A SIDO BUCK CONVERTER WITH ULTRA LOW POWER MPPT SCHEME FOR OPTIMIZED VIBRATIONAL ENERGY HARVESTING AND MANAGEMENT

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Abstract: In this work a new architecture for optimal vibrational energy harvesting is presented. The proposed power management system is based on a Single Inductor Dual Output (SIDO) DC/DC buck converter. The piezoelectric transducer is dynamically placed in optimal conditions thanks to an ultra low power Maximum Power Point Tracking (MPPT) scheme and a voltage controlled DC bus provides a high efficiency power path, which can supply any sensor, data logger, or microprocessor. The complete circuit has been virtually prototyped and simulated at component level using VHDL-AMS language. These simulations show that 3 times more energy can be harvested compared to a standard architecture. This makes our power management circuit an interesting building block for autonomous wireless sensor node realization.

Keywords: Vibrational energy harvesting, SIDO DC/DC, MPPT

INTRODUCTION

The recent development of the Ambient Intelligence and other Wireless Sensor Network comes with a strong need for remote power supplies. Even if considerable technological progresses on batteries have been done this last decade, they still remain unsuitable for certain applications due to their limited lifespan. Indeed, in bridges or buildings Structural Health Monitoring applications, the costs for batteries periodic replacement would be prohibitive [1]. Consequently energy harvesting from the ambient environment can be considered as a solution to extend the battery runtime or even to completely do without it [2].

This paper proposes a new optimal power management architecture for piezoelectric harvester. In a first part the piezoelectric harvester is described and experimental characterisation results are presented. Then, after an analysis of different solutions for optimal power harvesting, the selected architecture and the proposed control scheme are described. Finally, simulation results of the complete virtual prototype of the system are presented, and the efficiencies of the different stages are characterised.

PIEZOELECTRIC HARVESTER

Description

Piezoelectric energy harvesters are generally made of a clamped composite beam, with one or several piezoelectric layers, of which resonance frequency is fixed by design for a given application. A mass can also be added on top of the cantilever in order to increase the inertial effect that stresses the piezoelectric material. We use Volture Raw Harvester V21BL presented Fig. 1 which is a commercial harvester supplied by the Midé Technology Corporation. Bimorph beam dimensions are 60x17mm².

Fig. 1: Midé piezoelectric energy harvester.

The resonance frequency is tuned to 50 Hz with a 4.108g tungsten mass on top of the free end of the beam. Considering the low operating vibrations level, i.e. < 0.5g, the two active piezoelectric layers are connected in serial in order to increase the output voltage.

Characterization

In order to draw the electrical characteristic of the device, various resistive loads were placed across the output of the harvester. For each load peak-to-peak and rms value of the output voltage are recorded and average power calculated (Fig. 2). The acceleration of the clamped end of the beam is measured by a 3-axis accelerometer (Freescale MMA7260Q) placed into the framework of the harvester connected to the shaker. Several set of measurements were done for three different values of acceleration: 0.1g, 0.3g and 0.5g at 50Hz (see Fig. 2). In the following of this paper we will exploit an equivalent electrical model for the piezoelectric harvesting device. This model, previously described in [3], is based on the experimental characterization results of the Midé beam and leads to an average error of around 72mV in the range of 0.1g to 0.5g.

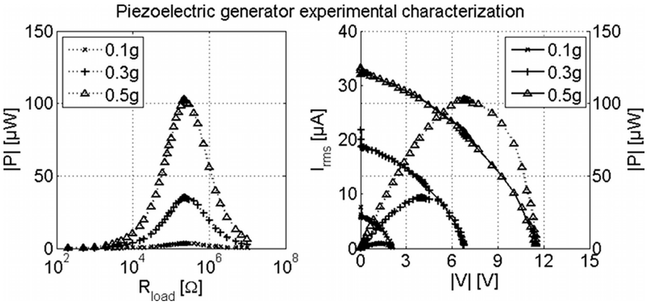

Fig. 2: Harvester characterization results.

Maximum Power Point Tracking (MPPT)

As it can be seen on Fig. 2b the harvested power versus the harvester polarization voltage is a bell-shaped curve. Thus there is a voltage, V_{MPP}, for which the power, P_{MPP}, delivered by the harvester is maximum. After this Maximum Power Point the power decreases as the voltage increases until it reaches V_{OC}, the Open Circuit voltage of the harvester for which the harvested power is null.

Table 1: Harvester characterization summary.

Vib. level [g]	$\lvert P_{MPP}\rvert$ [W]	$\lvert V_{MPP}\rvert$ [V]	$\lvert V_{OC}\rvert$ [V]	$\lvert V_{OC}\rvert/\lvert V_{MPP}\rvert$
0.1	$3{,}5.10^{-6}$	1,26	2,10	0.6
0.3	$35{,}5.10^{-6}$	4,02	6,77	0.59
0.5	103.10^{-6}	6,83	11,48	0.59

Consequently in order to achieve an optimal power, our micropower management system will have to regulate the polarization voltage of the harvester and place it close to the Maximum Power Point (MPP). This problem has been addressed in the literature, using a charge pump [4] or with inductive DC/DC converters [5,6,7,8] in order to isolate the piezoelectric film from heavy electrical load and be able to control the polarization of the source independently of the load voltage. But contrary to [5,8], our work aims at handling power in the range of the tens to hundreds of µW, without making use of external control signals as done in [7]. The solutions proposed by [6] and [8] are interesting but all the power consumed by the load passes through the storage element and two converters (Fig. 3b), which decrease the overall efficiency of the system. The proposed solution provides a high efficiency direct power path from the source to the load in addition to the MPPT scheme by using a Single Inductor Dual Output (SIDO) DC/DC converter (Fig. 3c).

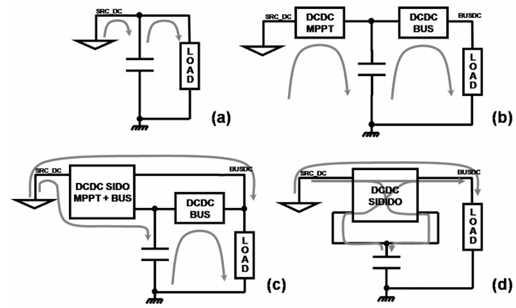

Fig. 3: Architecture of different power harvesting an management systems.

POWER CONVERSION AND MANAGMENT

First stage: AC/DC

The first stage of our system consists in an AC/DC converter. Indeed with vibrations based piezoelectric harvesters the AC voltage and current need first to be redressed. To maximise the efficiency of this stage we will use a passive Graëtz bridge full-wave rectifier (Fig. 5).

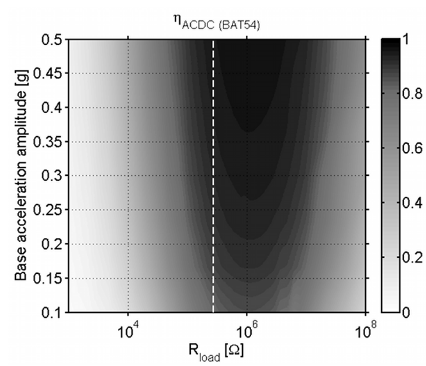

Fig. 4: AC/DC efficiency versus load and vib. level.

Our simulations leads that with BAT54 serie diodes the passive AC/DC stage average efficiency is 90% between 0.1g and 0.5g with a maximum value of 95% at 0.5g (Fig. 4).

Second stage: DC/DC-SIDO MPPT

As stated in the previous section, the second stage of the proposed micropower harvesting and management system is a SIDO DC/DC embedding a MPPT control scheme. A complete and detailed description of the MPPT circuitry can be found in [3]. The main function of the MPPT stage is to periodically sample the open circuit voltage of the harvester in order to provide a reference voltage, V_{MPPT}, to the DC/DC converter. Indeed as shown in Table 1, the ratio V_{MPP}/V_{OC} is constant over the whole vibration level range (0.1g to 0.5g). Thus the DC/DC converter regulates the harvester polarization voltage around V_{MPP} leading to a maximal power emission with an average efficiency of 95% [3].

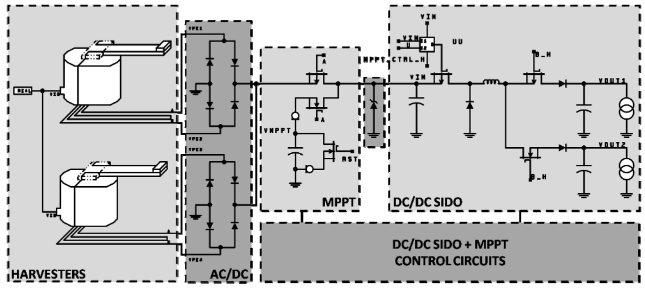

Fig. 5: Schematic of the power chain of the system.

The second function of the DC/DC converter is to handle the harvested power to provide a high efficiency regulated DC output that can supply any sensor, data logger, or microprocessor, while rerouting the power excess to an energy tank through a second output. Here the investigated tank is a simple capacitor but other electrochemical devices as super-capacitor or even battery can be used. We implement a Single Inductor Dual Output (SIDO) DC/DC converter to achieve this result. SIDO DC/DC converters are part of the Single Inductor Multiple Output DC/DC converters family which has been investigated this last decade for power management at the chip scale [9] but we show that they can efficiently used in power harvesting applications.

DC/DC-SIDO MPPT Control circuitry

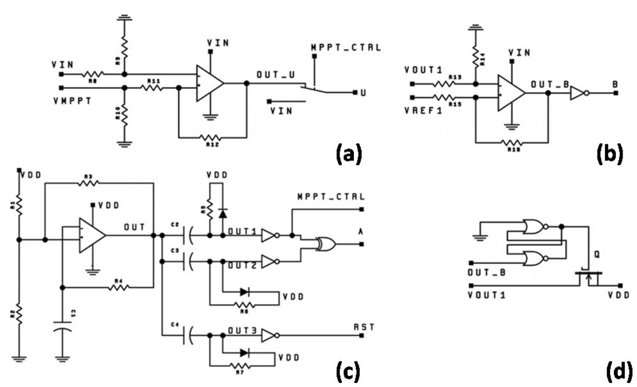

Fig. 6: Schematics of the DC/DC control circuitry.

We developed an analog control circuitry in order to be able to deploy the proposed power supply without any condition on the hardware and on the functions embedded in the supplied wireless sensor node. First the input voltage of the DC/DC converter is regulated with an hysteretic control (Fig. 6a). R11 and R12 are set in order to obtain the desired hysteresis value (700 mV). With an input capacitor C_{IN} of 100nF the switching frequency of the converter is set around the hundreds of hertz minimizing thus the switching losses. R10 is a compensation resistor which insures the stability of the sampled V_{MPPT} voltage. Second, the output voltage regulation is done by Ordered Power Distributive Control [10]. Again an hysteretic comparator (Fig. 6b) decides which of the two output should be fed. R15 and R16 set the regulated output voltage ripple to 10mV.

Finally all the control signals necessary to the good functioning of the MPPT circuit presented in [3] are provided by an ultra low power hysteretic oscillator (Fig. 6c). The frequency of the MPPT algorithm is set by C1 and R4. C2, C3, C4 and R5, R6, R7 values allow to control the respective duration of the MPPT process, of the sampling phase and of the reset signal. A RS-latch besides permits a proper startup of the whole control circuitry allowing an auto-initialization of the MPPT algorithm even if there is no available power stored in the tank capacitor.

Table 2: Components nomenclature

Component	Reference	Supplier
Diodes	BAT54	Fairchild
Power MOS (N&P)	Si1551	Vishay
Vdd MOS	Si1300BDL	Vishay
Zener	BZX84C8V2	NXP
Inductance	LB2518_470	Taiyo Yuden
CLD	CCLH150	Central Semi
MUX 2:1	DG419L	Vishay
Reference Voltage	ISL60002	Intersil
Comparators	LMC7215	National Semi

VIRTUAL PROTOTYPING RESULTS

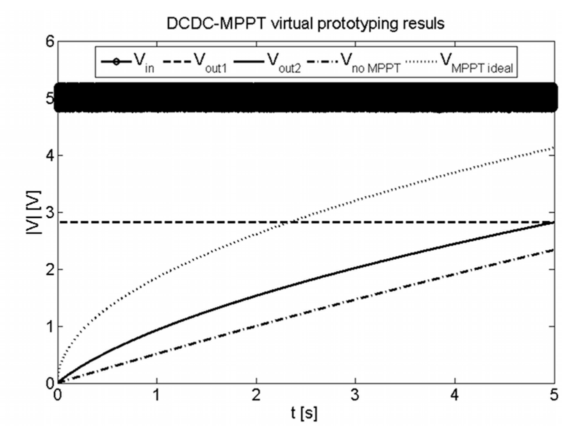

Fig. 7: DC/DC MPPT virtual prototyping result

The whole power harvesting and management system has been simulated at component level using VHDL-AMS language under SystemVision; Mentor ®. All the implemented part references and their associated providers are listed in in Table 2. Proprietary constructor SPICE models are used when available so that the proposed virtual prototype of the system is meant to be the closest virtual representation of the reality. Hence the following simulation results can be considered as quantitative results. Fig. 7 confirms the efficiency of the proposed power conversion and management system. More than providing a 2.8V regulated DC output, the circuit of Fig. 5 permits to extract up to 7 times more energy (3 times more in average) compared to a standard architecture (Fig. 3a) which confirms again the interest of the proposed ultra low power MPPT scheme for vibrational power harvesting.

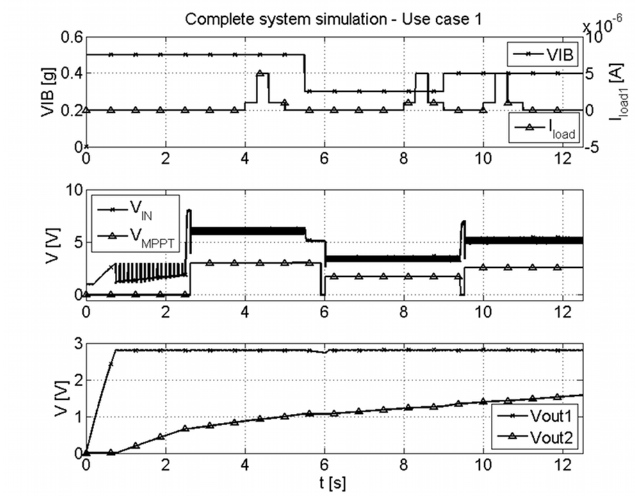

Fig. 8: Complete system use case simulation

Fig. 8 shows that even in changing environment and with a time-varying load the output voltage is still regulated. More, as expected, the system achieves a correct sampling of the MPP voltage leading to an optimal power harvesting.

CONCLUSION AND PERSPECTIVES

This paper shows that SIDO DC/DC converters can efficiently be used in power harvesting and management. The power harvesting and management system has been virtually characterized. 3 times more energy can be harvested compared to a standard architecture and the power chain efficiency is about 50%. Such a value is acceptable considering the low level of power and the use surface mounted components. Moreover the requested functional range of vibration level is nearly reached. Indeed, if vibrations level is > 0.12 g the system is able to perform self-starting in less than 3 seconds. Then the polarization voltage of the harvester is controlled around 95% of the MPP. The resulting optimal power extraction is shared between a 2.8V±10mV regulated output and a tank capacitor. If level is > 0.5 g, e.g. in case of shock, the circuit is still functional thanks to a Zener over-voltage protection.

The presented system is readily adaptable to other power harvesting sources that present the same V_{MPP}/V_{OC} property (as solar cells or thermo-generators for example). A forthcoming realization of the circuit should confirm these modeling results and will be presented during the conference. A new version of the system using a Single Inductor Dual Input Dual Output (Fig. 3d) which fully handles charging and discharging of a thin-film LiPON battery is currently being designed.

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