Electronic Device Design for Energy Harvesting of indoor and outdoor light sources for multiple low power usage.

STELIOS KOURIDAKIS, PANAGIOTIS GIAKOUMAKIS
Department of Electronic Engineering
Hellenic Mediterranean University
3 Romanou st, Halepa, Chania
GREECE
kouridakis@hmu.gr ; panagiotisgiak@gmail.com

Abstract: - After developing technology in ultra-low power systems and sensors, a very good effort has grown on developing units capable to energy harvesting of limited power levels inherent to the surrounding environment. These energy species are vibrational, acoustic waves, temperature, e/m waves, motion and light sources. We can exploit those energies to turn in electric energy for powering modern sensors or sensor units, placed on any inaccessible places. The device design we describe and explain on this paper is an energy harvester of light sources from electric lamps in closed rooms to sunlight. It's based on a small photovoltaic panel (PV) of $100cm^2$ and an MSP430F5529LP microcontroller (μC) board, responsible to track the direction of max light intensity and control two servo motors for moving the PV panel towards it. In addition, the μC derives maximum power from PV keeping the operation to Maximum Power Point (MPP). The device has a circuit to charge a battery, too, to keep powering the sensor unit during dark or very low-level lighting periods of a day.

Key-Words: - energy harvesting, photovoltaic panel, MPPT, microcontroller, servo-motor, max light tracker.

1 Introduction

Environment around us has a lot of sustainable energy sources, like wind, geothermal, thermal, sea wave, tidal and solar energy. We use different methods and technics to derive energy from those sources and convert to electric. An attempt is made to improve the efficiency of conversion, harnessing electromechanical systems and dedicated electronic circuits. Besides that, another important parameter on producing more electric power is to study statistical data of energy maps of the area, then to choose best place with great energy potential to construct our system. As an example, wind turbines are installed on the top of hills and mountains where wind potential is higher than on urban places, so efficiency of produced energy is much higher. Such installations produce tens to hundreds of megawatt electric power. Solar park installations, as a second example, are established on places with no obstacles, like trees or buildings, to avoid shadows. Photovoltaic panels have to be oriented to the direction of sun for the whole day for their best performance and higher efficiency on sun power conversion. Fixed solar panels have lower efficiency than sun-oriented ones. This is an important benefit for an installation to have solar trackers for sun and move panel surface following its orbital movement. Establishments of medium and large-scale solar power systems give electric power of hundreds of kilowatts to megawatts.

Nowadays, as the technology grows rapidly on microelectronics, new designs integrate electronic micropower systems and as a consequence their power demand is minimized reaching the lowest energy consumption needs. Modern designs and applications with micropower sensor units arose the need for energy harvesting from sources surrounding these. It happens very often to find these placed on points, sometimes inaccessible and unpowered, as power wires are far away. These sensor systems are supplied usually with an RF transmitter, for communication between sensors and host computer and need electric power to work, exceeding from some μW to a few Watts at least cases. So, the need of designing and implementation of micropower energy harvesting systems grew up for powering such sensor systems and other remote applications, depending on individual system demands. Energy harvesters are based on energy sources located to the environment of such sensors or any other micropower units. These power sources include vibrational, thermal (temperature), sound, RF, light and sunlight sources. Between them we notice that ambient light of an illuminated office has an average power density of $100uW/cm^2$ and from direct sun $100mW/cm^2$ (3 orders of magnitude more than in office) as we see in Table 1[1]. This density is far away greater than other type sources as vibrational,

thermal, sound or RF. This is the reason our design is based on light sources, indoor and outdoor.
On energy harvesting system designs we meet two basic architectures [2]. A) *Harvest-Use architecture:* Such harvesting systems supply the target units directly after energy conversion to electric.
B) *Harvest-Store-Use Architecture:* Systems based on this, store energy to a battery or a supercapacitor (supercap). Such systems continue to in case there is no energy to harvest, like solar panels in a dark room. For best performance, utilization of both a primary and a secondary storage constitutes the best choice for excess power availability and long-lasting power back up.
On our project we chose to design our device based on light energy harvesting, as it has more indoor and outdoor power density, for applications on places like an office or for installations of a camera at the outer walls of a building. It consists of a 100cm^2 PV panel which collects energy from different light sources. A feature of this design is to track and choose between light sources, the source with maximum light density. It is capable of searching existing lights on the surrounding area and locates the light with maximum intensity. Following this it turns PV panel towards that light to gain more power for harvesting, so it has more power availability and is capable to support loads with excessive power demands. Another feature for this device is the ability for Maximum Power Point Tracking (MPPT) with a proper firmware on it. It is of a great importance for systems based on PV powering technology, to support MPPT operation. System efficiency gets maximum and PV feeds the device with its max power [3]. Design is based on Harvest-Store-Use Architecture. Rest of power is stored to a rechargeable battery backup and a supercapacitor to power up device and sensors on periods with no light sources.

2 Description of device.

Device design implemented for portable or permanent installation applications, for electrical power supply to sensor systems or other types of micropower based electronic units for limited power consumption. For permanent installations, the choice of good luminosity positions is advised so that incident light to PV panel should have more intensity levels and therefore the device approaches to maximum efficiency on energy harvesting from surrounding area.
For understanding the operation and functions of device, a block diagram follows in Fig.1. On this diagram we see some sub units required for system integration as we will explain later on.
It consists of a PV panel of 10cm*10cm area. This is the unit for light energy harvesting and converts it to electric energy for powering the device itself for its proper functioning and to power up remote sensor units and/or other micropower units. Reliability and degree of usage depend on PV panel, itself, on its electrical characteristics, efficiency [4] and mainly on light power availability, as we will see on experimental results.

Energy Source	Power Density & Performance	Source of Information
Acoustic Noise	0.003 µW/cm3 @ 75Db	Rabaey, Ammer, DA Silva Jr., Patel & Roundy, 2000
Temperature Variation	10 µW/cm3	Roundy, Steingart, Frechette, Wright, Rabaey, 2004
Ambient Radio Frequency	1 µW/cm2	Yeatman, 2004
Ambient Light	100 mW/cm2 (direct sun) 100 µW/cm2 (illuminated office)	Available
Thermoelectric	60 µW/cm3	Stevens, 1999
Vibration (micro generator)	4 µW/cm3 (human motion - Hz) 800 µW/cm3 (machines – kHz)	Mitcheson, Green, Yeatman,& Holmes, 2004
Vibration (Piezoelectric)	200 µW/cm3	Roundy, Wright, & Pister, 2002
Airflow	1 µW/cm2	Holmes, 2004
Push Buttons	50 µJ/N	Paradiso & Feldmeier, 2001
Shoe Inserts	30 µW/cm2	Shenck & Paradiso, 2001
Hand Generators	30 W/kg	Starner & Paradiso, 2004
Heel Strike	7 W/cm2	Yaglioglu, 2002 Shenck & Paradiso, 2001

Table 1 Energy Harvesting resources and their Power Density

Device design and operation is based on the characteristic and requisite demand, the minimum power consumption for its operation. This is summarized in the selection and use of materials and integrated circuits of least power consumption on their duty cycle and least current flow during the periods they remain on standby operation mode. The design is built around the microcontroller unit MSP430F5529LP of Texas Instruments [5], Fig.2, which operates with very low current consumption of the order of 2μA to 1mA on full operation, which is considered a necessary condition for energy harvesting systems. Specific routines run on the microcontroller unit, based on software we developed to integrate and control device operation.

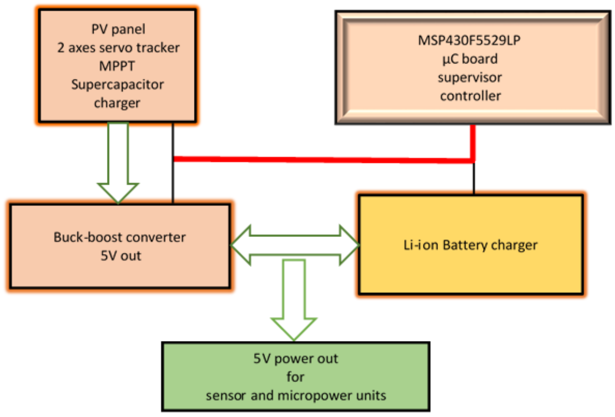

Fig.1 Block diagram of device

In order to maximize the power extraction, an electronic unit and its corresponding software were developed and this is a realistic advantage implementing our device. It is capable of detecting the surrounding light sources, which possibly may be more than one and to locate light source with the highest power density.

As an example, we mention the indoor application case where the lighting comes from distributed lamps on different roof points. At regular 10-minute time interval, μC wakes up and samples the light intensity on a 3D observation procedure, it locates the maximum light intensity position and then activates the light tracking unit and moves PV panel to orient to the maximum power source. Tracking system has two axles to achieve full orientation in the light source of maximum power and consists of two servo motors with their electronic power supplies.

Movement control and orientation of the panel are supported by the activation of the corresponding procedure in the microcontroller that activates the servo motors.

Next to light tracked PV panel, the Maximum Power Point Tracking (MPPT) [6] circuitry is involved with a supercapacitor charger circuit for the case of max efficiency and optimum performance. On MPPT operation all electrical power obtained by PV panel is delivered to the device. It's very important to this kind of applications, with energy harvesters, to manipulate even the smallest amount of energy, thoroughly. On this operation, a fraction of PV power is fed to the device for operation and the remnant charges a supercapacitor and a Li-ion battery. It is accomplished with a dedicated functional procedure which runs on μC and controls the operation. Therefore, with the storage circuits of excess energy in two different elements, the supercap and the battery, we have a guaranteed operation even under very adverse conditions. This implementation is the second advantage for the device.

For reliable device operation, regardless of the growing voltage in the PV, which in turn depends primarily on the incident light power on it, there is the buck-boost converter unit to 5V output.

The regulated output voltage of 5V is independent of input supply of the converter which can range from about 0.3V to 18V which is much higher than the maximum voltage in PV.

Fig.2 MSP430F5529LP μC board

The 5V voltage, as shown in Fig.1, is the main output voltage of the system that powers the device and any unit connected to it, such as sensors and micropower units.

Concluding the description of device block diagram, we also observe the Li-ion battery charger unit, which during its operation draws part of the accumulated energy of supercap and directs it to charge Li-ion battery.

Its operation is controlled by μC depending on the charging level of battery and stored energy on supercap. On periods of low capacitor charging, such as long dark periods, battery works as the power backup and supplies the circuits and sensor units.

In the next Fig.3 we see the device we implemented, with the rotating PV panel, the two servo and the other units, like the μC, the supercap, 5V buck-boost converter, battery charger, battery and max light tracking sensors.

Some detailed description of units and circuits of device we see on next subsections.

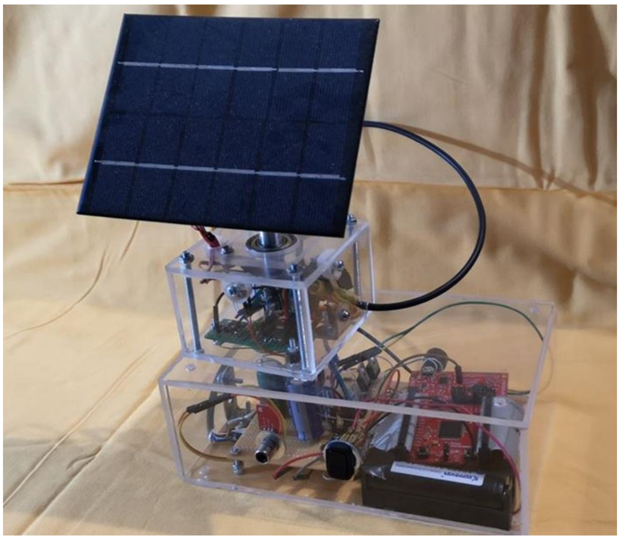

Fig.3 The device: Light energy harvester

2.1 PV panel-2 axes tracker-MPPT-supercap charger

Electrical characteristics accompanying PV Panel by manufacturer are: material Monocrystalline Si, Voc≈ 5,5V, Isc≈ 240mA and P_{PV}≈1W at solar power of 1000W/m^2 under the global AM1.5 spectrum. This PV panel is suitable as an energy harvester for the needs of electric powering of our applications. It is supported with a 2-axes tracker system consisting of two servo. One is dedicated to move the panel on azimuthal direction from 0^o to 180^o and the other on tilt angles from 0^o to 180^o. Servo motors we chose are lightweight, small in volume and need 5V to work with least of energy. Maximum light tracking for device is achieved by four light sensors. These are allocated in four quarters of hemisphere space, above the horizon. Each of them tracks its region of space to detect possible existence of any light source. Microcontroller collects signaling information concerning these sensors and locates to the most intensity light. Following these, μC manipulates both servos to move and locate PV panel towards this source, so system efficiency is maximized. For system energy conservation the above procedure repeats between dedicated time intervals.

An MPPT - supercapacitor charger circuitry has been designed for system best performance, including a PWM buck conversion circuit. From PV input side, μC controls a MOSFET electronic switch by modulating its pulse width and reads PV voltage. When it reduces to about 78% of V_{OC}, PWM duty cycle is locked, respectively. This technical approximation gives best results for a satisfied approximation to theoretical MPP [7]. It is known from experimental results and confirmed with our measurements that PV MPP is between 0.78 to 0.82 (0.70 to 0.80 for our PV measurements) of V_{OC}. MPP circuit behaves as a current source to charge the existing supercap with a controllable current and increasing voltage, accordingly.

2.2 Buck – Boost Converter – 5V out

This circuit is implemented by an LTC3119 [8] integrated circuit (IC). Its mission is to operate with input voltage from supercap or from battery and outputs a constant voltage of 5V to supply all device circuits, plus any kind of sensor unit connected to device. Talking about some operating details, that converter normally operates with supercapacitor power, which in turn is sourced by PV panel. That energy, harvested by light, feeds all circuits as μC, battery charger and external micropower devices.

2.3 Battery charger

This circuit is implemented by an LT3652 [9] IC operating as the battery charger of unit. Its input voltage is 5V from Buck-Boost converter (BBC) and charges a Li-ion 3.7V/3400mAh battery, a good choice to avoid memory effect of other types of batteries. Battery supplies BBC on periods with no light for device to harvest.

2.4 Microcontroller (μC) Board

Device operates under some functional routines supported by μC. In our design ultimate goal is to maximize energy efficiency. It is easily achieved with the inclusion of a μC which detects voltage from PVs, supercaps and battery, then it calls some individual routines and finally controls all circuit units.

A general description of above routines follows:

Max light source tracking routine: As described above, μC reads 4 light sensors voltage level and due to this routine discriminates coordinates of maximum light source and directs PV panel towards this source. It is accomplished by driving servo motors with appropriate signals.

MPPT – supercapacitor charging routine: As described above, μC calls this routine and tracks MPP of PV, keeping its voltage between 0.7 to 0.8 of V_{OC}

and controls charging supercap with constant current, respectively.
Buck – Boost 5V converter (BBC) routine: This routine reads supercap voltage and if it is sufficient it drives BBC to supply system units and external micropower units with 5V output. Otherwise, when supercap voltage is lower than a threshold of about 0.8V, battery connects to the input of BBC and operates as a backup power.
Battery Charger routine: Charger operates exclusively when BBC is powered by PV and pumps remainder of power from PV. Alternatively, when μC detects poor or no power to PV, then charger is turned off and battery is connected to BBC input.

3 Experimental results

An important operating characteristic of design is total power consumption of system plus sensor units. Taking worst case average device current of 0.5mA and assuming a sensor unit connected to it, with 0.5mA average supply demands, we finally need 1mA of current from 5V supply, so our power needs are summarized to 5mW average. This is total average power PV should supply, at least. As a consequence, we firstly tested PV panel for its response to different luminance, different temperature of light and on sun light.
On direct sun measurements, PV feeds the device with a power of 1.2W, which is much higher than its total power needs of 5mW, in continuous mode. As a second remark MPP optimum load is around 20Ω with $V_{PV\text{-}MPP}$=5.3V and $I_{PV\text{-}MPP}$=265mA We notice that $V_{PV\text{-}MPP}/V_{OC}$ = 0.80 (Table 2).

Light source: Direct sunlight						
Lux: 115000						
Voc (V)	Isc (mA)	P_{MPP} (mW)	V_{MPP} (V)	I_{MPP} (mA)	R_{MPP} (KΩ)	$\frac{V_{MPP}}{V_{oc}}$
6.8	280	1400	5.45	265	20.6Ω	0.8

Table 2 Direct sunlight PV panel output

Next set of measurements we had to implement for our PV panel concerned its response to various types of LED bulbs. These had different lighting spectrum, equivalent to blackbody emission on temperatures of 3000°, 4000° and 6400 °K. As a consequence, we wanted to know experimentally light response of our PV panel to any type of indoor lighting. Measurement results can be seen on Tables 3 to 5.
When the bulbs were placed 0.5m away from PV and its luminosity was 2000 Lux, then it produced Max Power from 3.3 to 3.6mW (Table 3) with MPP current (I_{MPP}) from 0.91 to 0.95mA at V_{MPP}=3.7V average (avg).
On PV luminosity of 550 Lux and distance of 1m, we measured Max Power of almost 1mW (Table 4) with MPP current (I_{MPP}) of 0.32mA at V_{MPP}=3.1V.

Light Source: LED Bulb–Distance from PV: 0.5m						
Source temp (°K):3000/4000/6400-Lux (avg):2000						
Voc (V)	Isc (mA)	P_{MPP} (mW)	V_{MPP} (V)	I_{MPP} (mA)	R_{MPP} (KΩ)	$\frac{V_{MPP}}{V_{oc}}$
4.86	1.08	3.3	3.65	0.913	4	0.75
4.91	1.11	3.5	3.74	0.935	4	0.76
4.93	1.12	3.6	3.8	0.95	4	0.77

Table 3 PV response on LED bulbs, 0.5m away.

When luminosity on PV was about 250 Lux on a distance of 1.5m, it produced a Max Power around 0.28mW (Table 5) with MPP current (I_{MPP}) around 0.12mA at V_{MPP}=2.36V average.
We notice PV responsivity is slightly depended to bulb equivalent lighting temperature and strongly depended to luminosity and therefore to the distance of lamps in indoor use.
PV panel was tested on some more levels of luminance from 3000Lux to 10000Lux and its average response ranged from 6.8mW to 21mW on I_{MPP} of 2.1mA to 6.5mA respectively. Notice that 10000 Lux luminance is an average of a daylight diffused insolation (not direct sunlight) and is interesting for our device for a whole estimation on a 24 hours operation under every possible illumination.

Light Source: LED Bulb–Distance from PV: 1m						
Source temp (°K):3000/4000/6400 Lux (avg):550						
Voc (V)	Isc (mA)	P_{MPP} (mW)	V_{MPP} (V)	I_{MPP} (mA)	R_{MPP} (KΩ)	$\frac{V_{MPP}}{V_{oc}}$
4.14	0.38	0.92	3	0.3	9.8	0.72
4.19	0.39	0.96	3.06	0.31	9.8	0.73
4.21	0.40	1	3.1	0.32	9.7	0.73

Table 4 PV response on LED bulbs, 1m away.

We investigate another parameter, on Tables 2 to 5, the ratio of V_{MPP}/V_{oc}. It starts from 0.7 on low level luminance of 250Lux to 0.8 on direct sun light. Low ratio for low level light is ought to increasing equivalent series resistance and decreasing low level external circuit current because of shunt resistance of PV [10]. But as we notice this ratio is improved and moves from 0.76 to 0.8 as luminance increased from 2000Lux to full sunlight. Keeping in mind this remarkable notice we developed MPPT algorithm, based on this ratio tracking. Temperature differences

were ignored as their influence was negligible to our design.
For a better estimation on power harvesting of device and its autonomous availability on powering micropower units we quote Table 6 with luminosities measured on some places, as a reference. As we see it produces a remarkable power even in indoor environments like an office with luminosity between 320 to 500 Lux and corresponds with much more power from indirect (diffused) sun light from 10000 to 25000 Lux, reaching the top of power on direct sun light.

Light Source: LED Bulb–Distance from PV: 1.5m						
Source temp (^{o}K):3000/4000/6400 Lux (avg):250						
Voc (V)	Isc (mA)	P_{MPP} (mW)	V_{MPP} (V)	I_{MPP} (mA)	R_{MPP} (KΩ)	V_{MPP}/V_{oc}
3.24	0.15	0.270	2.27	0.119	19	0.70
3.34	0.16	0.293	2.36	0.124	19	0.70
3.4	0.17	0.301	2.39	0.126	19	0.70

Table 5 PV response on LED bulbs, 1.5m away.

Keeping in mind all above experimental results, we tested and controlled all subunits of our equipment. Max light detection procedure with corresponding PV panel movement towards that light operated fine, even in rooms with multiple lights from different orientations. It really oriented to max light source or to the point of max average light.

Luminosity (Lux)	**Environment**
320 - 500	Office
1000	Cloudy day
10000 - 25000	Indirect sun light
32000 - 130000	Direct sunlight

Table 6 Various environment luminosities

MPPT procedure with proper circuit kept V_{MPP}/V_{oc} ratio between the prescribed limits, independent of load. Supercapacitor charging circuit operated reliably, keeping charging current equal to I_{MPP}. Buck – boost converter and battery charger operation were as expected. That is main electric power for both electronic circuits comes from supercapacitor, but alternatively from battery when PV power is too low. All device subunits worked in conjunction with one each other and any residual energy stored in battery. As a final report this equipment complies to all technical requirements and prescriptions, it's a state-of-the-art design and has an efficiency very close to PV efficiency and in most testing cases the battery was fully charged.

4 Conclusion

Energy harvesting systems based on indoor and outdoor lighting approved as the best choice after the above detailed analysis and experimental results of our design and the implementation of described device. Many different designs could be approximated using PV panels of smaller or larger area, constructed with different materials, having max light tracking system or without it. All are free in design and depend really on power demands of micropower system or sensors to support. Talking about our design, it is the best approximation for energy harvesting systems as it keeps tracking max light, exploits MPP for PV max power efficiency and making use of double energy storing benefits, a super capacitor and a Li-ion battery. This results on time expansion for longer autonomy and the beneficial characteristic of larger energy capacity.

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