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Abstract—The success of wireless sensor networks and their pervasive use is somehow constrained by energy supply which, generally provided by batteries, is a finite resource. Energy harvesting mechanisms must hence be taken into account to grant a long time operational life, with solar energy being the most interesting one in outdoor deployments due to its relatively high power density. In this paper we propose a low-power Maximum Power Point Tracker (MPPT) circuit specifically designed for wireless sensor nodes (hence effective, flexible, low cost and power-aware), i.e., a power transferring circuit for optimally conveying solar energy into rechargeable batteries even in not optimal weather conditions. High efficiency is granted by an ad-hoc adaptive algorithm which, by keeping the MPPT electronics in its optimal working point, maximizes energy transfer from the solar cell to the batteries. The suggested implementation is particularly effective in critical weather conditions where traditional solutions do not work and is characterized by a flexible enough design for immediately hosting, in a plug in fashion, different solar panels and battery typologies.

Index Terms—Adaptive algorithms, Solar energy harvesting, Wireless sensor networks, MPPT Circuits, Power Converters.

I. INTRODUCTION

The need of energy harvesting in wireless sensor networks is a primary issue to be tackled to grant effectiveness of the technology in a wide spectrum of applications. In fact, wireless sensor nodes, being mostly planned for outdoor long time operations, only seldom rely on external energy supply sources which, in turn, requires the node to consider energy harvesting mechanisms. In principle, all energy sources should be exploited to extract the available energy: among the others, e.g. see [1] [2] [3] [4] [5], the solar one is generally the most effective in outdoor applications for the high power density provided and exploitable through solar cells.

Solar cells exhibit a strong non-linear electrical characteristic, which makes it low effective extracting energy in non stationary environments. Non stationarity can be associated with changing weather conditions (e.g., cloudy and not optimally radiating solar power environments) and aging effects or efficiency degradation in the solar panel (e.g., dust or rust on the cell surface). Moreover, the energy transfer mechanism is strongly influenced by the illumination condition such as the angle of incidence of the sunlight which varies along the day. All such phenomena can be interpreted as transient or permanent perturbations affecting -and reducing- the efficiency of the energy production phase.

Existing solar energy harvesting solutions for wireless sensor nodes envisage a simple on/off-thresholded charge mechanism relying on a diode connecting the cell with the rechargeable battery [8]. Unfortunately, in a diode-based solution the electrical working point of the cell is fixed and set by the battery voltage, hence preventing any adaptation: whenever the available power is below the threshold the diode disconnects the cell from the battery and no energy is wasted. A diode-based solution is extremely low cost and low power but it suffers from three main drawbacks:

1) the working point of the cell is set by the battery voltage and cannot be adjusted to maximise energy transfer in a changing environment;
2) the threshold prevents the system to operate efficiently at low radiating power rates (i.e., during not optimal solar conditions);
3) the electrical characteristic of the solar cell has to be chosen to properly match the nominal voltage of the battery (hence constraining solar panels and batteries).

All mentioned problems can be addressed by substituting the diode-based circuit with a Maximum Power Point Tracker system. Such design philosophy requires the development of an adaptive system to transfer the energy generated by the solar cell into a storage medium, such as a battery or a super capacitor, while maintaining the working point of the cell around the optimal one (for which the transferred power is maximized). Existing MPPT circuits, such as those used for traditional outdoor applications, are not suitable for wireless sensor network nodes; there it is assumed that the generated power is high enough to make negligible the power consumption of the MPPT electronics. Conversely, in wireless sensor units, the size of the solar panel must be as small as possible and a traditional MPPT circuit would consume, in the best case, all the generated power.

In general, traditional MPPT circuits differentiate themselves in the design of the power converting electronics and/or in the control strategy. Standard buck and boost DC to DC converters as well less traditional series capacitor and mutual inductor configurations have been reported, e.g., see [9], [10], [11]. The maximum power point detection has been performed with a priori modelling of the cell [12], [13], by analog control loops [7], or again, through artificial neural networks and fuzzy solutions [14]. Furthermore, the efficacy of sensing solely the output electric parameters of the converter has been demonstrated in [15].

Unfortunately, these solutions do not cope with three main constraints associated with wireless sensor nodes:

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1) availability of reduced HW resources on the node;
2) requirement for an extremely low power consumption of the MPPT to allow most of the harvested energy to be conveyed to the battery;
3) extremely low power operation rates.

In this paper we suggest a novel implementation of an adaptive digitally controlled MPPT circuit especially designed for wireless sensor nodes. The design has been carried out bearing in mind the requests of the embedded target device: extremely low power consumption of the MPPT, fast adaptation to the changing environment, high energy transfer efficiency and low cost.

The structure of the paper is as follows. Section II addresses the issues related to the design of the low power consuming MPPT circuits and its hardware realization; section III proposes the adaptive digital control technique employed to identify the optimal working point; section IV finally presents experimental results.

II. DESIGNING A LOW POWER, ADAPTIVE TRACKING POWER CONVERTER SYSTEM

The designed MPPT circuit is essentially composed of two main logical blocks: a) a voltage controllable power converter adapting the solar cell with the battery for power transfer; b) a control system keeping the solar panel working in the optimal point (the one maximizing the energy harvest). A high level description of the MPPT circuit is given in figure 1 while the detailed electronic design is provided in figure 2.

The step-up converter stage electronically adapts the solar cell (providing a voltage \( V_p \)) with the storage battery (characterized by voltage \( V_b \)). A priori, voltage \( V_b \) differs from \( V_p \) being the former dependent and fixed by the battery charge status. Conversely, \( V_p \) can be imposed (controlled) leaving to a power \( n I_p V_p \) transferred to the battery \( (n) \) is the power converter efficiency. Since \( V_p \) can be controlled it is our goal to set \( V_p \) to \( V_{opt} \), the voltage for which the trasfered power is maximum (aspects related to the control loop will be given in the next section).

More in detail, the proposed power converter stage is a modified single inductor step up converter built over the LT1303 integrated circuit [17]. The LT1303 natively implements a hysteretic analog control loop designed to stabilize the output voltage by operating its power switch at fixed duty cycle while the entire integrated power stage is turned on and off to control the power flow. This is accomplished by the hysteretic comparator C1 and the square wave generator G1 of fig. 2.

Moreover, the integrated circuit has an inductor peak current control scheme which avoids the inductor to saturate (the power switch SW1 is composed of two proportional units measuring the inductor current and disabling the switch when the current goes above a maximum nominal value, e.g., 400mA). This control technique is known to be effective especially for low power DC/DC stages as it assures high efficiency at low power rates and facilitates the design of the control loop [24] [25] [26]. This power stage as well as the analog circuit can be forced into an extremely low power consumption state through a dedicated CPU digital signal labelled "power down" in figure 2.

The analog control loop implemented by the LT1303, which we suitably modified by introducing a further external operational amplifier A1, grants that \( V_s \) input is kept at the optimal reference point of voltage \( V_p \). A1 is an extremely low power unit (50 \( \mu \)A supply current) with a reasonable large bandwidth (200 kHz gain-bandwidth product) and provides an amplified control error \( V_s - V_p \). The reference signal \( V_s \) is digitally provided by the control CPU [20] and needs to be converted into an analog signal. We opted for a PWM technique (instead of a power eager DAC) to perform the digital to analog conversion using a standard PWM modulator provided by the CPU followed by a second order passive low pass filter F1 to generate the analog reference voltage.

Since it was possible to directly connect the reference voltage to one of the high impedance inputs of the LT1490 operational amplifier, no buffer was needed, hence reducing the power consumption of the converter. Battery BT employed for storage is a 300mAh NiMH rechargeable battery with a nominal voltage of 4.8V (the battery pack is composed of two 150mAh units connected in parallel). We considered NiMH batteries instead of Pb-sealed, NiCd and Lithium-ions ones for their compactness, ease recharge ability and no memory charging effects.

The power delivered to the battery is \( P = V_b \cdot I_b \), where \( I_b \) is the battery current. To grant a suitable control action both \( V_b \) and \( I_b \) need to be measured. \( V_b \) can be simply acquired through the switched band-gap reference circuit BG1 while \( I_b \) requires a more complex procedure since the single inductor step up DC/DC converter provides an output current whose spectra starts at the switching frequency (155kHz for the LT1303). Moreover, the modified control loop (due to its time delaying PI action) may cause the power converter burst mode switching activity to slow down. This phenomenon might introduce burst mode oscillations on the output current waveform. As such, in order to remove these unwished frequencies, and to provide at the same time an accurate current reading, we employed a high side active current to voltage converter based on op-amp A2 and a second order passive low pass filter F2.

All circuits of the power converter system (LT1303, CPU and LT1490 op-amps) are powered from the "self power point" of figure 2, which is located before the current reading electronics. As such, the measured current represents the net current flowing into the battery (i.e. the total generated current minus that used to power the electronics). This accurate
reading allows the CPU for enabling the converter only when effective energy harvesting is possible.

III. THE ADAPTIVE DIGITAL CONTROL LOOP

As presented in the previous section the control loop of the MPPT circuit aims at keeping voltage $V_p$ at the optimal reference voltage $V_s = V_{m}$ maximizing the power transfer from the solar cell to the battery. Since power at the output of the converter is the product of $V_b$ and $I_b$ and the battery voltage can be assumed constant during the control cycle, the stored power is proportional to the output current (here the control requires few seconds while the order of the $V_b$ constant of time is the hour).

Figure 3 presents two typical behaviours for a solar cell illuminated in two different conditions; the generated current and power as function of the cell voltage $V_p$ are given (in curve A the radiating power is higher than in B). Whatever the technology of the solar cell is (e.g., inorganic or organic), the power versus the cell voltage curve $P(V_p, I_p)$ shows a convex behaviour characterized by a unique maximum associated with the energy transduction phenomenon [16].

De facto, the control algorithm in execution on the CPU has to identify the optimal voltage $V_m$ for which the transferred power is maximized and, due to changing conditions, track it so that adaptively $V_s$ converges to $V_m$ which, in turn changes over time. The identified optimal $V_m$ at a given time instant will become the reference value to be considered by the analog control loop. Figure 4 presents a block diagram for the proposed control scheme executed by the CPU.

In its current form, the algorithm providing $V_m$ is a simplified gradient-ascend technique on the $P(V_p, I_p)$ curve w.r.t. $V_s$ ($V_s$ coincides with $V_p$ at the end of the transient phase of the controller). The starting point of the iterative indirect algorithm is provided by a low cost amplitude search technique which periodically scans the power curve in voltage. Starting from the identified sub-optimal point the gradient-ascent algorithm updates $V_s$ to converge towards the optimal point and, once the optimal point neighborhood is reached it tracks environmental changes by modifying $V_s$ accordingly.

Assume the unit starts from a situation without power delivery (e.g., at night). The control CPU is enabled every $T_{off}$ seconds (in our implementation 1 minute) through a polled timing mechanism and, once active, it turns on the converter and scans $V_s$ for identifying a good starting point. This is accomplished by linearly decreasing $V_s$ from a maximum to a minimum value and measure the induced $I_b$. The voltage associated with the maximum value of $I_b$ is the one considered as starting point for the gradient-ascent algorithm (since $V_b$ can...
be considered constant during this procedure here we don't need a sophisticated exploration mechanism as differently considered in [19] for a not power-aware MPPT circuit). The gradient control mode is then enabled to track changing weather conditions with a parameterised \( T_{\text{grad}} \) step update (e.g., 5s).

Conversely, if no power is generated the CPU turns off the converter and waits for the next wake up signal. More articulate actions, e.g. based on predictive algorithms for optimally setting \( T_{\text{off}} \) could be envisaged in a future release. The initialisation+tracking algorithm must be as simple as possible for power consumption reasons, prompt enough to detect the parameters have been perfected on the field to maximise control loop performances (promptness in reaction and stability) and evaluating its effect on the controlled one. To detect the parameters used to generate the perturbation signal. Parameters \( \theta \) and \( M_p \), as well as the perturbation waveforms, have been initially identified through SPICE simulations. Afterwards, parameters have been perfected on the field to maximise control loop performances (promptness in reaction and stability) and grant accuracy in current measurements (this aspect will be addressed in more details in subsequent sections).

Finally, the implemented adaptive algorithm can be synthesised as:

\[
V_{s,i+1} = \begin{cases} 
  V_{s,i} + \eta & \text{if } X > \theta \\
  V_{s,i} - \eta & \text{if } X < -\theta \\
  V_{s,i} & \text{otherwise}
\end{cases}
\]

The frequency and shape of the superimposed perturbations are critical since the converter requires a zero phase transfer function in the perturbing signal spectra to operate correctly (from equation 4 the converter must not alter the cell power perturbation phase to provide a correct reading). We identified, through numerical simulations, a triangular shape to be a good compromise between signal generation simplicity and frequency requirements. Figure 5 provides a SPICE simulation...
of the converter subject to a 2.5Hz 400mV peak to peak triangle wave superimposed to the working point and the cell characteristic of figure 3. Noise affecting the voltage of the cell is due to the parasitic voltage ripple introduced by the converter.

More specifically, the upper plot of figure 5 simulates the case where a perturbation is superimposed to the working point in a negative power gradient case. As expected, the controlled variable manifests a negative correlated behaviour with the control variable. Instead, the central plot presents a situation where the perturbation affects the working point in correspondence with a positive gradient and the controlled variable is positively correlated. Finally, the lower plot shows the situation where the control variable is set to its optimal value and the controlled variable correctly introduces an almost null correlation with the control one. With SPICE circuit simulations we evaluate the effectiveness of (4) once subject to a triangle wave perturbation of 1s period and 400 mVpp amplitude (which represents the 10% of the estimated working range of the cell voltage). Parameter \( M_p \) has been set to 20 (10 points per semiperiod are then used to synthesize the perturbation wave). Finally, \( \theta \) has been identified through a trial&error procedure so as to guarantee an acceptable level of noise immunity (here we used \( \theta=3 \)).

We believe that the proposed Hebbian-like tracking algorithm if effective provided that:

1) The spectrum of the perturbation wave is limited to the region for which the converter \( V_s \rightarrow I_s \) transfer function is flat in modulus with zero phase. Additionally perturbation wave amplitude must allow current channel perturbations arising outside the maximum working point to be separated from noise at the ADC level (satisfaction of this design constraint can be verified at simulation level).

2) The update gain to be used in gradient ascent is small enough to guarantee convergence towards the unique maximum, yet providing enough reaction ability to tracking the changes (the parameters can be identified with simulations and perfected after implementation, as done in this work).

During operational activity the control CPU also monitors the battery voltage and disables the converter whenever the voltage is above a safety voltage threshold (hence introducing an extra charge limiter). Moreover, the CPU performs a digital zero compensation of the current channel readings, sampling the channel before the converter is turned on. This digital zero compensation is necessary since the low current/low power analog current reader has an intrinsic bias which needs to be removed to grant an accurate detection of the zero power condition.

The implemented algorithm runs on a 8 bit PIC16F870 CPU at extra low power 32.768kHz clock frequency so that the CPU consumes only 30\( \mu \text{A} \) and does not need to be necessarily switched off [20]. The data interface was written in TinyOS [21] so that power-related information necessary to the control CPU can be easily acquired by the master CPU of the WSN node (executing TinyOS code); such information can be fruitfully exploited in energy aware contexts such as routing [22].

IV. EXPERIMENTAL RESULTS

The whole electronics, suitably adapted to be plugged onto a CrossBow Mica2 wireless unit, was implemented and completed with rechargeable batteries and a solar panel. In the following we will consider three amorphous silicon solar cells characterised by 50mW, 200mW and 400mW units, respectively (as previously said the electronics and the control system are able to host any small power solar panel without any adaptation needs). The suggested WSN unit was then deployed for test in an alpine valley (Italy, north of Como Lake) for more than 100 days starting from the summer of 2005. There, because of the alpine microclimate, thunderstorms, rain and clouds are the norm rather than the exception; experiments presented in this section must hence to be intended in this operational framework. An operational picture of the WSN node is given in figure 6.

Figure 7 shows an operational situation where the amplitude exploration is activated to identify the initial operational working point; afterwards the algorithm commutes to the gradient tracking modality. We considered a 50mW amorphous silicon solar cell. The upper plot of the figure represents the voltage across the cell whereas the lower one the current coming from the converter (proportional to the generated power). The converter is initially off; then the CPU provides a zero current compensation (point A in the figure), activates the converter and identifies the optimal initial working point through amplitude exploration. This exploration (from the maximum to the minimum value) induces the system to scan the characteristic function of figure 3. Such a convex function can be neatly seen in point B. Once this amplitude exploration has been accomplished, the algorithm selects the initial working point.
associated with the maximum generated power (the maximum value in the plot and the CPU switches into the gradient-based tracking mechanism (point C onwards)). The second situation depicted in Figure 8 represents a case where the adaptive control algorithm takes an active part. The system, once in the control modality, maintains $V_s$ around 1.5V (point A). The superimposed triangle perturbation waveform can be seen in the control variable but not in the controlled one since the system operates in the optimal working point. In point B we observe that there is a power increment coming from the cell associated with a current increment. This change in radiating power requires $V_s$ to be dynamically updated towards the new optimal point at about 2V. Such a value is then maintained (point C onward) explaining a stable radiation condition. We appreciate the fact that the system reacts and reaches a stable condition in about 10s, which we considered to be a good performance in an extremely low power systems (we could easily increase the speed of the controller at the expenses of additional consumed energy).

We generated a realistic situation resembling a node deployment (which depends on the specific application). Here, the node was executing a simple code: a) acquisition of a sensorial information (the one associated with the energy level); b) processing (a local sliding window averaging the acquired data); c) transmission (the processed information was sent to the host every half minute). We positioned the solar panel so that it was receiving only a limited direct radiation (about 3 hours per day) being mostly in shadow during the daylight time.

Figure 9 shows the evolution of the harvested power (upper plot) and its corresponding battery voltage level (lower plot) over 5 days. Here, the power cell is a 400mW amorphous silicon solar panel.

The system generates a significant amount of power even when the cell is not directly illuminated by the sun (tails A in the figure) and in correspondence with a bad weather (curves B). In particular, the second day was characterised by a strong all-day storm). A zoom of the first day of acquisition is given in Figure 10. The solid line curve represents the power generated by the cell whereas the dashed one refers to the $V_s$ imposed on the cell by the system. The activation of the control algorithm can be clearly seen: in the early morning the system activates the converter immediately when there is enough power coming from the cell to justify a net
gain in energy (the initial working point is set at $V_s=1.5V$). Afterwards, the diffuse luminosity rises in intensity and the net transfer of power increases as well. In correspondence with point A the sun directly illuminates the cell and the power suddenly rises to its maximum value (and $V_s$ stabilises around 2.2V). Direct radiation ceases at point B and the panel goes into shadows: $V_s$ is adaptively lowered to extract power also during this non optimal condition. At the sunset, when the CPU identifies not enough power to be generated, the system switches into a sleeping modality which, as we have seen, implies a periodic wake up to control if it is time to return into an energy harvest modality. The effectiveness of the control algorithm can be associated with a good correlation between the produced power pattern and the control voltage one; this is particularly evident in the lower power region, where the adaptive controller is necessary to extract power.

Obviously, the generated energy is simply the integral of the power curve over time. For instance, the total energy generated in figure 10 is $E = \int_{t_0}^{t_f} P(t)dt = 2596 J$

A good figure of merit to evaluate the effectiveness of the proposed system is the percentage of energy generated during shadow periods where traditional solutions are not effective. By considering the [0 - point A] interval and from point B onwards we obtain $E_{\text{shadow}} = 652 J$ which represents a

$$\theta = \frac{E_{\text{shadow}}}{E} = 25.1\%$$

of the total energy generated during the day.

We experimentally discovered that the minimum power for which there it exists a net energy production (available power at the battery minus the one consumed by the electronics) is one 400th of the nominal power for the cell (being around 1 mW in absolute units for the envisaged cell).

A long on-the-field deployment

In order to validate the system in the long run we considered a 200mW amorphous silicon solar cell (we remind that different solar panels can be directly connected to the electronics without requiring any modification) continuously operating for 74 days (from August 8th 2005 to October 20th 2005). In this time period we experience, on the alps, a good average weather first, becoming worsening in September and even worsening in October. Moreover, the solar radiation decreases over months getting closer to the winter.

During operational life we acquired and transmitted three sensorial information characterising the system in its solar energy harvesting ability:

1) Cell generated power
2) Cell working voltage $V_p$
3) Storage battery voltage $V_b$

The sample rate was set to 1 acquisition per minute for a total of more than 1 hundred thousands points. Figure 11 presents the harvested energy per day (upper plot) and the cell battery voltage (lower plot) over days.

As in the previous experiment the Mica2 mote performed a sliding window average over the acquired data and a subsequent data broadcast towards the base station 24h per day. We verified that, once fully charged, and without any energy harvest mechanism, the system was running out energy after about eight days. Figure 12 shows the cell’s working points during the whole test. We see that the system is experiencing, during its life, all feasible working conditions ranging from 1mW to 200mW. The working voltage is fixed at about 2.2V when the power rate is above 50mW where at lower power rates the working points are forced to stay on a convex curve starting at 1.5V and ending at 2.2V. We can observe that the working point at high power rates (i.e. above 25% of the nominal power capacity of the cell) is constant but not rigidly imposed as it happens with a diode circuit or an a priori given cell model; at low power rates (up to 25% of the nominal power capacity of the cell) the converter adapts to efficiently extract energy.

The effectiveness of the system can be seen by referring to figure 13. More specifically, the upper plot represents the daily generated energy which must be compared with the lower plot representing the process efficiency:

$$\eta_i = \frac{\int_{\{d_i,P(t)<P_{th}\}} P(t)dt}{\int_{\{d_i\}} P(t)dt}$$

where $d_i$ refers to the i-th day time and $P_{th}$ is a pre-set
power threshold, which we fixed at 50 mW. De facto, the $\eta$ plot provides the daily percentage energy generated by the system at low power rates (i.e. below 25\% of the nominal power capacity of the cell), characterized by those working points residing on the high curvature of power manifold of figure 12 (in these positions a controlled converter is mandatory for an efficient energy generation). It can be seen that this fraction is high not only during days characterised by low energy generation (for which all energy is generated in the low power region, so that $\eta$ equals 100 \%) but also during days characterised by a medium energy generation. Only during days with the highest energy generation (which were prevalently sunny days) this percentage is negligible.

The most relevant information related to the quality of the harvesting process is the overall energy generated in the low power region compared to the total, i.e., the regions where the adaptive algorithm is extracting energy otherwise not extractable by a simple diode solution, leads to a

$$
\frac{\sum_{i=1}^{74} \eta_i \cdot E_i}{\sum_{i=1}^{74} E_i} = 26.40\%
$$

(8)

Fig. 14. Comparative experimental results with a 500mW policristalline silicon cell

Comparing traditional and adaptive solutions

The last experiments are devoted to compare performance in terms of energy harvested by the suggested adaptive algorithm with the more traditional and - simple one- based on a single diode recharging circuit. In order to carry out comparison with the set up suggested in [8], the proposed MPPT was connected to a 500mW peak power policristalline silicon cell while a second identical cell was connected to a 2.4V NiMH battery pack through a single diode. The two cells were deployed outdoor, one next the other, in the same environmental conditions. Figure 14 shows a typical power generation pattern obtained by the two systems. Trace T1 is the power generated by the adaptive system whereas trace T2 is the power generated by the diode circuit.

The power curve generated by the controlled circuit (continuous line) is above the one generated by the diode solution (dotted line) indicating that the former is more effective in transferring energy to the battery than the latter. A zoom of the first plot is given in the lower one and shows that the diode-based circuit does not generate energy at power levels below 10mW whereas the suggested solution generates energy at power levels as low as 1mW. We also experimented that the power consumption of the suggested adaptive circuits requires less than 1mW to operate and that the power stage efficiency is about 50 - 60 \%; we are currently investigating this issue to further improve performance.

V. CONCLUSION

A low power maximum power point tracker has been suggested in the paper to maximize the energy generation from a small, low power solar cell. The entire design of the system, from the power converter to the digital control system has been expressly designed for low power operations, independently from the specific nature of the solar panel and the battery type. Experimental results show that the suggested control system is able to generate an energy transfer rate particularly high also when the cell is in shadow or the
weather is cloudy, differently from existing solutions for WSN nodes that do not produce energy in these situations. In future releases we will improve efficiency of the power stage by analysing and reducing inductor auto oscillations affecting power stage efficiency and by investigating series-parallel cell reconfiguring circuits which can introduce further degrees of freedom in the cell characteristic hence improving the energy harvest possibilities. Furthermore MPPT algorithm steady state oscillations will be possibly optimized as suggested in [23].

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