

Chapter 2

The Fundamentals of Energy Harvesting

2.1 What's Energy?

Energy is the capacity to do work; in the physics field, work is something resulting from the action of a force such as that of gravity. In Nature there are different types of energy: the most classic case is solar energy and all that energies come from the universe in the form of cosmic rays, X-rays, gravitational waves, dark matter, etc. A system that produces energy can be represented from a kite that “floats” in the clouds by means of wind, or a wave of light is passing through a space. According to the energy conservation law, for example, one of the first laws of thermodynamics, the total energy of a system is conserved, although it can be transformed into another form. Two billiard balls can collide, for example, and energy transformations are involve with sound and heat at the contact point: this phenomena is derived from energy conservation law after the collision. In few words, all forms of energy can be converted into another. This had already begun when the man (or woman) lit the first fire by burning wood with the transformation of the chemical energy of the molecules in the form of heat. The energy transfer is based on energy conservation. Other examples, a battery that generates electrons from chemical reactions, a toaster, the automobile, and many others. The sound is a form of kinetic energy: it is caused from vibration of the air molecules described as mathematical models. This vibration energy is transformed into electrical pulses that can be interpreted from the human as sound wave. In some systems such as that for the production of nuclear energy, the atoms are involved in multiple processes: the atoms of the nuclear fuel are divided by releasing the creation of thermal energy which is capture as water vapor to drive a kinetic energy generator. Subsequently, a motor turns it into a current flow to provide power supply. Renewable energy (replenished naturally) is generated from natural sources such as sunlight, wind, rain, tides, and geothermal heat, which are renewable (that are replenished naturally). Alternative energy is a term used for an energy source that is an alternative to the use of fossil fuels with a low environmental impact [1–6]. In the International System of units (SI), the unit

of energy is the joule, named thanks to James Prescott Joule. It is a derived unit and matched to the energy expenditure (or work) by applying a force of one Newton for a distance of one meter. However, energy is also expressed in many other units that are not part of the SI, as ergs, calories, British Thermal Units, kilowatt hours, and kilocalories, they require a conversion factor when expressed in SI units. In classical mechanics, from a mathematical point of view, energy is a conserved quantity. The work, a form of energy, is a force over a given distance described by the following equation:

$$w = \int_C F ds \quad (2.1)$$

Eq. (2.1) tells us that the work is equal to the line integral of the force along a path C. In the energy field some terms are used: Hamiltonian and Lagrangian. The total energy of a system can be expressed by Hamiltonian by using motion equation of William Rowan Hamilton. Another energy-related concept is called Lagrange, from Joseph-Louis Lagrange. This formalism is mathematically more convenient than the Hamiltonian for non-conservative systems (such as friction systems). The Lagrange is defined as the kinetic energy minus the potential energy.

2.2 Why Energy Harvesting?

An energy harvesting system captures the environmental energy and converts it into electricity. There are many techniques about this field: for example, to capture the energy lost or dissipated as heat, light, sound, vibration, or movement, then using special electronic circuits to manage the collection energy and then transform it into electrical signal.

This is important, because our existing electrical infrastructure is extremely wasteful in its use of energy. For example, some today's technologies used in the production of electricity are not energy efficient. The old incandescent bulbs, now they are no longer sold, transform into heat a good percentage of electricity.

An energy harvesting system can be described as in Fig. 2.1. The blocks are described in the following points:

- Energy transducer used to convert ambient energy into electrical energy of input. Environmental sources of energy available for the conversion may be the following: heat (thermoelectric modules), light (solar cells), RF radiation (antennas), and vibration (piezoelectric).
- Rectifier and super capacitor: a rectifier and an optional storage system for energy management.
- Voltage regulator: a controller system for adapting the voltage level to the requirements of the powered device.

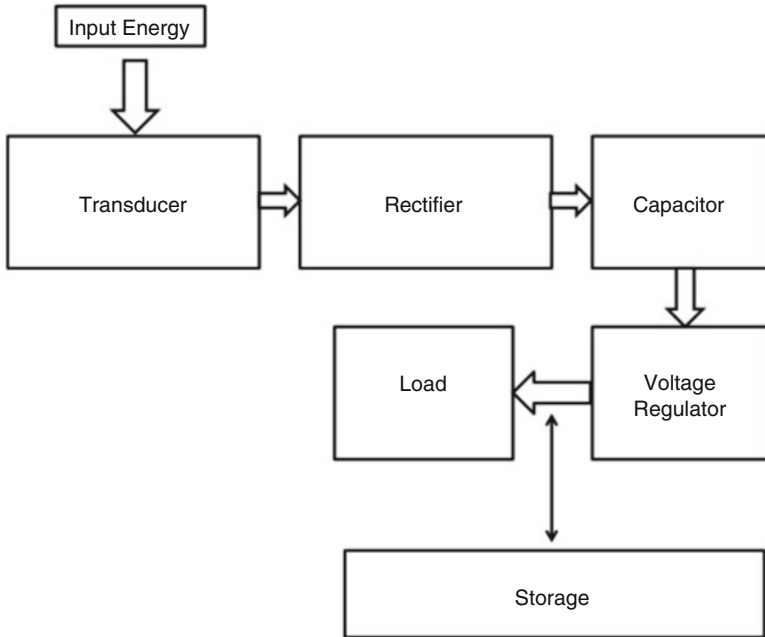


Fig. 2.1 General system of energy harvesting

- Optional energy storage element: depending on the requirements of application, it is possible to use a battery as an energy storage element. In some systems it can be activated at intervals of time, in others it is powered (or recharged) permanently.
- Load: the impedance of the system to power. It may have different ways of energy consumption making the whole system work in low-power mode.

The electrical energy obtained from an energy harvesting system is very small (about 1 W/cm^3 to 100 mW/cm^3) and therefore has a working point in low-power mode. A typical electronic load is constituted by a sensor, a microcontroller, and a wireless transceiver (Fig. 2.2). Energy consumption is about of μA for the first two components and a few mA for the transceivers. These considerations will be used in the design of the energy harvesting system.

2.3 Free Energy

The main energy sources “freely used” are solar, mechanical, and thermal. The self-powered devices are normally of small dimensions that belong to the category of wearable devices or otherwise forming part of the Internet of Things (IoT) system. A possible comparison can be made in terms of power density per unit volume. In Table 2.1 are summarized the main sources of energy [7–13].

Fig. 2.2 Typical electronic load

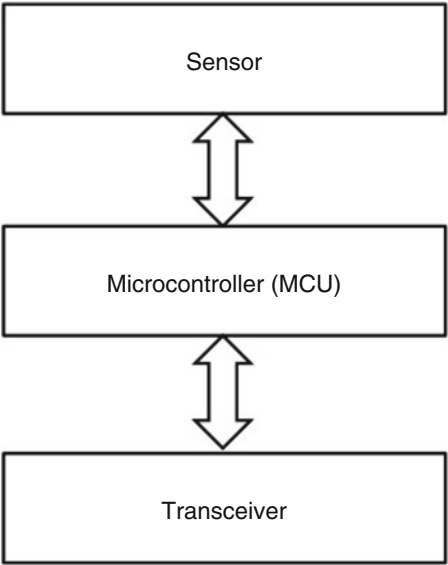


Table 2.1 Main energy sources of energy harvesting

Energy	Category	Harvested power
Human	Vibration/Motion	4 $\mu\text{W}/\text{cm}^2$
Industry	Vibration/Motion	100 $\mu\text{W}/\text{cm}^2$
Human	Temperature	25 $\mu\text{W}/\text{cm}^2$
Industry	Temperature	1–10 $\mu\text{W}/\text{cm}^2$
Indoor	Light	10 $\mu\text{W}/\text{cm}^2$
Outdoor	Light	10 mW/cm^2
GSM/3G/4G	RF	0.1 $\mu\text{W}/\text{cm}^2$
Wi-Fi	RF	1 $\mu\text{W}/\text{cm}^2$

The light is a source of ambient energy available for low and high power electronic devices. A photovoltaic system generates electricity by converting the solar for a large number of applications in the various range of power. The sunlight varies on the surface of the earth, depending on weather conditions and the position expressed in terms of longitude and latitude. For each position there is an optimal tilt angle and orientation of the solar cells in order to obtain the maximum radiation for powering high power systems; these conditions are not suitable in the case of small solar cells for the wearable electronics where there are not landmarks and the design is done in according to the general case [14–20]. The sun radiates towards the earth’s surface with a power density of at least 1350 J/m², with a total power on earth about 170 * 10⁹ MW.

As in almost all the transformations, kinetic energy is the base of the harvesting in terms of movement of particles such as photons (sun) or generic waves. The movement or deformation is converted into electrical energy in three main modes: inductive, electrostatic, and piezoelectric [21–26].

Table 2.2 Vibration sources

Source	Peak acceleration (m/S ²)	Frequency (Hz)
HVAC vents	0.2–1.5	4 50/60
Microwave oven	2.3	121
Dryer	3.5	121
Notebook with CD/DVD	0.6	75
Washing machine	0.5	109

The vibrations is the energy source for mechanical transducers and are characterized by two parameters: acceleration and frequency. Table 2.2 visualizes a list of peak accelerations and frequencies for different vibration sources in the industrial field. From these data can be noted that the vibrations of industrial machines have accelerations between 60 and 125 Hz. There is another possibility to use human body as a source of vibrations. The vibrations associated with the human body have accelerations with frequencies below about 10⁸ Hz.

The Human Walking, for example, is one of the activities that have more energy associated for the production of electrical signals. Two power modes can be distinguished: active and passive. The active power of electronic devices occurs when the user needs to do a specific work to power the device. The passive mode, instead, is when the humans must not do any works than their daily activities: finger movement, walking, heat of the body, etc.

2.4 Power Management Unit

The piezoelectric modules and the transducers operate with an output voltage of the order of mV, which changes in according to the environmental conditions and materials used. The electronic circuits, such as microcontrollers or wireless transceivers which are very often used in power supplies energy harvesting, generally work with a supply voltage of between 1.8 and 5 V. They need constant power to maximize their performance. The ripple oscillations declass the performance in terms of parameters such as noise figure and accuracy. The property to suppress that noise in a power supply line is expressed by the PSRR. PSRR is introduced to indicate the amount of noise introduced from a power supply, it stands for “Power Supply Rejection Ratio” expressed in *dB* as the ratio of the variation of the supply voltage in an operational amplifier and the equivalent output voltage (differential). PSRR is the main design parameter in modern SoC [27–32]. In order to limit the oscillations, different circuits of power management such as boost converter are used. The problem of the threshold voltage is reflected in the possibility of not power a circuit if it doesn’t exceed 0.3 V. Various techniques (star-up circuits) are used during the startup when the battery is not present in the system. After a level transition, as soon as the converter provides stable voltage to the circuit, the start-up circuits are disabled. These circuits are used primarily with thermogenerator.

Another important aspect is the system impedance. With a certain power, the source must provide maximum power for a given load. To adapt the impedance, Tracker MPPT circuits such as those employed in the photovoltaic panels are used. In the switching regulators, frequency variation is reflected in an input impedance change. In this way, the tracker controls the input resistance to achieve maximum transducer power. For a piezoelectric, to extract more energy implies a perfect layout of power management. A transceiver requires a certain time and then a current to run a data transmission in a specific time. These considerations can be expressed as the following:

$$T_a = \frac{1}{d_r * \frac{1}{\frac{D}{n} * m}} \quad (2.2)$$

where d_r is the data flow or data rate (bytes/s), D are the bytes of data to be transmitted, n are the bytes of a data package, and m is the length of the package. In the procedure for sending and receiving data, all necessary blocks are activated unlike the sleep mode. The average current required by the transceiver is the following:

$$I = \frac{I_{\text{sleep}} T_{\text{sleep}} + I_T T_T}{T_s} \quad (2.3)$$

where I_{sleep} is the current absorbed by the transceiver in the sleep mode with the corresponding sleep time, I_T is the current consumed during a transmission time T_T , and T_s is the transmission period which is the sum of the sleep and transmission time. The important parameters in the selection of a sensor for energy harvesting applications are the current consumption in both active and passive mode, the average power and the sleep time. Sensors can provide an analog or digital output. The I2C/SPI bus provides a direct interface for transmitting data to digital circuits such as microcontroller. The sensitivity of the sensor is the amount of variation of the output signal in according to the variation of the measured parameter. A conditioning circuit to manage the output voltage before being sent to a control device is required. The response bandwidth of a sensor is expressed in Hertz and is the maximum rate at which the sensor can work correctly. The microcontrollers have different working operation mode in according to the current consumption. In the active mode the consumption is obviously higher than passive mode with some circuit parts turned off. In the active mode of low-power microcontrollers, the current consumption is higher than passive mode and all the clocks are active, while in the low-power consumption mode the CPU and some of the internal clocks are disabled. In Fig. 2.3 is visualized a generic block diagram of a low-power microcontroller, while Fig. 2.4 shown a typical current profile for a wireless transceiver. In an general energy harvesting system, the transceiver is in standby mode in most of the time to keep the average power consumption to a minimum. When the data are to be transmitted, the transmission mode is activated and then the maximum peak current is consumed [33–35].

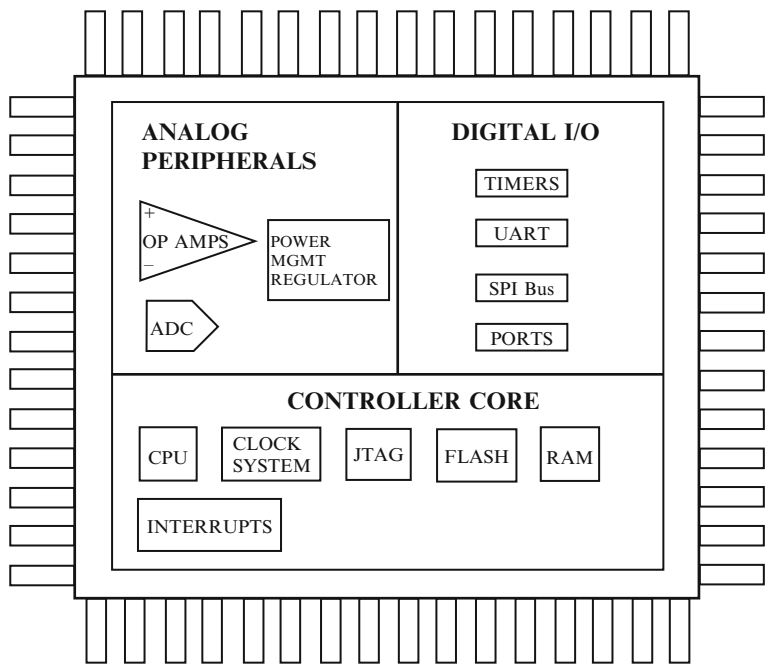


Fig. 2.3 Block diagram of a low-power microcontroller

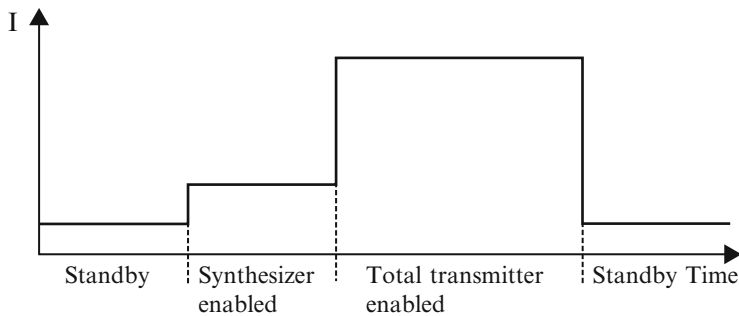


Fig. 2.4 Typical current waveform for a wireless transceiver

2.5 Storage Systems

In an energy harvesting system, the output voltage is not constant in time. It's very important to have the same amount of constant energy over time, a bit as in photovoltaic devices. That means have the same average power in the time interval in according to load system. An energy storage element is not necessary if the power consumption of the electronic device is always less than the power generated by energy harvesting generator that is actuated only when there is power generated.

For the rest of the cases, an energy storage element is required such as a battery. The goal is to present a way to compute the initial storage element charge before the commissioning and the maximum amount of energy needed to store. First, you must define the energy supplied by the transducer element of energy storage and energy consumed by the load in a mathematical way must be defined. The average power can be defined as measuring in the time interval T :

$$p_s = \frac{1}{T} \int_0^T P_s(t) dt \quad (2.4)$$

Considering T_{l-i} the time duration during which P_s is less than p_s and T_{h-l} is the opposite case, i.e., P_s greater than p_s , we can define a deficit (minimum) energy for the first case, while in the second case an excess (maximum) energy is defined.

The energy collected by the transducer and sent to the element of energy storage will be within a certain margin:

$$E_{\min} \leq \frac{1}{T} \int_0^T P_s(t) dt \leq E_{\max} \quad (2.5)$$

The goal for a wearable device, such as also a node of WSN, is to eliminate the need to replace or recharge the battery. Therefore, it is necessary to ensure that the battery is always maintained to the energy required by the electronic device. To ensure this, the total energy must be greater than that consumed by the load, in other words (with B the energy stored in the battery):

$$\sum E > 0 \quad (2.6)$$

$$\sum E \leq B \quad (2.7)$$

The energy available in the system is equal to the initial energy stored in the energy collected by the transducer less battery energy consumed by the load and any losses due to parasitic factors:

$$\sum E = B + E_s - El - \int_0^T P_{\text{leak}} T dt \quad (2.8)$$

where P_{leak} is the leakage power of the storage element. In the case of a load with different power consumption modes as displayed in Fig. 2.4, the calculation of the required power is done by considering the following equation:

$$\tau = \sum_{i=1}^N T_i \tau \quad (2.9)$$

T_i is the time interval where the consumption power is P_i . Generally the following equation can be defined:

$$p_l = \sum P_i T_i \quad (2.10)$$

To acquire data from remote locations, the sensor nodes designed for the Internet of Things (IoT) must be able to function for as long as possible on a single battery charge. In an ideal approach, it would not need a battery because its existence can complicate the management of the system. One major problem is that the power is difficult to “catch,” it comes as a very low level but with phase problems to resolve. Accordingly, specialized techniques are required for the inputs, which include a boost converter capable of handling the low-voltage sources, high impedance, and other characteristics of many energy harvesting modules. Furthermore, circuits such as boost converters may introduce high frequency noise that may disturb radio communications.

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