Review of Energy Harvesting Techniques and Applications for Microelectronics

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ABSTRACT

The trends in technology allow the decrease in both size and power consumption of complex digital systems. This decrease in size and power gives rise to new paradigms of computing and use of electronics, with many small devices working collaboratively or at least with strong communication capabilities. Examples of these new paradigms are wearable devices and wireless sensor networks. Currently, these devices are powered by batteries. However, batteries present several disadvantages: the need to either replace or recharge them periodically and their big size and weight compared to high technology electronics. One possibility to overcome these power limitations is to extract (harvest) energy from the environment to either recharge a battery, or even to directly power the electronic device. This paper presents several methods to design an energy harvesting device depending on the type of energy avaliable.

Keywords: Energy harvesting, wearable devices, wireless sensor networks

1. INTRODUCTION

One of the most important trends in the electronic equipment technology from its origins has been the reduction in size and the increase in functionality. Nowadays small, handheld, though very powerful devices are commercially available that allow the user to play music, to wirelessly communicate or to compute practically everywhere or, in other words, ubiquitously. In the next years there will be new products available providing vision and other extended functions to the wearer. The size of such devices is becoming so small that instead of portable devices they are becoming wearable devices that can be integrated in everyday use objects like watches, glasses, clothes, etc.[1]

All those units, based on today's microelectronic technology, need an external power supply. The size of the electronic circuit and the energy needed to perform a single (binary) operation[2] has been drastically reduced during the last decades, following Moore's Law. Therefore, advances in low power design open the possibility to harvest energy from the environment to power electronic circuits.

This work presents current approaches of using energy extracted from the environment to power microelectronic devices. The electrical energy to power the electronics is generated from either kinetic, electromagnetic or thermal energy. The obtained energy can then be used to recharge a secondary battery or, in some cases, to power directly the electronics. The output voltage and current of the generators is transient and discontinuous in nature, and must be converted to a DC signal. Therefore it is necessary to design a converter and/or storage circuit that needs to take into account the output signal of the generator and its impedance.

The structure of the paper is as follows: First, in section 2, the technology trends for both battery (energy generation) and electronic devices (energy consumption) are briefly sketched. Then, energy harvesting devices are classified in section 3 according to source and type of energy. Sections 4 through 6 review the principles behind different types of energy conversion. In section 7 it is discussed the power conditioning needed by electronic devices relying on energy harvesting, depending on their consumption and energy generation possibilities. Finally, in section 8, the conclusions of the work are presented.

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Table 1. Characteristics of batteries.

Battery type	Vol. Energy density Wh/dm^3	Grav. Energy density Wh/kg	Self-discharge % per year	Cycle Life no.
Alkaline	300	125	4%	1
Ni-Cd	100	30-35	15-20%	300
Ni-MH	175	50	20%	300
Li-ion	200	90	5-10%	500

2. TECHNOLOGY TRENDS

2.1. Battery evolution

In the great majority of today's wearable or portable devices, the energy necessary for their operation is provided by batteries. Batteries are a significant fraction of the total size and weight of the system. As technology scales down, this fraction is expected to further increase. Also very important is the requirement for proper maintenance of batteries, with the need to either replace or recharge them. This is a serious limitation to computing paradigms like ubiquitous computing or sensor networks, in which there are dozens or hundreds of small systems with batteries to maintain.

Of course, these inconvenients do not hide the advantages of batteries as a reservoir energy source. For example, we can characterize the batteries by their energy density, with respect to volume and weight, called volumetric and gravimetric energy density respectively. Table 1 shows some typical values of energy densities and self-discharge values for commercial batteries. It is seen how the most modern batteries (Li-ion) present better characteristics of energy density, self-discharge current and number of cycles.

It is worth noting that these values of energy density are the best option available today. Recent advances in capacitor technology have led to the development of the so-called ultracapacitors, with a capacitance value of the order of kF. Such impressively large capacitors, however, present an energy density around 3 Wh/kg, very far from average battery values.[3] The main advantages of ultracapacitors is the supplied peak power, and the number of cycles. These characteristics make them more oriented to automotive applications than to low power electronic devices, where batteries are still the choice for energy storage.

Still, battery technology has evolved very slowly compared to electronic technology.[4] For example, while disk storage density has increased over 1,200 times since 1990, battery's energy density has increased only about 3 times. New approaches are on the way for very small size portable batteries that may enable the size and weight reduction of wearable systems and sensor networks. They are based on new technologies as the thin-film Lithium-ion or Lithium polymer cells and some of them are still under development.[5] One of the most promising alternatives is the fuel cell, power generators that use chemical fuels (i.e. Hydrogen or Methanol). The gravimetric energy density of fuel cells is expected to be three to five times larger than Li-ion cells and more than ten times better than Ni-Cd or Ni-MH batteries whereas the volumetric energy density is six to seven times larger than Li-ion.[6] However, the maintenance problem is not solved; these cells need to be refueled or alternatively they have to be manufactured carrying enough fuel to sustain the battery operation during all its expected lifetime.

Secondary batteries are in principle a better choice for ubiquitous or wearable systems because they can be recharged in several ways, in many cases without extracting the battery from the system. Actually, one of the possibilities to recharge such batteries is to use energy harvested from the environment.[7] In this sense, energy harvesting is not trying to replace batteries, but instead alleviating some of their drawbacks, especially in relation with the maintenance issue.

2.2. Power consumption of microelectronic devices

Following Moore's law, integrated circuit technology evolves following a transistor size shrinking trend. Together with this trend and because of reliability reasons the supply voltage (V_{DD}) is also reduced. The net result is a reduction in energy consumption due to the reduction in the size of parasitic components. For a scale reduction

Table 2. Classes of energy harvesting devices.

Energy Source	Type of Energy
Human	Kinetic, Thermal
Environment	Kinetic, Thermal, Radiation

with a factor α ($\alpha > 1$), the energy consumed by a given shrunk circuit performing a given task is reduced by $(1/\alpha)^3$, as dicussed elsewhere.[8]

It is also important to consider the use model of the electronic device. For example, the power consumption of a wearable can be scaled following two different scenarios:

1. Maximum performance use: the improvement in technology allows to reduce the time per service, but it is used to give a higher number of services. In this case the total power consumption for the processing functions is scaled as $(1/\alpha)^2$.
2. Constant number of services: the improvement in technology reduces the time per service and the power consumption but the user does not increase the number of required services. The power consumption for the processing functions is scaled as $(1/\alpha)^3$.

Current portable electronic devices have different low power or sleep modes to save energy during times of inactivity. The management of these modes is very important in relation with an energy harvesting strategy, allowing to "refill" the energy reservoir of the system during these periods of low activity. This means that generally, a discontinuous operation use model is mandatory for the energy harvesting approach.

3. ENERGY HARVESTING DEVICES

Before starting to discuss the different methods of energy harvesting, let us look at the definition of an energy harvesting device as understood in this paper.

An energy harvesting device generates electric energy from its surroundings using some method of what is called in the literature Direct Energy Conversion techniques.[9] Therefore, the energy harvesting devices here considered do not consume any fuel or substance, so that the maintenance problem mentioned above does not apply. On the other hand, as the environment energy levels are very low (at least for today's electronic devices requirements), the use models mentioned in the previous section are very important.

3.1. Classification of Energy Harvesting devices

We may classify the different energy harvesting devices in two ways: considering who or what provides the energy for conversion, and what type of energy is converted. Table 2 relates the two classification schemes.

In the first classification scheme we can distinguish between two kinds of devices. First, devices that use part of the energy of the user of the electronic appliance. It will usually be a human, but it could be also an animal, for example for a remote monitoring device. We call this first kind of devices Human Energy* devices.[10] The second kind of energy harvesting device gets its energy from the environment, and thus we call them Environment Energy devices. This classification takes into account that, following the first principle of thermodynamics, a greater amount of energy must be spent to obtain a certain amount of electrical energy. In the case of Human Power it is the user that in some way or other provides this energy and, though the energy levels are very small, the effect may prove noticeable when several devices depend on the activity of a single user. In order to evaluate the burden of energy harvesting on user activities, it is possible to use a simple biomechanical model to calculate the energy involved in a human step,[11] obtaining around 40 J. In comparison, the energy of a short RF transmission can be evaluated in the order of 100 μW. This means that the extra energy demanded to obtain

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*In most of the literature the term Power is used instead of Energy. We prefer the term Human Energy instead of Human Power because energy is a more meaningful magnitude when dealing with discontinuous events, as discussed in subsection 7.1.

enough energy is very small for some applications, and therefore it makes sense to consider human beings as a possible energy source.

The second classification scheme may consider three types of energy: kinetic, electromagnetic radiation (including light and RF), and thermal.

For Human Energy devices only kinetic and thermal energy are available. In the case of kinetic Human energy, one may distinguish between those actions made specifically to generate energy and casual movements made during normal behavior. These two cases are called by the Human Power research group of the Delft University of Technology[12] Active and Passive Human Energy respectively. Following this definition, thermal Human Energy is always passive.

Environment Energy sources include kinetic energy in the form of vibrations, radiation as solar energy or RF radiation, and thermal energy. The energy harvesting devices may pick up vibrations when located on machines, building elements or other places near vibrating sources. Radiation may come from natural or artificial sources. Thermal energy depends on the existence of a temperature gradient. While the transducing methods may be similar to the Human Energy devices, the excitation magnitudes, frequency spectra and periodicity are very different, and therefore each case must be studied separately. This will also have consequences in the electrical power conditioning circuit.

3.2. Some working examples

There are several examples, both commercial and in the research stage that apply energy harvesting to power electronic products.

3.2.1. Human Active Energy

This is an old concept that has revived recently, basically improving the ratio of time of use with respect to time of charge.

Devices in the market using human energy as the only energy source include radio receivers, electric torches and phone battery chargers.[13–15] These devices use kinetic energy provided by winding a hand crank, or shaking the device, and they offer a good ratio between charging time and use time.[16]

3.2.2. Human Passive Energy

While Human active energy is interesting as an industrial concept, it is Human Passive Energy that presents a real challenge and is most attractive because it eliminates the power maintenance problem in portable and wearable devices.

Among commercial products, the first devices were wristwatches, because they have a very low power consumption. Both kinetic and thermal energy powered watches have been commercialized, although currently, only the kinetic is being manufactured by several companies. For kinetic energy, the power output is 5 μW in normal conditions, and up to 1 mW when the watch is forcibly shaken. For thermal conversion, around 1.5 μW or more is generated when the temperature difference is 1–3°C.[17]

Miniature thermoelectric generators are also developed[18] that converts body heat flow into electricity. It is claimed that it can generate 40 μW at 3 V with a 5 degree difference in temperature. Potential applications include attachable medical devices, electronic wrist watches, self powered heat sensors, and mobile electronics.

Another application already commecialized for energy harvesting is in the remote control area. The mechanical force employed to push down the switch is used to bend a cantilever piezoelectric ceramic.[19] This kind of devices is considered as Human Passive energy harvesting because the same movement of pushing the switch is used to generate the energy for a wireless communication.

3.2.3. Environment Energy

Several approaches have been made during the last few years in order to harvest energy from the environment to power wireless sensor networks. Batteries are not a recommended power source for wireless sensors since the power source would limit the lifetime of the sensor. The energy needed by a wireless sensor is in the order of hundreds of micro watts. The main power sources studied for wireless sensor networks are solar power (outdoors or indoors) and mechanical vibration. Roundy et al.[20] analyzed and fabricated a bimorph piezoelectric (PZT) generator with a steel center shim. The cantilever structure has an attached mass. The volume of the total structure is 1 cm^3. A model of the developed piezoelectric generator was made and validated. For an input vibration of 2.25 m/s^2 at about 120 Hz, power from 125 μW to 975 μW were generating depending of the load. The power recovered was analyzed connecting the generator directly to a resistive load or to a capacitive load. Later, a DC-DC converter was included and the generator supplied power to a low power transceiver. The radio transmits at 1.9 GHz and consumes 10 mA at 1.2 V and the vibration source was 2.25 m/s^2 at 60 Hz.

4. KINETIC ENERGY

Kinetic energy is one of the most readily available energy source, both for Human and for Environment energy harvesting devices. This section briefly explains the principles of the different transducers for obtaining electrical energy from kinetic energy.

4.1. Types of kinetic energy transducers

The principle behind kinetic energy harvesting is the displacement of a moving part or the mechanical deformation of some structure inside the energy harvesting device. This displacement or deformation can be converted to electrical energy by three methods, that are explained in subsequent subsections: by a piezoelectric material (subsection 4.2), by electrostatic energy (subsection 4.3) and by magnetic induction (subsection 4.4).

With respect to mechanical structures, there are two types of possible converters. One responds to the kinetic energy with a vibration or displacement of a proof mass. The energy obtained will depend on this mass, and therefore we will call this first class Inertial converters. Mitcheson et al.[21] have classified inertial converters in function of the force opposing the displacement of the proof mass as Voltage Damped Resonant Generators (VDRG), appropriate to describe magnetic induction transducers, Coulomb Damped Resonant Generators (CDRG), which describe vibrating electrostatic transducers, and Coulomb Force Parametric Generators (CFPG) that correspond to displacement electrostatic generator type. There are also inertial converters based on piezoelectric, in which an accelerated mass causes a deformation of a piezoelectric material, either by impact or vibration.

Many inertial converters are based on a spring-mass system that resonates at a particular frequency. When the mechanical stimulus vibrates at that resonance frequency, the enery obtained is maximum. However, as the converters are miniaturized to integrate them on microelectronic devices, the resonance frequency increases, and it becomes much higher than characteristic frequencies of many everyday mechanical stimuli. For example, typical acceleration frequencies of the human body in movement are below 20 Hz.[22] As was recognized by Mitcheson et al.[21] for such cases, either a CFPG type of converter, or a non inertial converter is best suited.

In the second case (Non-Inertial converters), an external element applies pressure that is transformed as elastic energy, causing a deformation that is converted to electrical energy by a piezoelectric material. In this case, the obtained energy does not depend on the mass of the converter, but generally, on the rate of deformation, thus given by mechanical constraints like Young's modulus or geometric dimensions.[23]

4.2. Piezoelectric generator

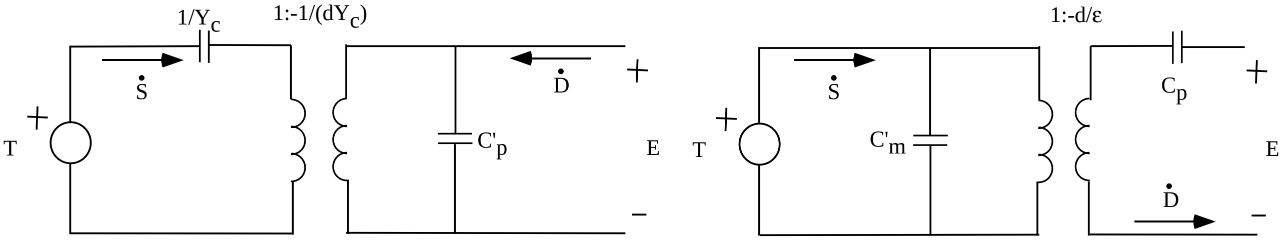
The piezoelectric effect was discovered by Jacques and Pierre Curie in 1880. Curie's brothers found that certain materials, when subjected to mechanical strain, suffered an electrical polarization that was proportional to the applied strain. This is the piezoelectric effect used for mechanical to electrical energy conversion.

The phenomenon of piezoelectricity is described by the following equations:

$$\begin{array}{l} \{S_i\} = \{\frac{1}{Y_{c,ij}}\}\{T_j\} + \{d_{ik}\}\{E_k\} \\ \{D_l\} = \{\epsilon_{lm}\}\{E_m\} + \{d_{ln}\}\{T_n\} \end{array} \quad \text{for } j,n = 1,\ldots,6 \text{ and } i,k,l,m = 1,2,3 \tag{1}$$

Table 3. Subscripts of the reduced notation for piezoelectric constitutive equations.

Reduced notation	Corresponding direction of axes
1	Longitudinal in x direction
2	Longitudinal in y direction
3	Longitudinal in z direction
4	Shear y-z
5	Shear z-x
6	Shear x-y



(a) (b)

Figure 1. Piezoelectric coupling circuits, relating mechanical and electrical magnitudes.

In these equations, subscripts correspond to the 6 directions of the axes, three cartesian directions plus the shear around the three axes, as shown in Table 3. Repeated subscripts in the products imply a summation over the different components: T, applied mechanical stress [N/m^2]. E, applied electric field [N/C]. d, piezo strain tensor [(C/m^2)/(N/m^2)]. ϵ, permittivity tensor [F/m]. D, electric displacement [C/m^2]. S, mechanical strain [m/m]. Y_c, Young's modulus tensor [N/m^2].

A piezoelectric material mechanically stressed at a low frequency can be modelled electrically by a time-dependent charge source, that is accumulated in a capacitor.

If the piezoelectic constitutive equations are transformed to the Laplace domain, the following equations are obtained:

$$\dot{S} = j\omega\tfrac{T}{Y_c} + j\omega d E \quad \dot{D} = j\omega\epsilon^T E + j\omega d T \tag{2}$$

This relationship is represented by the piezoelectric coupling circuit of Figure 1(a). The transformer relates mechanical magnitudes (stress) and electrical magnitudes (electric field).

$$C_p^{'} = \epsilon^T\left(1 - \frac{d^2 Y_c}{\epsilon^T}\right) = \epsilon^T(1 - k^2) \tag{3}$$

Another possibility for the representation of the piezoelectric coupling circuit is shown in Figure 1(b), where capacitors C_m' and C_p are given by:

$$C_m' = \tfrac{1}{Y_c}\left(1 - \tfrac{d^2 Y_c}{\epsilon}\right) = \tfrac{1}{Y_c}(1 - k^2) \quad ; \quad C_p = \tfrac{\epsilon^T A}{t} \tag{4}$$

The two most common types of piezoelectric materials are PVDF, polyvinylidene fluoride, and PZT, lead zirconate titanate. There are three different ways to excite a piezoelectric material in order to generate electrical energy: by compression, slap and bending.

For the analysis of the piezoelectric response, it is assumed that electrical terminals are located along direction 3, parallel to the poling axis (the direction of the polar molecules that form the piezoelectric effect). The two most common ways to employ piezoelectric materials are modes 31 and 33. In mode 31, the stress is applied in

Table 4. Voltage V_3 and charge q_3 obtained applying a mechanical stress in direction 1, mode 31, and in direction 3, mode 33. Constants g_{ij} are defined as d_{ij}/ϵ.

	Mode 31	Mode 33
V_3	$g_{31}\frac{F_1}{W}$	$g_{33}\frac{F_3}{WL}H$
q_3	$d_{31}\frac{F_1 L}{H}$	$d_{33}F_3$

direction 1 whereas the electric field (voltage mode) or the electric displacement (charge mode) are in direction 3. In mode 33, the stress is applied in direction 3.

Table 3 gives the obtained voltage or charge resulting from an applied force in a certain direction, F_1 or F_3 for each mode.

If the same force is applied in direction 3 and in direction 1 over a piezoelectric material with similar dimensions in length L, width W and thickness H, mode 33 excitation can generate more charge and voltage than mode 31 because d_{33} is usually larger than d_{31}. However, the geometrical dimensions of the material play a very significant role. For example, in a thin PVDF film, the ratio L/H is on the order of 1000, while $d_{31} = 23 \cdot 10^{-12} m/V$ and $d_{33} = -33 \cdot 10^{-12} m/V$.[24] If it is considered again that F_1 is equal to F_3, the obtained value for V_3 and q_3 for the mode 31 will be on the order of 700 times greater than for the mode 33. Therefore, the mechanical structure must take into account both the geometry and the mechanical coupling in order to apply the deformation in the optimum way.

Piezoelectric thin films are used for several systems due to their adaptability. In this case, the most advantageous way of excitation is by bending piezoelectric materials configured in cantilever-like structures. There are different kinds of support, and different vertical structures of the material that is going to be bent. The combination of these structures generates several options.[23]

When several piezoelectric elements are present in the structure, they can be connected either in parallel or in series. In a parallel connection, the charge generated by the piezoelectrics is added whereas in a series connection, the charge generated corresponds to the strain of one of the piezoelectric elements connected, and the voltage of the piezoelectric elements is added. In order to adequately connect the piezoelectric elements in series or parallel, the orientation of the poling axis has to be taken into account.

In summary, piezoelectric converters have most of the advantages of inductive and electrostatic generators, and they are also very robust. On the other hand, piezoelectric converters are difficult to implement on micromachined processes, and therefore to miniaturize.[20]

4.3. Electrostatic energy generator

The principle of electrostatic generators is that the moving part of the transducer moves against an electrical field, thus generating energy.

Meninger et al.[25] of MIT presented an electrostatic generator that employs a variable micromachined capacitor. Two different designs were studied: a parallel capacitor operated with a constant charge and a comb capacitor operated with a constant voltage. These generators are also called Coulomb-damped resonant generators (CDRGs) because they are based on electrostatic damping. If the charge on the capacitor is maintained constant while the capacitance decreases (e.g. reducing the overlap area of the plates or increasing the distance between them), the voltage will increase. If the voltage on the capacitor is maintained constant while the capacitance decreases, the charge will decrease.

Figure 2 illustrates the process of charging and discharging the capacitance following constant charge (path A-B-D-A) or constant voltage (path A-C-D-A) approaches. The energy enclosed by the total path is the energy extracted in the process.

The charge constrained conversion cycle starts when the micromachined capacitance (given by the slope of the Q-V curve) is maximum. At this moment, a voltage source charges the MEMS capacitor to an initial voltage, V_{start}, that has a smaller value than V_{max}, and therefore the cycle conversion goes from point A to point B. The path B-D corresponds to the plates moving from maximum capacitance, C_{max}, to minimum capacitance, C_{min}

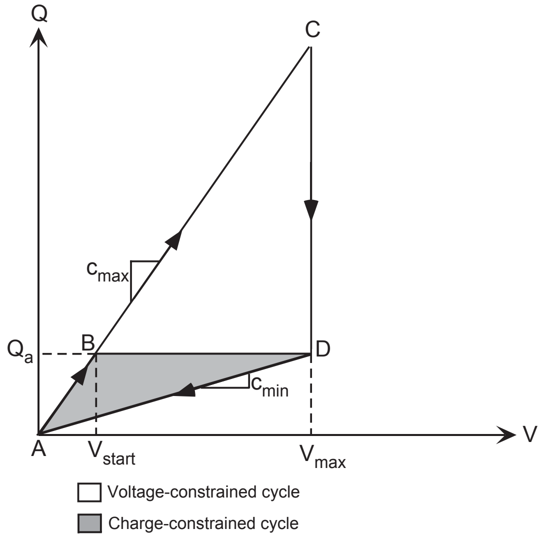


Figure 2. Diagram explaining electrostatic energy conversion. Adapted from Meninger et al.[25]

with constant charge, Q_0. As the capacitor decreases and charge is maintained constant, the voltage increases its value. The charge is returned to the reservoir in path D-A. The net energy out is equal to the area A-B-D.

The voltage constrained conversion cycle starts when the micromachined capacitance is maximum. At this moment, a voltage source charges the MEMS capacitor to an initial voltage, V_{max}, and therefore the cycle moves from point A to point C. The path C-D corresponds to the plates moving from maximum capacitance, C_{max}, to minimum capacitance, C_{min}. Path D-A shows the discharge of the capacitor. The mechanical vibration that takes place in path C-D is converted to electrical energy with a constant voltage. The net energy gained corresponds to the area A-C-D.

The energy gained in the conversion process is pumped from the MEMS capacitor along path DA for both charge and voltage constrained cycle. As shown graphically, the mechanical energy converted into electrical energy is greater if the voltage across the capacitor is constrained than if the charge across the capacitor is constrained. However, the initial voltage source needed has a smaller value for the constant charge case. A way to increase the electrical energy for the charge constrained method is to add a capacitor in parallel, C_{par} with the MEMS capacitor, C_{MEMS}. The disadvantage of this solution is that the initial voltage source has to increase its value.

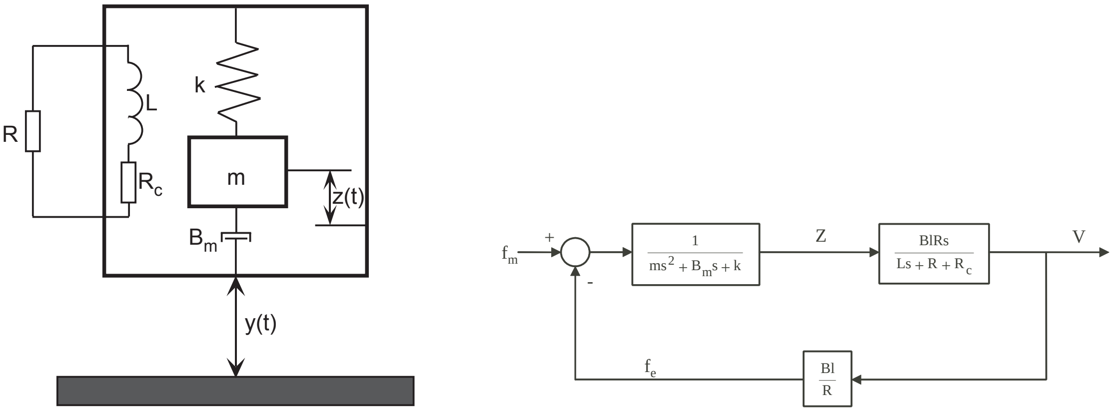
As explained, the proper operation of the switches, or when the charges are transferred, is critical for a good efficiency. The operation of the switches must be synchronized with the mechanical oscillation. The frequency of the mechanical oscillation depends on the resonance frequency of the mechanical structure. For best results, then, the mechanical source must have a vibration with a frequency close to that of the resonance frequency of the transducer, which is in the order of kHz for miniaturized components.

Other approaches use non-resonant structures[21] that are more suited for mechanical excitations at lower frequencies.

4.4. Magnetic induction generator

The magnetic induction transducer is based on Faraday's law. The variation in magnetic flux, Φ_m through an electrical circuit causes an electric field. This flux variation can be realized with a moving magnet whose flux is linked with a fixed coil or with a fixed magnet whose flux is linked with a moving coil. The first configuration is preferred to the second one because the electrical wires are fixed.

As the relevant magnitude here is the magnetic flux through a circuit, the size of the coil is inversely related to the obtained electric field and therefore, to the generated energy. This means that big transducers with large



(a) (b)

Figure 3. Magnetic induction transducer model. Adapted from Ching et al.[26]

area coils will perform better than smaller transducers, unless a larger time derivative is involved with the small scale generators.

We briefly present the analysis of a simple generator.[26] When the generator vibrates, the oscillating mass has a relative displacement with respect to the housing. The magnetic induction generator converts this relative displacement into electrical energy. The transducer is modelled as a damped spring-mass system, since the energy extraction damps the mass movement with a factor B_m. The mass m, the magnet, which is joined to a spring with a spring constant k moves through a constant magnetic field, B, when the generator oscillates.

The relative displacement, $z(t)$, is related to the voltage across the coil by a first order system as can be shown in Figure 3(a). L is the inductance of the coil, R_c is the parasitic resistance of the coil, l is the length of the coil, and R is the load resistance.

Figure 3(b) shows the transfer function block diagram that relates the mechanical input force with the output voltage. The current induced in the coil generates an electromechanical force, f_e that dampes the movement of the magnet. From the Newton's second Law of motion, the transfer function between the input mechanical force, f_m, and the relative displacement of the mass can be obtained. After some algebra, the transfer function that relates the output voltage V, across the load resistor with the input mechanical force f_m is:

$$\frac{V(s)}{f_m(s)} = \frac{(BlR)s}{(Ls + R + R_c)(ms^2 + B_m s + k) + (Bl)^2 s} \tag{5}$$

The third order system can be simplified to a second order system by assuming that the electrical time constant is much smaller than the mechanical time constant. With this assumption, the transfer function is expressed as:

$$\frac{V(s)}{f_m(s)} = \frac{\frac{(Bl)s}{m}}{(s^2 + 2\zeta\omega_n s + \omega_n^2)} \tag{6}$$

where ζ and ω_n are the damping factor and the spring natural frequency, respectively.

$$\omega_n = \sqrt{\frac{k}{m}} \tag{7}$$

$$\zeta = \frac{B_m R + (Bl)^2}{2R\sqrt{mk}} = \frac{B_m}{2\omega_n m} + \frac{(Bl)^2/R}{2\omega_n m} = \zeta_m + \zeta_e \tag{8}$$

The damping factor is expressed as the addition of a mechanical damping factor ζ_m, and an electrical damping factor, ζ_e.

The power generated for a sinusoidal input displacement, $y(t) = Y_0 \cos(\omega t)$, is given by:

$$P = \frac{m\zeta_e Y_0^2 (\omega/\omega_n)^3 \omega^3}{\left[1 - \left(\frac{\omega}{\omega_n}^2\right)\right]^2 + 2\zeta \left(\frac{\omega}{\omega_n}\right)^2} \tag{9}$$

The output power is maximum at resonance, and proportional to the third power of ω_n, while the corresponding voltage V_{pmax} is proportional to ω_n:

$$P_{max} = P(\omega_n) = \frac{m\zeta_e Y_0^2 \omega_n^3}{4\zeta^2} \tag{10}$$

$$V_{pmax} = \sqrt{2 P_{max} R} = \frac{B l Y_0 \omega_n}{2\zeta} \tag{11}$$

Several examples following this principle can be found in the literature.

Amirtharajah et al.[27]designed with an electromagnetic VDRG built using discrete components which generates a power on the order of 400 μW using human walking as a vibrational power source.

Williams et al.[28] from the University of Sheffield fabricated an electromagnetic MEMS VDRG. A mm scale demonstrator, implementing an electromagnetic micro-generator, generates 0.3 μW from a 4 MHz excitation input.

Li et al.[29] from the University of Hong Kong have fabricated an electromagnetic MEMS VDRG with a volume of 1 cm^3. The micro-generator generates 10 μW power at 2 V DC with 64 Hz input frequency and 1000 μm input vibration amplitude.

5. ELECTROMAGNETIC RADIATION

Another source of energy present in the environment is electromagnetic radiation, either in the form of light (known as solar energy), or lower frequency RF radiation. Both methods are extensively used in many present devices, and only some comments will be made here, regarding their prospect as energy harvesting strategies.

5.1. Solar energy

Solar energy is a mature technology for large scale energy generation. Photovoltaic systems are found from the Megawatt to the milliwatt range producing electricity for a wide range of applications: from wristwatch to grid-connected PV systems. The application of photovoltaics in portable products is a valid option under the appropriate circumstances.

Outdoors, solar radiation is the energy source of the PV system. Solar radiation varies over the earth's surface due to weather conditions and the location (longitude and latitude). For each location exists an optimum inclination angle and orientation of the PV solar cells in order to obtain the maximum radiation over the surface of the solar cell. Yearly irradiance is for example 992 kWh/m^2 in The Netherlands and 2026 kWh/m^2 in Tanzania. However, indoor irradiance is smaller, around 3.5 to 20 W/m^2. Nowadays, the majority of solar cells are made from semi-conductor materials: crystalline silicon (89%), amorphous silicon (10%), cadmium telluride (0.5%), copper indium, diselenide and gallium arsenide. The power conversion efficiency of a PV solar cell is defined as the ratio between the solar cell output power and the solar power (irradiance) impinging the solar cell surface. For a solar cell of 100 cm^2, 1 W can be generated, if the solar irradiation is 1000 W/m^2 and the efficiency of the solar cell is 10%.

5.2. RF radiation

RF radiation is employed to power ID cards by directing high power electromagnetic energy to the devices from a nearby source. In addition to energy, it is possible to send information as well.

However, the term energy harvesting implies that it is the same device which gets its energy from the environment. In cities and very populated areas there is a large number of potential RF sources: broadcast radio and tv, mobile telephony, wireless networks, etc. The problem is collecting all these disparate sources and converting them in useful energy. The conversion is based on a rectifying antenna (*rectenna*), constructed with a Schottky diode located between the antenna dipoles.

The energy levels actually present are so low that no present electronic device can use them. However, future technologies may allow the fabrication of lower power devices that would "recycle" RF energy generated for other purposes by different elements.[30]

6. THERMAL ENERGY

Thermal energy is the other form of energy readily present in the environment. Thermal energy harvesting devices could use the thermal energy of different sources: persons and animals, machines or other natural sources.

A thermoelectric generator basically consists of a thermocouple, comprising a p-type and n-type semiconductor connected electrically in series and thermally in parallel. The thermogenerator (based on the Seebeck effect) produces an electrical current proportional to the temperature difference between the hot and cold junctions. An electrical load is connected in series with the thermogenerator creating an electric circuit. The Seebeck coefficient is positive for p-type materials and negative for n-type materials. The heat that enters or leaves a junction of a thermoelectric device has two reasons: 1) the presence of a temperature gradient at the junction 2) the absorption or liberation of energy due to the Peltier effect.[9]

Carnot efficiency puts an upper limit on the heat energy that can be recovered. In the case of temperature difference between the human body and the environment, e.g. room temperature (20°C), Starner[31] estimates that the Carnot efficiency with this temperature conditions is 5.5%. In a warmer environment the Carnot efficiency drops while in a colder environment the Carnot efficiency rises. The recoverable energy yields 3.7-6.4 W of power. However, evaporative heat loss account for 25% of the total heat dissipation, and therefore the maximum power available drops to 2.8-4.8 W. The previous calculations are made assuming that all the heat radiated by the human body can be recovered and transformed into electrical power, so that the obtained power is overestimated. Another problem is the location of the device dedicated to the capture of the heat of the human body. When the skin surface detects cold air, a rapid constriction of the blood vessels in the skin reduces the skin temperature to the temperature of the cold air. Therefore, the efficiency of the Carnot device will drop. Some research is needed to more accurately evaluate the feasibility of thermal energy harvesting from human activity. A thermal human body model is necessary in order to know how much heat energy can be harvested from a part of the human body without disturbing the user.

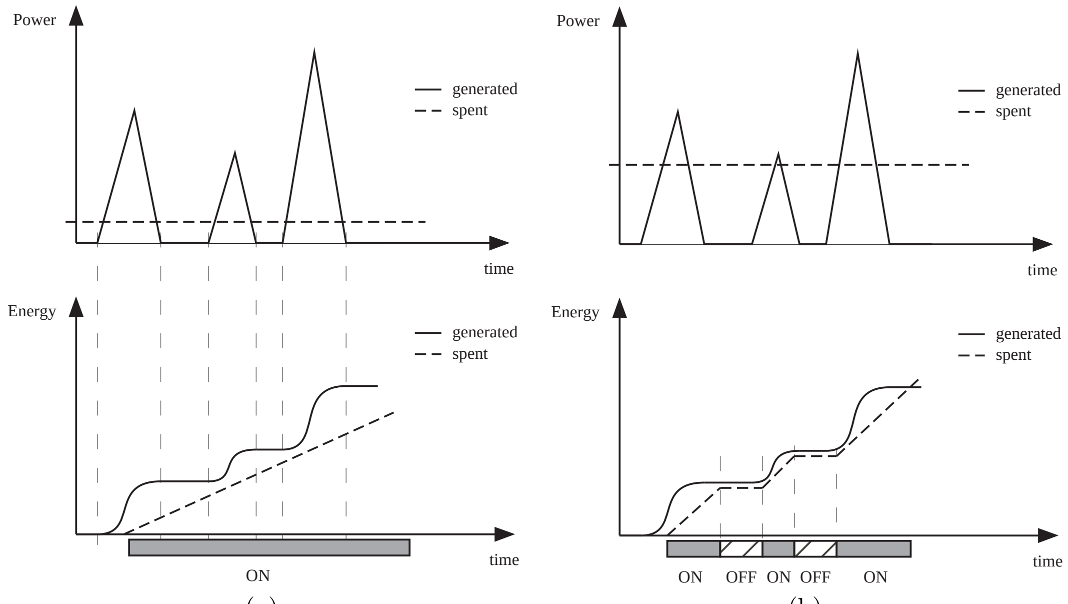
7. POWER CONDITIONING CIRCUITS

The energy present in the environment that can potentially be harvested is discontinuous in nature. Therefore, not only the voltage level must be adjusted, but, because at times there is no energy at all, there must be some way to store the energy for use at a convenient time. This storage element can be a capacitor, or a secondary battery.

7.1. Operation modes

The discontinuous nature of energy harvesting has consequences on the way the electronic devices powered by energy harvesting are operated. The electronic device will be able to operate only when there is enough energy in its energy storage element. In principle, we can distinguish two situations:

1. The power consumption of the electronic device is lower than the average power provided by the environment. In this case, the electronic device may operate continuously.



(a) (b)

Figure 4. Case of continuous (a) and discontinuous (b) operation. In the case of discontinuous operation, the device must be OFF until enough energy is collected in the storage element.

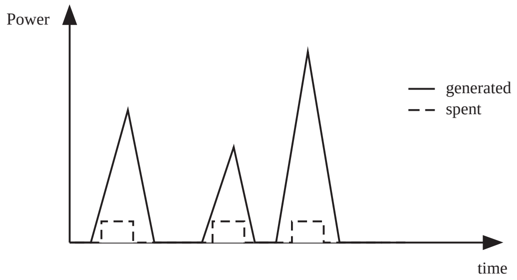


Figure 5. Generated and spent power when the device operation is only at times when there is energy generation.

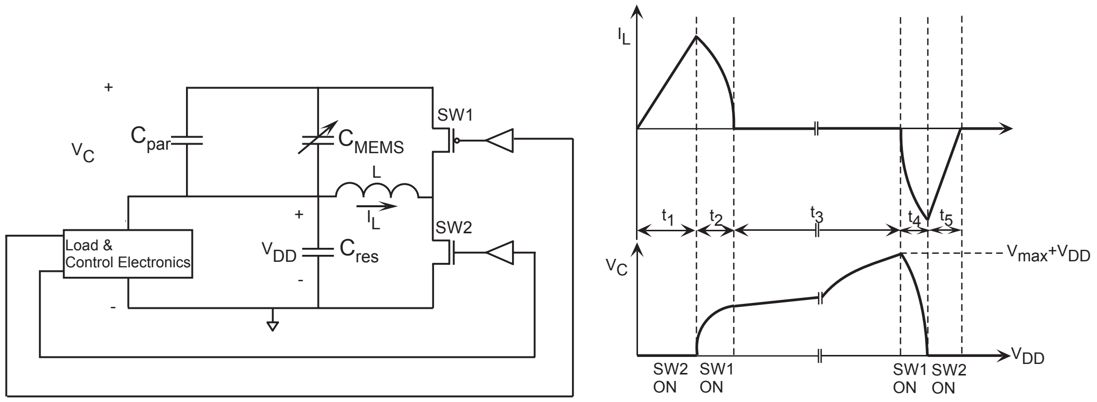
2. The power consumption of the device is greater than the power provided by the environment. The operation must be discontinuous, and the time between operations depends on the stored energy of the device.

Figure 4 schematically shows the two cases. It is seen how for both cases the energy storage element is necessary to provide energy during the moments where transiently the generated power is zero. A special case would be one in which the device is operated exclusively during the time when there is generated power, and the power consumption is at all times smaller than generated power (Figure 5). In this case, the energy storage element is not necessary, although voltage regulation is.

In the general case of discontinuous operation, energy is a more relevant magnitude than power when discussing generation, because it is generated energy which determines the time between operations.

7.2. Power conditioning for piezoelectric energy harvesting

A piezoelectric generator can produce voltages on the order of two to tens of volts and currents on the order of two to tens of microAmps.[20] These are the voltage and current levels that the piezoelectric power conditioning circuit has to manage. In addition, a piezoelectric source for human walking activity has low frequency (approximately one cycle per second) and low-duty-cycle current pulses.



(a) (b)

Figure 6. Diagram explaining electrostatic energy conversion circuit (adapted from Meninger et al.[25]).

The simplest method of power conversion is by direct discharge.[32] The piezoelectric element is connected to a diode bridge to rectify its output. The charge is transferred to a tank capacitor, C2 where the electrical energy is stored for use by the electronic system to be powered. This circuit is appropriate for applications where a low power device has to be power supplied at tens-second intervals. The storage capacitor C2 is connected to the electronic system each time that its energy reaches a value enough to power the application.

In this scheme, each time that the piezoelectric device is stressed, a certain amount of current flows, charging the piezoelectric element capacitor, C1, as well as the storage capacitor, C2. If the piezo element is cyclically excited and the current is rectified, the observed voltage in C2 will increase its value for each cycle, until a limit is asymptotically reached. The choice of the storage capacitor and the range of voltage when it should be connected are not arbitrary, but depend on the energy requirements of the load and the piezoelectric characteristics.

Ottman et al.[33] presented a circuit that uses a switch-mode dc-dc converter after the tank capacitor. They present an analysis of the converter in order to obtain the optimal duty cycle of the converter that maximizes the harvested power, taking in to account the generated current and internal capacitance of the piezoelectric. The use of the system proposed increases the harvested power by 325% as compared to when the battery is directly charged with the piezoelectric rectified source. However, the switch mode converter also spends some energy. They present a solution making a two-mode converter circuit. When the generated energy is too low to power the switching converter, it is accumulated in the battery in a manner similar to the direct discharge method. When there is enough energy, the switching converter starts up to increase the efficiency of the conversion.

7.3. Power conditioning for the electrostatic energy generator

The MEMS variable capacitor designed by Meninger et al. presents a power electronics circuit. The low-power controller directs energy conversion cycles by generating the timing pulses to control the gates of the FETS of the power circuit. It is responsible for charging the MEMS capacitor to V_{start} and V_{max} during the charge and the voltage constrained case, respectively.

Fig 6 shows the converter and the associated waveforms for the charge constrained case. t_1 starts when it is detected that $C_{MEMS} = C_{max}$. During t_1 SW2 is ON and SW1 is OFF, and therefore energy is transferred from the initial voltage source to the inductor L. During t_2 SW1 is ON and SW2 is OFF, so the energy is transferred from L to MEMS capacitor. During t_3 both switches are OFF and the MEMS capacitor changes its value from C_{max} to C_{min} due to mechanical vibration. During t_4 SW1 is ON, SW2 is OFF, and $C_{MEMS} + C_{PAR}$ transfer electrical energy to inductor L. t_4 corresponds to the path D-A of Figure 2. During t_5, SW2 is ON and SW1 is OFF and the energy stored in the inductor is transferred to the reservoir capacitor, C_{res}.

8. CONCLUSIONS

Nowadays there is an active research area investigating a number of alternatives to extract energy energy from the environment and convert it to electrical energy to power an electronic device. Taken one by one, each alternative still provides a low level of energy compared to the power requirements of today's electronic devices, except for specific applications. However, it is expected that energy harvesting will have an important role in future microelectronic devices for a number of reasons.

First, it is possible to increase the generated energy using new transducer designs or new materials, as well as innovative power conditioning circuits and energy storage elements. Also, the combination in the same device of several energy harvesting strategies will increase its capabilities to obtain energy in different situations. However, as observed with the comparison between past evolution of batteries and electronic technology, it is in the part of electronic consumption that there are more possibilities to close the gap between generated and spent energy. Electronic technology will continue its evolution of decreasing energy consumption thanks to continuing scaling down of devices, nanotechnology and eventually, molecular electronics. New processing and communication techniques will also help reducing power consumption.

Finally, the trend of increasing mobility and autonomy of electronic devices has a natural step in the energetic independence from the user. In this sense, such electronic devices will be completely autonomous entities, blurring the frontier between live beings and inanimated objects.

ACKNOWLEDGMENTS

This work has been partially supported by the Spanish Ministry of Science and Technology and the Regional European Development Funds (FEDER) from the European Union through project TEC2004-03289.

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