to the fact that for low voltages the *MPP* unit does not work properly, since the step-up converter is still switched-off.

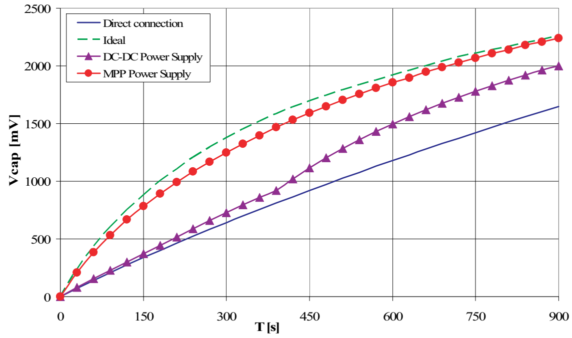

Figure 5. Comparison of different charging curves

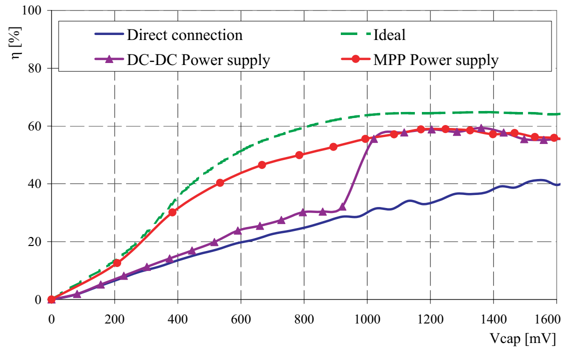

Figure 6. Efficiency of the power conversion

Fig. 6 shows the same situation, but plots the efficiency, defined as in (6), over the voltage level of the supercapacitor. Looking at the curve with triangles, it is even more evident that only when the energy level of the buffer is high enough to turn the DC/DC on, the scavenger can work properly and increase the efficiency.

6.3 Tracking efficiency

To evaluate the performance of the *MPPT*, we tested how the scavenger efficiency varies if the *MPP Tracker* unit is switched off. Fig. 7 shows the efficiency defined in Section 6.2 using a different irradiance from the previous plots. Also here the lowest continuous curve depicts the direct connection between *PV* module and supercapacitor, while the dashed curve is the ideal case using a constant P_{MPP} as source. The curve with dots is obtained with

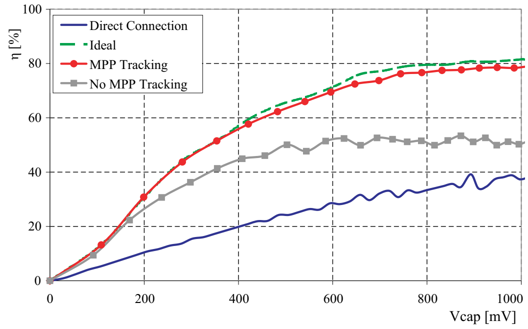

Figure 7. Efficiency of the tracking system

the *MPPT* proposed, and can achieve levels up to 80%. If *MPP Tracker* unit is excluded the efficiency curve varies widely with the irradiance condition, ranging from the dashed curve to below the continuous one, representing the direct connection. The figure displays a case in which η decreases to around 50% (curve with squares).

In Fig. 8, we also analyze the operating point V_{PV} with and without the tracker over the elapsed time. The ideal situation, depicted in the picture on the left, is obtained when the *MPP Regulator* is driven by a signal generator tuned at $100\,kHz$ and duty-ratio $D = 78\%$. D is computed in order to obtain an optimal behaviour, in fact the operating point continuously matches V_{MPP} at the given irradiance. Under the same condition, the proposed scavenger tightens around V_{MPP} (as shown in the middle picture), because it automatically generates a control signal with $D = 80\%$. The size of the window is due to a lower switching frequency ($16\,kHz$). Finally, the operating point of the circuit without the tracking system is plotted in the right picture. Since the duty cycle of the generated signal is very different from the ideal one (in this case $D = 91\%$), the *PV* module will never operate at the *MPP*.

6.4 Powering a sensor node

Our scavenger is very flexible and can be attached to commercial sensor nodes which are not designed with energy harvesting features. To verify the sustainability of our solar energy harvester, we power a *Tmotesky* [14] sensor node with a simple example application. The application does not perform any duty ratio activity, neither any low power techniques. It just sequentially turns on the on-board LEDs, and transmits a message using the radio.

The average power consumed by the application is $90\,mW$. Using a fading light intensity for which the incoming average power is not enough to sustain the sensor node, the behavior of the node is shown in Fig. 9a. The plot displays the voltage level of the supercapacitor used as energy reservoir. When the trace becomes larger the sensor node is active. It is easy to verify that the energy, required by the step-up converter to boot, is higher than the energy left when the DC/DC turns off again. Adopting a $50\,F$ supercapacitor, this amount of energy is computed as $\Delta E = \frac{1}{2}C\left[V_{ON}^2 - V_{OFF}^2\right]$ and it is around $6,93\,J$ allowing the sensor node to operate continuously for about $64\,s$. This is an appreciated feature because, even under scarce irradiance, the scavenger guarantees a minimum operating time interval which is sufficient to perform some basic operations and to save the data before shutting down again.

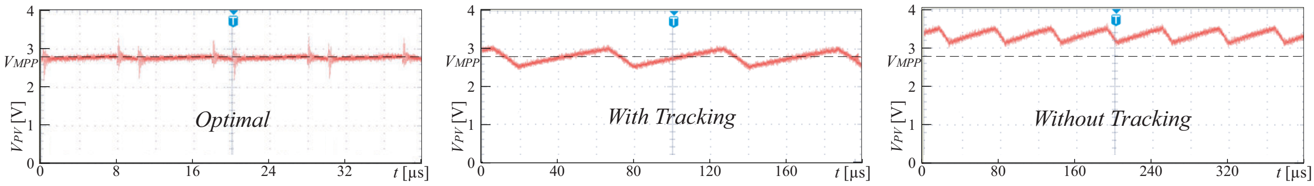

Figure 8. Comparison of the operating point with and without tracking circuit

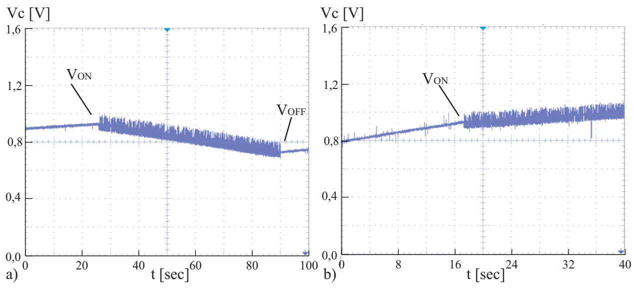

Figure 9. Sustainability of the scavenger under different light conditions

Of course when the incident light increases, the power generated by the *PV* module becomes enough for continuous sensor node operations and for energy buffer replenishment (see Fig. 9b).

7. Conclusion

A highly efficient solar energy harvester for wireless sensor nodes and environmental embedded systems has been proposed. The adoption of a *MPPT* circuit leads to several benefits such as: the possibility to shrink the size of *PV* modules, to reduce the capacity of the energy reservoir, or to allow higher power consumption of a sensor node. The presented circuit performs a high-efficiency conversion through an ultra-low power *MPPT* technique that requires less than $1\,mW$. The estimation of the peak power point is done automatically, using a small *PV* pilot cell as reference, whereby sensing operation does not require additional power. The scavenger can be used with any kind of embedded sensor node, because it is completely independent of the node operation. Experimental results have shown that the global efficiency diverges from the ideal situation by less than 10%. Finally, a case study on a real sensor node demonstrates the complete sustainability of the system with solar regenerative energy.

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