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Nonlinear bi-stable vibration energy harvester at work

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Abstract: An extreme low power energy rectification, storage and management circuitry has been developed and used to power a small digital wireless sensor with a piezoelectric non-linear bi-stable vibration energy harvester for automotive application. All the system has been designed with off-the-shelf components and sends data in the 2.4 GHz band.

Keywords: energy management; energy harvesting; wireless sensor; low power systems

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1. Introduction

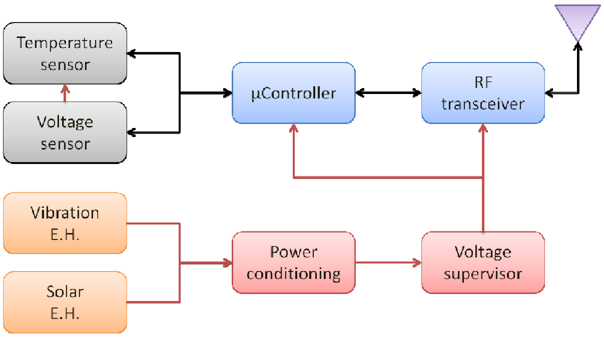
The requirement of being extremely low power is becoming a main issue in the realization of today's portable or not portable devices and systems, mostly in the wireless sensor network application field for sensing, control, automation or monitoring purposes. Generally the power requirements are related to at least three main factors: the amount of time the system has to remain ON (duty cycle), the number of the electronic devices that compose the system and their building technology. In this work a low quiescent current circuitry is proposed for the rectification, conversion, storage and supervision of the power coming from a piezoelectric non-linear bi-stable energy harvester. A comparison between a linear and a non-linear energy harvester has been done and the results are presented: the advantages of using a nonlinear energy harvester will be presented. It has been also used a small microcontroller and a radio frequency transceiver in the 2.4 GHz band. All together they compose a complete energetically autonomous wireless sensor. This wireless sensor can be used in all the situations where extreme low power consumption is mandatory. In particular, the aim of this article is to propose an autonomous wireless sensor powered only by the vibrations generated by different vehicles on different roads: no batteries on board are required. This approach has now become popular as "energy harvesting" [1] [5].

2. Block diagram of the system

The block diagram of the system is depicted in **Error! Reference source not found.**.

As can be seen the system is mainly composed by a randomly variable voltage source and its rectifier, a voltage regulator, energy storage, a voltage supervisor, one or more sensors, a microcontroller and a radio frequency transceiver. In general, two or more different voltage sources can be applied at the same time by using an appropriate circuitry for their coupling, giving the electronic device the energy it requires with a good probability of continuity. This is very important to reduce the energy wasted in the situations where the system has to perform several tasks during the power-on cycle, e.g. the authentication in a wireless network.

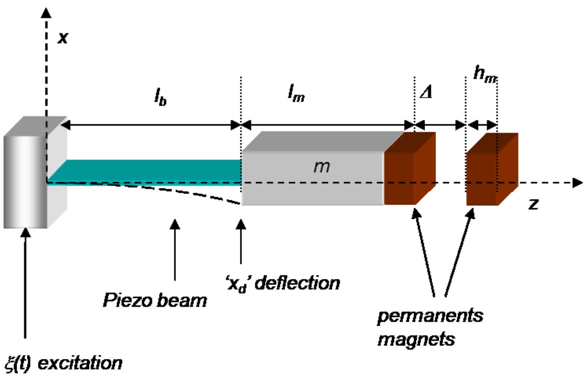
Figure 1. Block diagram of the system



3. Vibration energy harvester

In this block a piezoelectric nonlinear bi-stable vibration energy harvester has been used to convert energy from the environment: it is able to power the electronic circuitry. Our laboratory tests demonstrated that a nonlinear bi-stable piezoelectric energy harvester [2] have a higher efficiency in energy conversion than a linear one of the same sizes. In general real vibrations are wide band signals, rarely it is possible to have mono tonal accelerations. This means that the energy is spread over tens, hundreds or thousands of hertz. Given that a linear oscillator is a tuned system that can collect energy only from signal at or very close to its resonance frequency. A nonlinear energy harvester is a wide band system. The nonlinear harvester is composed by a piezoelectric cantilever, a inertial mass and two permanent magnets as depicted in **Error! Reference source not found.**.

Figure 2. Nonlinear bi-stable piezoelectric energy harvester



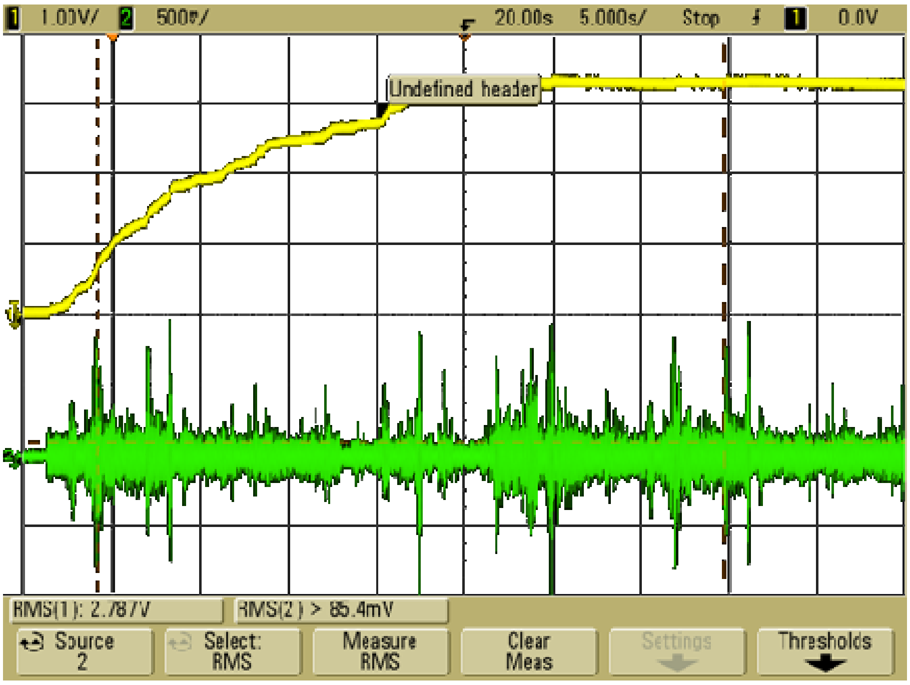
With the typical vibrations of a car, up to 1 mW of electrical power can be converted using a double layer piezoelectric cantilever (sizes 38.2 x 16.7 x 0.8 mm by Mide Technology Corporation [9]). The same vibrations, applied to a piezoelectric linear energy harvester of the same size and same structure, give around 0.3 mW.

The vibrations used for the tests have been recorded from real environments using a professional accelerometer: model 7132A by Measurement Specialties. They can be reproduced by an arbitrary signal generator, in the experiment an Agilent 33522A, and a shaker, K2007E01 by The Modal Shop Inc. In this way it is possible to have a good approximation of the real behavior of the system in several conditions. The recorded time series are collected into a public database available through the web [3]. A typical time series of the acceleration in a car can be seen in **Error! Reference source not found.**. The upper line represents the voltage across a storage capacitor of 1000μF from 0 V up to the desired operating voltage of 3.3 V. The bottom one represents the acceleration time series (different scales).

Different rectifiers have been tested, but the best solution for randomly variable signals appear to be the classical four silicon Schottky barrier diodes bridge rectifier. The components used, four LL103, have been chosen among several different models taking into account the differences of energy losses due to the diodes threshold voltage.

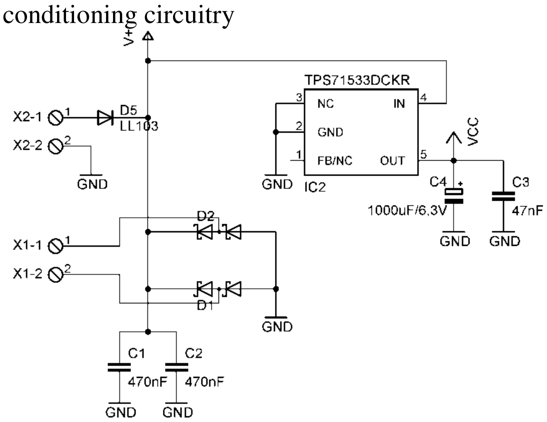
An active-diode based rectifier could have been used, but it would have required additional control circuitry meaning more energy consumption: as a result the simple diodes bridge appeared as the best solution, especially when the dynamic of the current coming from the harvester is order of magnitude larger than its RMS value. The coupling with another source can be made by a fifth diode that prevents the current flows from one source to the other.

Figure 3. Typical acceleration in a car and capacitor charging



The schematic of the circuitry is depicted in **Error! Reference source not found.**. After the rectification the voltage is stored in a couple of ceramic capacitors to provide first energy storage. The use of this kind of capacitor is required because they can work up to a quite high voltage level, for example 16V or more. A piezoelectric vibration energy harvester in fact can produce a voltage that in some situations can reach values higher than 20 V and a low voltage capacitor, for example a tantalum type, is not suitable for this purpose. Then a LDO voltage regulator is used to regulate the voltage: it was preferred to a switching type because in several tests strange behavior of commercial devices in the OFF-ON cycle has been observed.

Figure 4. Schematic of the power conditioning circuitry

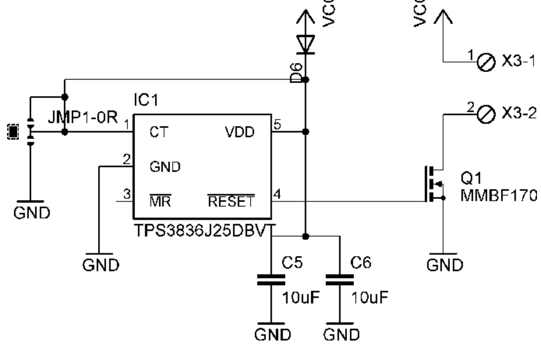


The device used in this work is the TPS71533 from Texas Instruments: its output voltage is 3.3 V, suitable for a large range of electronic devices such as microcontrollers and RF transceivers. Its quiescent current is 3.2 µA at 50 mA output current. The output of the voltage regulator is connected to a 1000µF tantalum capacitor and its charging is depicted in 4. In this way it is possible to drive high current demanding devices like a radio transceiver with peak current up to 25 mA or more.

4. The supervisory circuitry

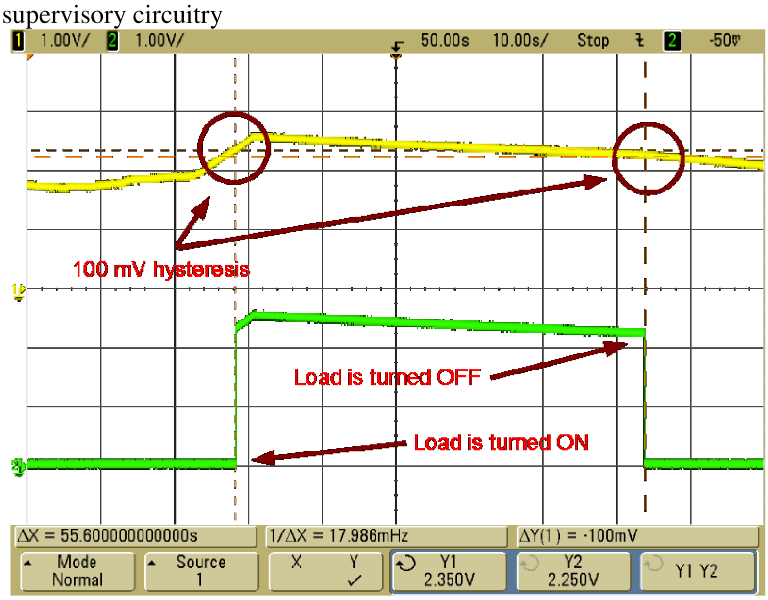
Given that real environment vibrations can be not constant in amplitude, the power flux from the harvester is not constant and a power management system is then required to regulate and to manage the energy coming from the generators. The supervisory circuitry is mainly realized by a voltage comparator, a voltage reference and a solid state small signal switch; the schematic is depicted in Figure 5. The device used is the TPS3836J25 of Texas Instruments: its supply current is typically 220 nA. It mainly compares the incoming voltage from the regulator to a reference value, and it turns ON or OFF the load accordingly to its level. Using a FET connected to its CMOS output pin, the supervisor performs the correct ON-OFF sequence of the microcontroller and of the radio frequency transceiver. In this work a small signal N-Channel enhancement mode field effect transistor, a MMBF170, has been used: its gate-body leakage current is less than 10 nA.

Figure 5. Schematic of the supervisory circuitry



It is important to note that a hysteresis in the threshold voltage is mandatory to avoid a continue repetition of the ON-OFF and OFF-ON transitions. This threshold has been increased to around 100 mV, from the original 30 mV of the device, using a diode and a capacitor to isolate the input power pin of the supervisor from the global power source. Thanks to its low current requirement, around 220 nA [4], two small ceramic capacitors are enough to power the device for several seconds even if the global source voltage goes below the nominal OFF threshold, as shown in Figure 6.

Figure 6. Hysteresis of the supervisory circuitry



5. Microcontroller and radio

Once the output voltage of the voltage regulator is high enough, typically over 2.35V, the supervisor turns ON a microcontroller. It measures the temperature of the system and the supply voltage. Then it turns ON the radio-frequency transceiver and prepares the data for the transmission. When they are ready it sends them to the radio and let the transmission start.

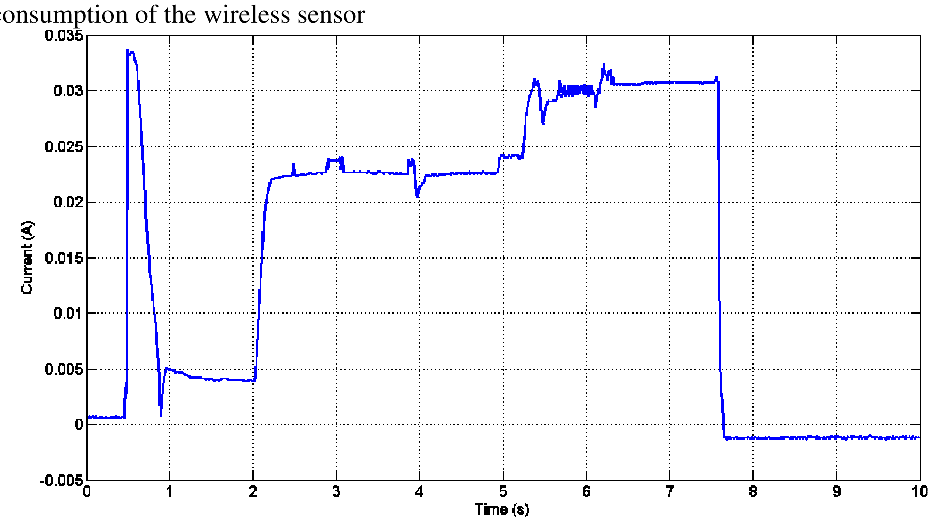
The used microcontroller (PIC24F family 16 bits device by Microchip Technology) has been chosen for its low power consumption. It uses an external temperature sensor and it can be programmed in C language.

When the data have been acquired, the microcontroller turns ON the transceiver and prepares them for the transmission: they have to be packetized according to the custom protocol, a simple peer-to-peer one. In this way it is possible to reduce the computational cost of this procedure, a key aspect for the overall energy harvesting system performance.

The RF transceiver is also made by Microchip Technology. The device is the MRF24J40 and it operates in the 2.4 GHz ISM band. It can support O-QPSK modulation with a standard datarate up 250 kbaud, according to the 802.15.4 standard. Its RF power can be adjusted from -36 dBm to +0 dBm. In this way the power consumption can be tailored depending on the specific application: in case of short distance communication the lowest power level can be used.

The current requirement of the microcontroller and the radio frequency transceiver during a complete cycle, from the wake-up to the end of the transmission, is variable from few µA to around 30 mA, as can be seen in Figure 7. The highest power consumption is measured during the transmission and it lasts for around 1.5 ms. The entire sequence, from the wake-up of the microcontroller to its sleep lasts around 7 ms.

Figure 7. Current consumption of the wireless sensor



6. Conclusions

The proposed device circuitry has been realized and tested with different vibration time series. The global quiescent current requirement at variable input voltages is depicted in Figure 8. As it can be seen there is a peak in the current required when the voltage is below the nominal 3.3 V of the voltage regulator output. This is due mainly to a not perfectly predictable behavior of the electronic components, especially the voltage regulator and will be the subject object of future researches.

This device is an evolution of the Hybrid Autonomous Transceiver – HAT, a wireless sensor node composed by a microcontroller and a radio frequency transceiver in the 2.4 GHz band [6] [7] powered with a nonlinear bi-stable vibration energy harvester and solar cells. When vibrations are not strong enough, the solar cells can help powering the circuitry. This can happen, for example, when a car is stopped at traffic light or the engine is turned off. The proposed device can be seen in Figure 9 and in Figure 10. On the left in Fig. 9 the small PCB carries the microcontroller, the temperature sensor, the radiofrequency transceiver and the 2.4 GHz printed antenna.

Figure 8. Quiescent current of the proposed system

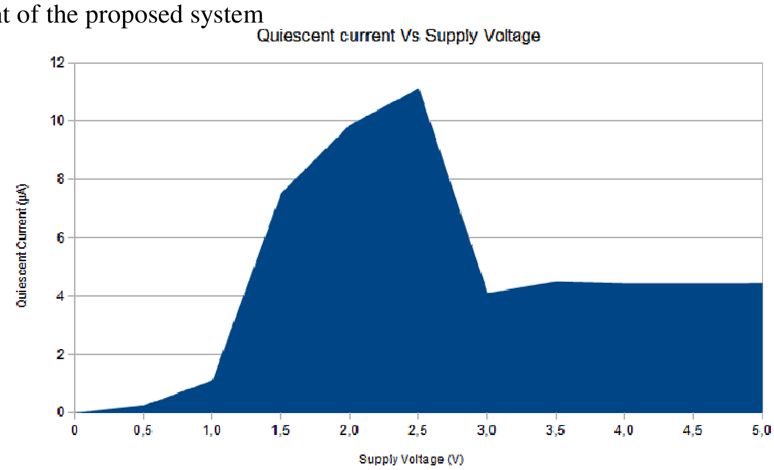


Figure 9. Top view of the autonomous sensor

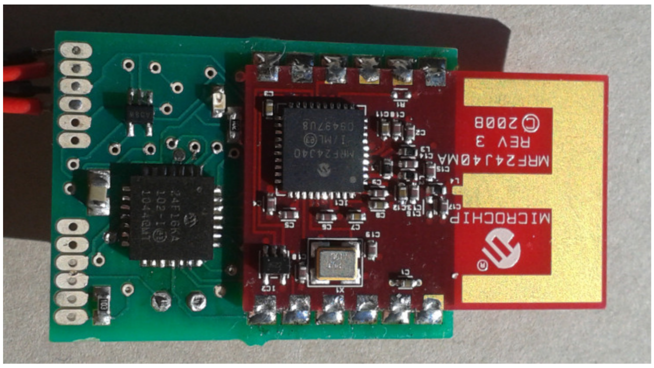
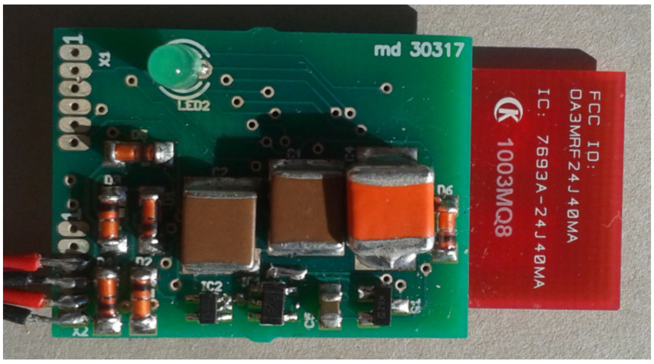


Figure 10. Bottom view of the autonomous sensor



The bottom side of the proposed sensor is depicted in Figure 10. On the lower left corner four diodes make the rectifier bridge. On the lower side, from left to right, take place the voltage regulator, the voltage supervisor and the FET switch. The capacitances of the capacitors in the center of the picture are, from left to right, is 100 µF, 100 µF and 1000 µF.

Figure 11. Bi-stable nonlinear piezoelectric energy harvester

The piezoelectric energy harvester can be seen in Figure 11: two magnets create a double well potential in the dynamic of the cantilever oscillator [2]. A tip mass decreases the resonant frequency of the corresponding linear oscillator. Globally the proposed device is able to work without any battery thanks to the use of nonlinear bi-stable piezoelectric vibration energy harvester. This means that the sensor can be placed practically anywhere in a vehicle: it doesn't require any wire for the power supply. An application of the present work to the automotive sector is presented in ref. [8].

Conflict of Interest

The authors declare no conflict of interest.

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