Solar Energy Harvest on Bicycle Helmet for Smart Wearable Sensors

Daniele BIBBO, Silvia CONFORTO, Antonino LAUDANI,
Gabriele Maria LOZITO

Dep. of Engineering, Roma Tre University, Via Vito
Volterra 62-Corpo B, Rome 00146, Italy;
daniele.bibbo@uniroma3.it; antonino.laudani@uniroma3.it;
gabrielemaria.lozito@uniroma3.it;
silvia.conforto@uniroma3.it.

Abstract - **In this paper is presented the research towards the implementation of a prototype helmet for cyclists, equipped with a distributed array of PV cells. The work aims to create a power supply, either independent or auxiliary, for smart and wearable sensors. The implemented prototype has been characterized both in a controlled environment and on the field to assess the amount of generated useful energy. The system proposed in this paper can be used to produce energy to supply a smart sensor based device placed on the helmet; as an application, this could be used to send an alarm in case of an accident occurred to a cyclist, without placing heavy or dangerous battery on the head of the final user.**

Keywords—energy harvesting; cycling; wearable system; smart sensor; maximum power point tracking (MPPT); photovoltaic device; microcontroller unit.

I. INTRODUCTION

The monitoring of human activity is, on the technical point of view, a continuous challenge in terms of design and development of innovative smart and wearable systems that aims to the dimension reduction and to the increase of the energy autonomy. These devices can implement many features, such as the human physical activities [1-2] or sport performance assessment [3], this last relying on accurate measurements carried out with optimized instrumentation [4]. In order to ensure the good performance of a smart device, especially in terms of proper accuracy [5-8], specific algorithms are required. The optimization of the computational costs for those algorithms [9-12] is an absolute requirement to guarantee a long duration of power supply. Yet this might still not sufficient to provide the necessary autonomy, especially if large size batteries cannot be used. For outdoor sport activities such as running, cycling and hiking, when smart sensors are involved, an optimal management of the tradeoff between energy supply weight and duration must be considered. Almost all smart sensors are based on Microcontroller Units (MCU) that require a steady supply of current at a voltage that can be regulated at 3.3V for standard digital electronics. Voltage regulation is, in general, achieved through step-up converters. The magnetic elements that are often present in such converters are still an open modeling problem [13-16], especially at small scales.

Regardless of the technological advances achieved, battery life is still probably the most central issue. This topic is even more central for outdoor prolonged activities or in urban areas, where distributed power generation using renewable energy [17] is a leading technology for smart sensor integration. Among different approaches that can be used to power the sensors, energy harvesting by photovoltaic (PV) effect is one of the most interesting. Indeed, since the obtained power depends strongly on the irradiation level, even for outdoor activities an accumulator is in general a required component for the power supply unit (PSU). Another key aspect is the management of the strong non-linear current-voltage (I-V) characteristic of the device. The voltage generated by the PV device needs to be adapted for the application by a direct current converter (DC-DC). At the same time, the DC-DC must manage its input resistance to keep the PV device operating point as close as possible to the maximum power point. This process is called Maximum Power Point Tracking (MPPT). This is a major issue for PV energy generation at any scale, and becomes more dramatic for rapidly changing environmental (irradiance G and temperature T) conditions.

The last aspect to consider is battery management. The most common choice for energy accumulation in a sensor application are Lithium based batteries. However, Lithium batteries has a very small internal resistance and can discharge very rapidly if shorted. For this reason, overcurrent and thermal protection are in general implemented. Moreover, the recharge process is complex as well, requiring a circuit able to exhibit both constant current and constant voltage. In this work, a complete system for energy harvest by a PV source, featuring all the aforementioned aspects, is presented. The system is composed of an array of PV cells, a Lithium-Ion (Li-Ion) battery, and a control board including both battery management and a DC-DC step-up converter implementing an MPPT algorithm. The setup was assembled and mounted on a cycling helmet. The system was tested in several steps both in laboratory under artificial lighting, and outside to test the capabilities in changing environmental conditions. The single components of the PV array were individually tested under artificial light. Then, the battery recharge system was tested in a controlled environment. Finally, the system was validated in several outdoor scenarios to assess the effective energy generation in irregular environmental conditions.

978-1-5386-3906-1/17/$31.00

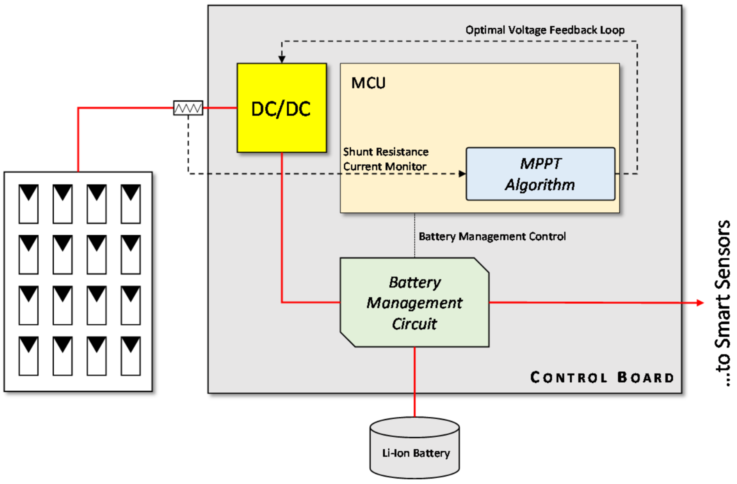

Fig. 1. Overview of a system for PV power harvesting, featuring a source PV array, a control board and a buffer battery.

For all the tests, the system was monitored in terms of generated current and voltage by means of a Lab-View controlled measurement device. The paper is structured as follows. In Sec. II, the topic of smart sensing for outdoor sport activities, with particular interest in the energy requirements, is introduced. In Sec. III, the general concept of harvesting by PV devices is discussed, pointing out the major issues and possible solutions. In Sec IV, the proposed system and the individual subsystems are explained. In Sec. V, the test setup and results are discussed. Conclusions and final remarks close the paper.

II. SMART SENSOR

Among the different sensors used to monitor human activity, many devices have been developed in the recent literature in cycling, useful both for the performance monitoring and for the road safety improvement. To do this, the system described in this paper can be used to produce energy to supply an accelerometer-based device, placed on the helmet, which could send an alarm in case of an accident occurred to a cyclist. This system could have a typical consumption in the range 30-200μA while acquiring and storing data; on the other hand, this requires a high peak current when transmitting an alarm with a low range radio device (i.e. 50-70mA for 30s using a UMTS). With those requirements, these devices could be supplied with a solar cells array coupled with current storage elements, to avoid the use of heavy batteries placed on the helmet.

III. PHOTOVOLTAIC ENERGY HARVESTING

Energy harvesting is the process of extracting small amounts of energy present in the environment for specific applications. It represents a very smart strategy to increase wearable smart devices energy autonomy, especially when combining these features with sensors [18]. Solar energy harvesting tries to cover surfaces exposed to solar radiation with PV devices able to transform the radiation in electric energy. The amount of energy produced is strongly dependent on the surface covered with PV devices. Indeed, if a surface is not natively thought to host a PV device, it is not necessarily flat, or oriented to give maximum exposure. Moreover, in mobility applications, the surface can be subject to variable irradiation profiles. Thus, the choice of a suitable surface to be covered with PV devices is a critical decision. Even assuming the devices are arranged in a correct way, harvesting solar energy requires a complex control system to manage:

- the nonlinear nature of the PV device
- the time variability of the primary energy source.

A system that can possibly manage such issues is the one shown in Fig. 1. On the left, the generating array is shown.

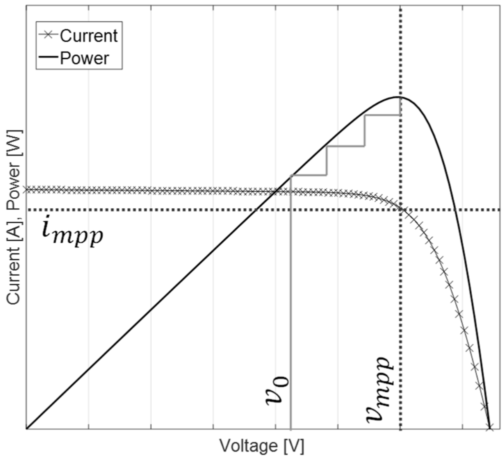

Fig. 2. Working principle for the MPPT algorithm “Perturb and Observe”. bold line is the Power-Voltage curve. Dashed line is the Current-Voltage curve. The algorithm aims to reach the maximum power point at v_{mpp} starting from a generic non optimal point v_0.

The connection between the devices is arbitrary, however, being the surface irregular, for such an application partial shading of the cells is an issue to be taken in consideration. A solution could be the connection of several higher voltage modules in parallel, to increase the current production. The control board is connected to the array through a small shunt resistance used to measure the current generated from the PV device. The current, along with the device voltage, is required to compute the instantaneous power, which is the parameter optimized by the MPPT algorithm. Several approaches exist in literature to compute the MPPT in embedded environments [19]. Then a programmable DC-DC converter elevates the voltage of the cell, making it suitable to recharge a Li-Ion battery. Moreover, it dynamically changes its input resistance to ensure the PV array works as close as possible to the MPP. In general, commercial MPPT controllers use a technique known as "Perturb and Observe" to track the maximum power point. The technique works by altering the operating point of the panel (i.e. by changing the input resistance of its load, which is the DC-DC) and its basic working principle is explained in Fig. 2. The initial operating point, shown in blue, is v_0, and it is non-optimal. The algorithm perturbs this point in the direction of increasing output power (thus, the necessity to measure the current output of the PV device) until it reaches a maximum at v_{mpp}. The technique is very simple and effective, but in case of rapidly changing environmental conditions, can be rather inefficient. This is because the shape of the Current-Voltage curve (and thus, the Power-Voltage curve) is very sensitive to irradiation and temperature levels, and following the maximum can be difficult. Several researches deal with this topic, and techniques that are more refined can be used if the computational power allows it. In particular, neural approaches proposed in [20, 21] are very robust when a highly variable irradiance is involved due to their deterministic approach. Indeed, the limiting factor is the response of the MPPT control system. Although modern MCU feature floating-point units, the fastest approach would be to use an Application Specific Integrated Circuit (ASIC) based on an FPGA developed NN [22]. Still, FPGA control systems often features large power consumption. For this reason, in the proposed approach, a MCU based control is preferable. The MCU based approach consists in using a very efficient NN (in terms of precision versus computational costs) to compute the optimal operating voltage of the PV device. The NN is memoryless and features three inputs and one output. The inputs are the actual panel voltage, the actual panel current and the actual panel temperature. The output is the v_{mpp}. The dataset used to train the NN comes from an identified circuit model able to represent the PV device under different environmental conditions. In this case, obviously, the network will be able to compute the MPP for a specific PV device only. If a different device is used, the network must be trained again. Microcontrollers have limited computational resources. For this reason, authors propose the use of an efficient NN architecture for embedded development, the Fully Connected Cascade (FCC) [21]. This architecture can achieve the same precision of a classic Feed Forward NN with roughly half the computational costs. Regardless of the methodology used to compute the v_{mpp}, this information yields an efficient voltage adaptation on the DC-DC. Adapted voltage is then sent to the battery management circuit. This circuit manages both the storage logic and the battery recharge procedure. The former is the control for the energy routing circuit, which manages the connection between the load, the DC-DC and the buffer battery in various working conditions. The latter manages the controlled protocol used to recharge Li-Ion batteries. The external Li-Ion battery is used as a buffer to stabilize the power supply to the sensors in the case of a variable irradiance level. Indeed, other options might be considered for the secondary accumulator; still, the Li-Ion option offers a very good tradeoff between charge density and easiness of recharge procedure.

IV. THE IMPLEMENTED PROTOTYPE

In Fig. 1 the scheme of our prototype is shown. The PV source is an array of 30 parallel PV Si monocrystalline cells KXOB-2204-X3. The cell parameters are reported by the producer in the datasheet at Standard Reference Conditions (SRC), i.e. irradiance G = $1000 W/m^2$ and temperature T = 25°C, and are reported in Table I.

TABLE I. PARAMETERS FOR THE KXOB-2204-X3 CELL DECLARED BY THE PRODUCER AT SRC.

Parameter	**Value**	**Unit**
Open Circuit Voltage (V_{OC})	1.89	V
Short Circuit Current (I_{SC})	15	mA
Maximum Power Voltage (V_{mpp})	1.5	V
Maximum Power Current (I_{mpp})	13.38	mA

In order to represent the behavior of a PV device at different environmental conditions, a suitable parametric circuit model is needed. Since the provided voltage at maximum power, for the single cell, is high enough for a step-up converter to be elevated at 3.3V, the configuration chosen for the cells is a full-parallel setup. This has two major advantages. First, the available current is increased potentially to about 400mA, which is a very large value for embedded sensing applications. Second, the parallel approach is more robust with respect to partial shading. As control board an Ultra-Low-Power Boost Converter (BQ25504, Texas Instruments) mounted on its Evaluation Module (EVM) was chosen. This implements a boost converter/charger that is specifically suited for sensors, which have stringent power specifics. The EVM allow measuring both voltage and current to the input (Vi,Ii) and to the output (Vo,Io) of the BQ25504, considering Rin and Rout typical of the device. The DC-DC step-up requires only few microwatts to work. The MPPT algorithm implemented on the board is very simple but effective. It periodically samples the Open Circuit Voltage of the cell and sets the operating point of the PV input at 80% of the sampled value. Moreover, if a more complex MPPT algorithm is available (e.g. by means of an external controller), this proportional logic can be bypassed and an arbitrary operating point can be set. The board implements advanced control features for the battery management as well, adding over-current and under-voltage programmable protection. As storage element, a simple button Li-Ion battery was used. The 30 PV cells were mounted on different strips upon a plastic cycling helmet and all the connections were made by simple wires, as shown in Fig. 3.

Fig. 3. PV Cells mounting on the cyclist helmet.

V. VALIDATION AND TESTS

In order to validate the system performance, two different kind of test were implemented: a) laboratory test, necessary to verify the datasheet declared performance of cells in the designed operative conditions; b) on the field test, in order to assess the system performances with the cells mounted on the helmet in real conditions. Both (Vi, Ii) and (Vo, Io) were measured during the tests. To do this, a USB Digital Acquisition Board (DAQ6210, National Instruments) was used, controlled through a Virtual Instrument panel (VI) developed in Labview. The time trend of the described quantities was acquired and the average data were calculated in different conditions.

A. Laboratory test

With the aim to evaluate the cells performances, a first test was conducted using a 1 kW reference lamp to illuminate the cells, 30cm distant from the cells, which were placed on a flat surface perpendicular to the center of the lamp. The cells were assembled in parallel arrays of different numbers (6, 4 and 3), corresponding to the ones to be mounted on the helmet. Data were acquired and averaged on a duration of 5 minutes for each module. Then, all the modules were mounted on the helmet and the same test was repeated, to verify if the designed cells position was the best one to minimize the shading. The helmet was positioned considering the same distance of single arrays from the lamp to its median height, thus obtaining some arrays closer to the lamp but some others more distant.

B. Field test

After the laboratory sessions, a series of tests were conducted to validate the device performances. At first, static tests were performed to evaluate the device functionality while charging the adopted battery. To do this, the helmet was positioned under the direct sun radiation around midday for a duration of 60 minutes. Tests were performed in 3 different sunny days, obtaining similar results, in Rome on the top terrace of the Engineering Department of Roma Tre University (Latitude: 41.854693, Longitude: 12.469587). The average values of voltage and current were calculated, considering the charging process of the adopted battery. Then a series of tests were conducted on a specific circuit, while a subject wore the helmet during normal cycling. In each test, the subject pedaled at constant speed for about 20 minutes on a rectangular circuit completely exposed to the direct sun radiation, with no obstacles or extended shadowed areas. The tests were carried out in 3 different sunny days, in the same location of the outdoor tests described above, with similar weather conditions, around midday with an external temperature ranging from 29°C and 32°C.

C. Results and discussion

The results of the test obtained on the cells array during the test with the lamp are reported in Table II. The results about the helmet under the same conditions give an overall value of 153±0.1mA. This value is coherent with the sum of single arrays: the shading effect is compensated by the relative position of each module with respect to the lamp.

TABLE II. OUTPUT CURRENT OBTAINED POSITIONING THE CELLS ARRAY UNDER A 1KW REFERENCE LAMP.

# of arrays	# of cells in array	Average Current
2	6 cells	≈29 mA
3	4 cells	≈21 mA
2	3 cells	≈16 mA

In general, the current values obtained show that in these conditions the cells efficiency is about 1/3 with respect the nominal one at the MPP, probably due to the non-optimal load of the cells. The results of the tests obtained on the helmet during the entire static test under the direct sun radiation are reported in Table III.

TABLE III. AVERAGE CURRENTS AND VOLTAGE OBTAINED DURING TESTS UNDER THE DIRECT SUN RADIATION.

Weather	time	V_{in}	Iin	Vout	Iout
☀	12:00	1,202± 0,143V	0,108± 0,012A	3,37± 0,19V	0,018± 0,0018A

The input values are coherent with the performances obtained using single arrays of solar cells, considering that the movement of the helmet on the head while pedaling can cause a different alignment under the sun radiation. The output values obtained depend on the battery adopted for tests, considering that the BQ25504 battery manager can automatically adjust the input voltage and current since the type of accumulator and its level of charge.

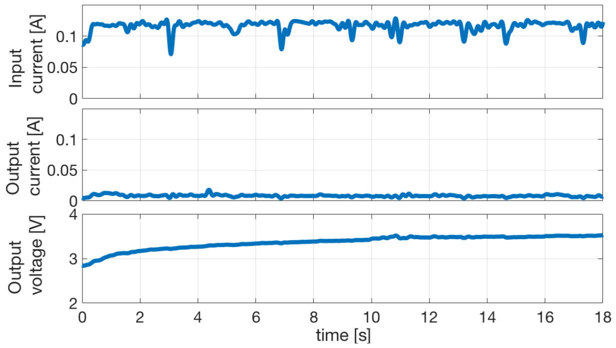

Fig. 4. Time trends of current and voltage while charging a test battery under the direct sun radiation.

In Fig.4 the current and voltage time trends of a test are shown to represent the charging process. It is important to highlight that in the input current trend there are some minimum peaks, due to the presence of small shadowed zones in the circuit that however do not affect the output current supply. At the same time, the correct battery charge process is guaranteed also in terms of output voltage, which increases with time.

A further test was performed in cloudy conditions and the corresponding time trends are shown in Fig.5. As in the previous case, the charging process of the battery is correctly guaranteed, thus demonstrating a good robustness of the system to the discontinuity of the radiation due to the presence of the clouds.

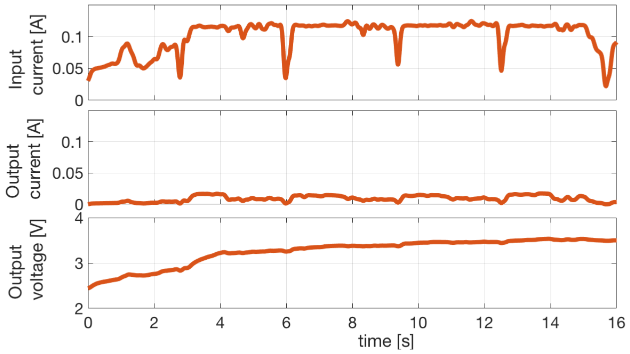

Fig. 5. Time trends of current and voltage while charging a test battery under the direct sun radiation in cloudy conditions.

In conclusion, the limited amount of supplied current related with the output voltage depends on the automatic algorithm used by the BQ25504, which guarantees a correct process of charging. Considering the tests performed without using it the system could provide higher levels of current. This could be useful to supply current storage capacitors directly, avoiding the use of batteries, thus reducing the total weight of the device.

VI. CONCLUSIONS

The research presented in this paper shows that the use of solar cells array positioned on the cyclist helmet could provide the necessary energy to supply a wide range of smart sensors, with application ranging from the human performance monitoring to the road safety improvement. The same device could be adapted in many different fields where a helmet is required and wearable sensors positioned on the head are necessary, as for example airbag activation in motorcycling. Moreover, since mounting large batteries near the head, especially when a considerable battery life is required, could be hazardous, such kind of systems could be a critical asset to ensure the user safety.

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