Handbook of Energy Harvesting Power Supplies and Applications

edited by Peter Spies | Loreto Mateu | Markus Pollak

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Preface

The power consumption of microelectronic circuits and systems is decreasing by successive development of circuit and semiconductor technology. On the other hand, the efficiency of energy transducers such as solar cells, thermoelectric, and inductive generators is increasing by means of material and system improvements. Thus, energy transducers are able to use ambient energy to power small electronic devices such as sensors, microcontrollers, and wireless transceivers. The technology has come to be known as “energy scavenging” or “energy harvesting,” the systems with these power supplies are often called “energy-autarkic” or “self-powered systems.”

On the one hand, energy harvesting power supplies replace batteries in conventional applications such as consumer products, household appliances, measurement and monitoring applications, and home automation systems. If the battery cannot be replaced completely, at least the length of time before the next recharge can be extended. By eliminating batteries, a significant reduction of waste and battery replacement effort is achieved.

On the other hand, new applications such as wireless sensors in remote or inaccessible areas become possible with energy harvesting. Examples are medical implants, integrated sensors in machinery, engines or plants or rotating equipment. Furthermore, unlimited operation and standby time are possible with energy harvesting.

The growing research into and development of wireless sensor networks are closely linked to energy harvesting. The full benefits of wireless sensor networks cannot be achieved with wires for power supply or battery replacement maintenance. Especially, with an increasing number of nodes in a mesh network, self-powered electronics are mandatory.

At present, several professional applications have established themselves in this domain, mainly in the area of building and home automation, consumer products and condition monitoring. In contrast, a huge new field of applications for energy harvesting, especially for powering wireless sensor nodes are addressed in research and development projects.

Contributions to this book have been made by the leading facilities of applied research in Germany, the Fraunhofer Gesellschaft and the Hahn-Schickard-Gesellschaft, which are both application-oriented research and development providers. They work in publicly funded projects and also conduct research and development for industrial companies around the world.

Thus, this book deals with the basics of energy harvesting technology with a focus on application-oriented implementation. Each chapter addresses a special core technology of energy harvesting including the different transducer principles and related materials, power management, storage devices, and system design. The final chapter introduces different applications of energy harvesting and related system architectures and application devices and discusses relevant converter types.

Chapter 1

System Design

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This chapter deals with the topic of designing an energy harvesting (also called energy-scavenging) system that is composed by an energy harvesting power supply and a low-power load. In such systems, the energy is collected from the environment employing a transducer that transforms the ambient energy into electrical energy for supplying energy autarkic electronic devices.

1.1 Introduction

A self-powered system based on energy harvesting is composed of several blocks (see Fig. 1.1) and each of them has a dedicated section in this chapter. The blocks are:

- Energy transducer (also called energy harvesting generator). It is used to convert the input ambient energy into electrical energy. The environmental energy sources available for conversion may be heat (thermoelectric

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modules), light (photovoltaic cells), radiation (rectifying antennas), and vibration (piezoelectric, electro-magnetic, electro-static transducers).

- Rectifier and storage capacitor. Some energy transducers do not provide DC power, and in this case it is necessary to rectify the current and accumulate it into a capacitor.
- Voltage regulator. It is necessary to adapt the voltage level to the requirements of the powered device or the optional storage element.
- Optional energy storage element. A battery or capacitor, depending on the requirements of the application, is employed as energy storage element. In some applications the powered device can be completely switched off during certain intervals and a battery is not necessary, while in others a permanent supply is mandatory. Furthermore, the energy storage element is required to provide pulse currents for radio transceivers that work in the burst mode; these cannot be generated by the energy transducer itself due to their large internal resistance. In any case, this battery will have a lower weight, volume, and capacity than a battery that is expected to supply power to an electronic device without an energy harvesting generator. Whether a capacitor can be used instead of a battery depends on the requirements of the application.
- Electronic load. It has typically different power consumption modes allowing to operate the device most of the time in a low-power consumption mode. It works in active mode only during limited time periods to decrease its total energy consumption.

1.2 Input Energy

The application of the energy harvesting system determines which energy sources are available in the environment to power it. The main environmental energy sources employed to supply power to, for example, wireless sensor networks (WSNs) are solar, mechanical, and thermal energy. Self-powered devices have normally reduced

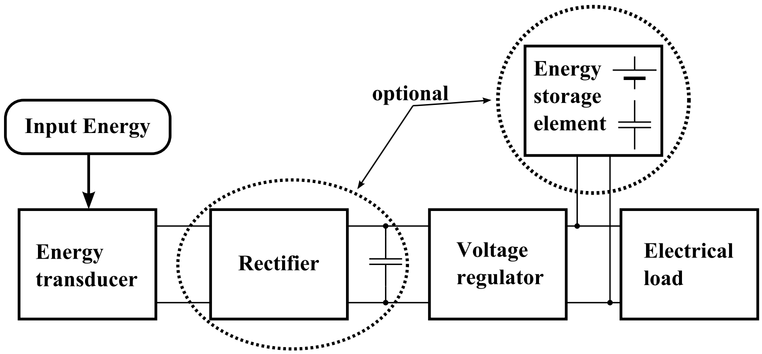

Figure 1.1 Schema of a generic self-powered device.

dimensions (volume around 10 cm^3 or lower) since their most frequent applications are as nodes in a WSN or wearable devices. The dimensions of the energy harvesting power supply are a constraint for the amount of electrical energy that is generated. That is why an accurate comparison of energy harvesting systems can be done only in terms of power per unit of volume (power density) or power per unit of area.

Roundy[4] summarizes in Table 1.1 a comparison between different energy harvesting sources (unshaded part) and energy storage elements (shaded part) in terms of power density (power per unit of volume). Power density for energy harvesting sources under the same input conditions remains constant with time while it does not for energy storage techniques due to leakage currents as it is shown in Fig. 1.2. That is why energy harvesting becomes an alternative to energy storage techniques in long operation time applications where it is not possible to replace or recharge the energy storage element.

Raju[5] gives an estimation of the available power per unit of area for different energy harvesting sources and scenarios. For the case of vibrations and temperature difference, Table 1.2 distinguishes between human and industry energy sources. "Human" refers to the use of the human body as input energy. Therefore, the temperature gradient existing between the human body and the environment and the vibrations associated to the human movement

Table 1.1 Comparison of energy scavenging sources and energy storage elements in terms of power density taking into consideration lifetime

	Power density ($\mu W/cm^2$) 1 Year lifetime	Power density ($\mu W/cm^2$) 10 Years lifetime	Source of information
Solar (Outdoors)	15,000—direct sun 150—cloudy day	15,000—direct sun 150—cloudy day	Commonly available
Vibrations	200	200	Roundy et al.[1]
Acoustic noise	0.003 @ 75 Db 0.96 @ 100 Db	0.003 @ 75 Db 0.96 @ 100 Db	Theory
Daily temp. variation	10	10	Theory
Temperature gradient	15 @ 10°C gradient	15 @ 10°C gradient	Stordeur et al.[2]
Shoe inserts	330	330	Starner 1996, Shenck et al.[3]
Batteries (non-recharg. Lithium)	45	3.5	Commonly available
Batteries (rechargeable Lithium)	7	0	Commonly available
Hydrocarbon fuel (micro heat engine)	333	33	Mehra et al.mehra2000six
Fuel cells (methanol)	280	28	Commonly available
Nuclear isotopes (uranium)	6×10^6	6×10^5	Commonly available

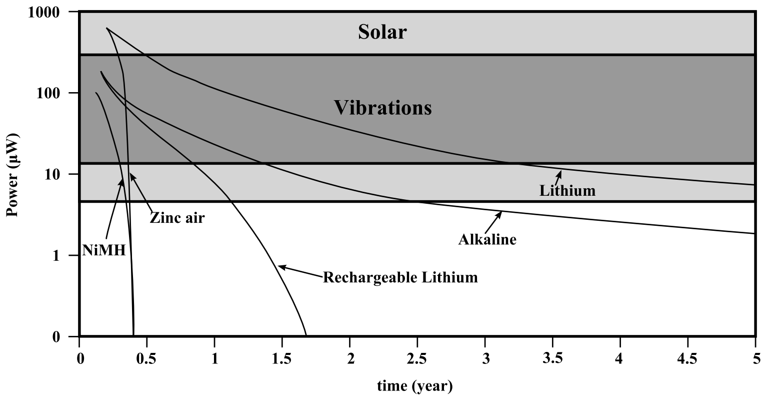

Figure 1.2 Power density versus life time for solar cells, vibrations and batteries.

Table 1.2 Comparison of harvested power per cm^2 for different energy sources and scenarios

Energy source	Harvested power
Vibration/Motion	
Human	4 μW/cm^2
Industry	100 μW/cm^2
Temperature Difference	
Human	25 μW/cm^2
Industry	1–10 mW/cm^2
Light	
Indoor	10 μW/cm^2
Outdoor	10 mW/cm^2
RF	
GSM	0.1 μW/cm^2
WiFi	1 μW/cm^2

can be the input energy of an energy harvesting power supply. In the case of industry, excess heat and machine vibrations are employed as energy source.

Light is an environmental energy source available to power electronic devices. A photovoltaic system generates electricity by the conversion of light into electricity. Photovoltaic systems are found

Table 1.3 Solar power measurements taken under different light conditions

Conditions	Outside, midday	4 inches from 60 W bulb	15 inches from 60 W bulb	Office lighting
Power ($\mu W/cm^3$)	14000	5000	567	6.5

from the megawatt to the milliwatt range producing electricity for a wide number of applications: from lighting to wristwatches.

Outdoors, the solar radiation is the energy source for PV system. This solar radiation varies over the earth's surface due to the weather conditions and the location (longitude and latitude). For each location, there 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.[6] Table 1.3 shows the power density measured under different light conditions with a silicon solar cell and Table 1.2 presents the power per unit of area for an outdoor and indoor light source. The power per unit of area is three orders of magnitude bigger in the outdoor than in the indoor case.[4] From the measurements displayed in Table 1.3, it is deduced that in the case of indoor light, the power density decreases with the inverse of the square of the distance between the solar cell to the light source.

The principle behind kinetic energy harvesting is the displacement of a moving part or the mechanical deformation of a structure inside the energy harvesting device. This displacement or deformation can be transformed to electrical energy by three different methods: inductive, electrostatic and piezoelectric conversion.

Vibrations are the input energy for the transducers that convert the displacement of a moving part into electrical energy. Vibrations are characterized by their peak acceleration and the corresponding frequency. With these data, an estimation of the electrical energy that can be generated employing vibrations is possible.[7] Table 1.4 gives a list of peak accelerations and frequencies for different industry vibration sources and from this data, it is deduced that vibrations of industry machines have associated accelerations between 60 and 125 Hz.

Table 1.4 List of vibration sources with their respective peak acceleration and frequency

Vibration source	Peak acc. (m/s^2)	Frequency of peak (Hz)
Base of 5 HP 3-axis machine tool with 36" bed	10	70
Kitchen blender casing	6.4	121
Clothes dryer	3.5	121
Door frame just after door closes	3	125
Small microwave oven	2.25	121
HVAC vents in office building	0.2–1.5	60
Wooden deck with people walking	1.3	385
Breadmaker	1.03	121
External windows (size 2 ft × 3 ft) next to a busy street	0.7	100
Notebook computer while CD is being read	0.6	75
Washing machine	0.5	109
Second story floor of a wood frame office building	0.2	100
Refrigerator	0.1	240

There is also the possibility of employing the human body as a vibration source. Vibrations associated with the human body have accelerations with frequencies under 10 Hz.[8] T. von Büren et al.[9] present a comparison of simulations done with vibrational generators employing measured acceleration data from walking motion at different locations of the human body. Walking is one of the human activities that have more energy associated.[10,11] Mateu et al.[12,13] are also presenting a simulation study for the case of a non-linear model of the electrodynamic generator employing measured acceleration data from different human activities and locations at the human body.

Jansen[14] employs the term human power as short for human powered energy systems in consumer products. The Personal Energy System (PES) research group of the Delft University of Technology distinguishes between active and passive energy harvesting methods when the input energy is provided by the human body. The active powering of electronic devices takes place when the user of the electronic product has to do a specific work in order to power the product that he otherwise would not have done.

The passive powering of electronic devices takes place when the user does not have to do any activity different to the normal tasks associated with the product. In this case, the energy is harvested from the user's everyday actions (walking, breathing, body heat, blood pressure, finger motion, etc.).

The option to parasitically harvest energy from everyday human activity (passive power) implies that an unobtrusive technique has to be adopted. Starner presented human power as possible source for wearable computers.[10] He analyzed power generation from breathing, body heat, blood transport, arm motion, typing, and walking and provides the power dissipated by the human body during several activities. A more recent study appears in reference[15] where the state of the art of passive human power to power body-worn mobile electronics is explained.

Heat can be used as input energy for energy harvesting power supplies where a temperature gradient and heat flow is present. The maximum efficiency for converting the harvested heat into electricity is given by Carnot efficiency:[10]

$$\eta_{\mathrm{Carnot}} = \frac{T_{\mathrm{Hot}} - T_{\mathrm{Cold}}}{T_{\mathrm{Hot}}} \tag{1.1}$$

where T_{Hot} is the high temperature and T_{Cold} is the low temperature of the temperature gradient.

Thermal energy is characterized by the temperature gradient and the heat flow. It is converted into electrical energy with thermogenerators that are fundamentally based on the Seebeck effect. This kind of energy is present, e.g., in machinery (industrial) and in the human body (see Table 1.5). The temperature gradient is mostly obtained between the heat source and the room temperature.

Starner et al.[16] makes an analytical study of thermoregulation in humans.

Leonov et al.[17] have experimental data of skin temperature and heat flow of humans dependence on air temperature for different locations on the forearm. Leonov et al.[18] present the thermal circuit of a thermogenerator on the skin that is composed by three different thermal resistances, the body, the thermogenerator and the ambient air.

Table 1.5 Characteristics of typical energy harvesting power supplies

Energy source	Characteristics	Efficiency	Harvested power
Light	Outdoor	10-25%	100 mW/cm^2
	Indoor		100 μW/cm^2
Thermal	Human	~0.1%	60 μW/cm^2
	Industrial	~3%	10 mW/cm^2
Vibration	~ Hz-human	25-50%	40 μW/cm^2
	~ kHz-machines		800 μW/cm^2
Radio frequency (RF)	GSM 900 MHz	~50%	0.1 μW/cm^2
	WiFi 2.4 GHz		0.001 μW/cm^2

1.3 Energy Transducer

The energy transducer is used to convert the available energy into electrical energy. The selection of the energy transducer depends on the kind of available energy for the application under consideration. Therefore, thermoelectric cells are employed for thermal energy and photovoltaic cells for light. For mechanical energy, three different transducers are considered: piezoelectric, electro-dynamic, and electro-static.

The location of the transducer determines the amount of input energy that is available for the energy harvesting power supply and, therefore, the output power obtained for supplying the electronic load. Consequently, to find the location that provides the higher amount of input energy for the relevant application is of special interest.

When the input energy are vibrations, it is necessary to measure the acceleration at the different possible locations of the energy harvesting transducer in order to determine the amplitude and the frequency range of the vibrations.

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 different methods: electro-magnetic, electro-static, and piezoelectric conversion. Each of these transducers can convert kinetic energy into electrical energy with two different methods: inertial and non-inertial.

Inertial transducers are based on a spring-mass system. In this case, the proof mass vibrates or suffers a displacement due to the kinetic energy applied. The transducer converts the relative displacement of the mass referred to the housing, which causes an inertial force, into electrical energy. Thus, this type of transducer is called an inertial converter. Mitcheson et al. have classified inertial converters as a function of the force opposing the displacement of the proof mass.[19] These converters resonate at one discrete frequency and many of them are designed to resonate at the frequency of the mechanical input source since at this frequency (resonance frequency), the energy obtained is maximum. However, as the converters are miniaturized to integrate them on MEMS devices, the resonance frequency increases, and it becomes much higher than characteristic frequencies of many everyday mechanical stimuli.

For non-inertial converters, an external element applies a pressure that is transformed into elastic energy, causing a deformation that is converted to electrical energy by the converter. In this case, there is no proof mass and the obtained energy depends on mechanical constraints or geometric dimensions.[20] The following paragraphs give an overview of piezoelectric, electro-dynamic and electro-static transducers.

Piezoelectric materials are employed as sensors, actuators, or energy harvesting transducers due to their properties. 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. Metallizing the piezoelectric materials and connecting electrodes provides a voltage associated with the charge when the electrodes are not short-circuited. The piezoelectric effect can be employed for the conversion of mechanical energy into electrical energy. Table 1.6 shows a summary table with some energy harvesting generators that employ piezoelectrics as transducers. Detailed information about these transducers is provided in Chapter 3.

Electro-dynamic generators, also called voltage damped resonant generators (VDRG), are based on Faraday's law. The principle of

Table 1.6 Summary table of piezoelectric inertial generators

Design Author	Mechanical excitation	Output power	Dimensions
S. Roundy et al.[21] Design 1	$a = 2.25$ m/s^2 $f = 85$ Hz	207 μW @ 10 V	1 cm^3
S. Roundy et al.[21] Design 2	$a = 2.25$ m/s^2 $f = 60$ Hz	335 μW @ 12 V	1 cm^3
S. Roundy et al.[21] Design 3	$a = 2.25$ m/s^2 $f = 40$ Hz	1700 μW @ 12 V	4.8 cm^3
H. Hu[22]	$a = 1$ m/s^2 $f = 50$ Hz	246 μW/cm^3 @ 18.5 V	—

these electromagnetic induction microgenerators is the generation of a current induced on a coil by a moving magnet relative to the coil. The relative motion produces a change in the electromagnetic flux through the coil that causes an electromotive force (EMF) in the coil, following Faraday's law. This induced EMF will generate a current related to the electrical load of the coil that in turn generates a force due to the electromagnetic field and this force will interact with the motion. 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, the length of the coil is directly proportional to the obtained electric field and therefore, to the generated energy. This means that big transducers with large area coils will perform better than smaller ones, unless a large acceleration is involved with the small-scale generators. Table 1.7 shows a summary table of electro-dynamic generators. The analysis of these transducers is given in Chapter 4.

Electro-static generators, also known as Coulomb-damped resonant generators (CDRGs), are based on electrostatic damping. The implementation of electro-static generators is done using a capacitor with one plate moving against the electric field. If the charge on the capacitor is maintained constant while the capacitance decreases by 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

Table 1.7 Summary table of electro-dynamic generators

Design author	Mechanical excitation	Output power	Dimensions
Williams et al.[23]	$f = 4$ kHz Amplitude $= 300$ nm	0.3 μW	mm^3
Li et al.[24]	$f = 64$ Hz Amplitude $= 1000$ μm	10 μW @ 2 V	1 cm^3
Ching et al.[25]	$f = 104$ Hz Amplitude $= 190$ μm	5 μW	—
Amirtharajah et al.[26]	$f = 2$ Hz Amplitude $= 2$ cm	400 μW @ 180 mV	—
Yuen et al.[27]	$f = 80$ Hz Amplitude $= 250$ μm	120 μW @ 900 μV	2.3 cm^3

Table 1.8 Summary table of electro-static generators

Design author	Mechanical excitation	Output power	Dimensions
Meninger et al.[28]	$f = 2.52$ kHz	8 μW	0.075 cm^3
Sterken et al.[29]	$f = 1,200$ Hz Amplitude $= 20$ μm	100 μW @ 2 V	–
Miyazaki et al.[30]	$f = 45$ Hz Amplitude $= 1$ μm	120 nW	–

capacitance decreases, the charge will decrease. The mechanical energy converted into electrical energy is greater when the voltage on the capacitor is constant than when the charge on the capacitor is constant. However, the voltage source needed to place an initial charge on the capacitor plates has a smaller value, if the charge across the capacitor is constrained. A way to increase the electrical energy for the charge constrained method is adding a second capacitor in parallel with the variable capacitor. The disadvantage of this solution is that the value of the initial voltage source has to be increased. The energy conversion principle of electro-static generators is explained in more detail in Chapter 5. Table 1.8 shows the results obtained with some electro-static generators.

A comparison table between piezoelectric, electro-dynamic, and electro-static transducers for the mechanical to electrical energy conversion with their advantages and disadvantages is given by Roundy[4] and Jia[31] and has been put together in Table 1.9.

Table 1.9 Comparison of vibration transducers

Type	Energy density equation	Practical maximum for energy density (mJ/cm^3)	Theoretical maximum for energy density (mJ/cm^3)	Advantages	Disadvantages
Piezoelectric	$U = \frac{\sigma_y^2 k^2}{2Y}$	17.7	355	No external voltage source required, Voltages of 2 to 10 V, No mechanical stops, Compatible with MEMS, Highest energy density	High output impedance, Depolarization, Charge leakage, Brittleness in PZT, Poor coupling in PVDF
Electrostatic	$U = \frac{\epsilon E^2}{2}$	4	44	Easier to integrate in MEMS, Voltage of 2 to 10 V	External voltage source needed, Mechanical stops needed
Electrodynamic	$U = \frac{B^2}{2\mu_0}$	4	400	No external voltage source, No mechanical stops	Maximum output voltage of 0.1 to 0.2 V, Difficult to integrate with MEMS

Table 1.10 Summary table of thermogenerators

Author	Output power	ΔT (K)	Absolute temperature
Stordeur et al.[2]	20 μ W @ 4 V	20	Room temperature to 120°C
Stordeur et al.[33]	15 μW/cm^2	10	—
Stevens[34]	—	10	—
Seiko[35,36]	1.5 μ W@1.5 V	1–3	—
ThermoLife[37]	28 μW @ 2.6 V	5K	30°C
Leonov et al.[18]	250 μW 20 μW/cm^2@0.9 V	—	Room temperature

The variables that appear in the energy density equation for piezoelectric transducers are the yield strength of the material σ_y, the piezoelectric coupling coefficient k, and Young's modulus Y. For the case of the electro-static transducer, ϵ is the dielectric constant and E is the electrical field between the plates. In the case of the electro-dynamic transducer, B is the magnetic field and μ_0 is the magnetic permeability.

Thermogenerators basically consist of one or more thermocouples, each of them composed of a p-type and a n-type semiconductor connected electrically in series and thermally in parallel. The TEG is based mainly on the Seebeck effect and produces an electrical voltage proportional to the temperature difference and to the number of thermocouples since the electrical connection allows to add the voltage obtained from each thermocouple.[32] Table 1.10 and Chapter 6 provide a detailed analysis of this transducer.

Light is another environmental energy source available to power electronic devices. A photovoltaic system provides electrical energy by the conversion of light employing solar cells as transducers. The employment of photovoltaics in portable products is a valid option under the appropriate circumstances. Chapter 7 explains this technology in further detail.

1.4 Rectifier

Piezoelectric, electro-static and electro-dynamic energy harvesting power supplies produce an AC output power. In order to power an electronic load, a rectification of the output power is necessary in those cases. The rectifier can be integrated with the power management unit, such as in the case of electro-magnetic generators,[38,39] and some piezoelectric generators.[40,41]

The rectification of the AC signal for piezoelectric transducers can also be done employing a voltage or a current multiplier.[42] It is also possible to choose between synchronous or asynchronous rectifiers and between half-wave and full-wave rectifiers. This topic is studied in detail in Chapter 9.

1.5 Power Management Unit

State-of-the-art TEGs produce, for instance, 50 mV open-circuit voltage per Kelvin thermal gradient. Typical piezoelectric modules can generate several volts depending on material and displacement. Electronic circuits such as sensors, microcontrollers or wireless transceivers, which are most often used with energy harvesting power supplies work with a supply voltage range between 1.8 and 5 V. Moreover, they need a very constant and well-regulated supply voltage to maximize their performance. Especially, peaks or oscillations generated from kinetic energy transducers will degrade their operation in terms of noise figure, accuracy, or resolution because of parasitic paths between the supply rails and the signal rails. The property to suppress such noise on the supply rail is called power supply rejection ratio (PSRR). This is the ratio between the gain from the input to the output and the gain from the supply rail to the output of the electrical circuit, e.g., an amplifier.

To close the gap between the outputs of the energy transducers and requirement of constant and decoupled supply rails at fixed voltage levels, different power management circuits are used. For employing low voltages, so-called up-converters or boost regulators are required. These blocks are important for thermogenerators when only small thermal gradients are present or when only a small number of thermo-couples are used to achieve a small system size or price. Furthermore, up-converters are helpful with solar cells for the same reasons. These converters are also used to discharge batteries below the required voltage of the circuit to supply. Usually, for a 3.3 V system, the battery is used down to 3.4 V, considering a 0.1 V drop of the power management, namely voltage regulator. Using an up-converter or a combination of an up- and a down-converter (buck-boost), you can discharge the battery down to the minimum battery voltage utilizing the total battery charge. The higher voltage for the application is produced with the up-converter. Care must be taken of the efficiency of these up-converters, which is often significantly lower than the efficiency of down-converters. Furthermore, the efficiency is often maximal only for a certain load current range. Leaving that range in the application, the efficiency will drop and the losses of the power management itself are increased.

Especially with thermogenerators, so-called start-up circuits are used, which enable an operation of the voltage converter down to several millivolts. Problem is the threshold voltage of semiconductors, which is presently at about 0.3 V. This would usually mean that you cannot power a circuit with a voltage below that range, because you are not able to switch any transistor. There are several techniques used in start-up circuits to cope with that problem. They are introduced and explained in detail in Chapter 8. These circuits are often only used during the start-up of the whole system when no battery is present. After a transient time, the voltage converter supplies itself from its own generated higher voltage via a feedback loop and the start-up circuit is disabled. The downside of such start-up circuits is often a very bad efficiency, thus it make sense to disable them during normal operation of the system.

Besides up- and down-conversion, another important of task of the power management is the impedance matching. As the power theory states, a power source will deliver the maximum power to a load if the impedance of the source and the load are equal. Especially, TEGs and solar cells alter their internal resistance due to aging and temperature. To match the internal resistance of the transducer as the source and the power management as the load, so-called maximum power point trackers are used. These systems were formerly used in large photovoltaic plants and are now adapted to energy harvesting systems by a significant reduction in power consumption and performance. The circuits are simply regulation loops of switching voltage regulators, which measure the output power of these regulators. They change the duty cycle of the switching regulator and monitor the output power to arrive at an optimum. An adjustment of the switching frequency of the regulator is equal to a change of its input resistance, which is given by the input inductance and the switching frequency. Thus, the maximum power point tracker adjusts the input resistance of the power management to achieve the maximum output power of the energy transducer.

Regarding piezoelectric transducer, the power management is used to extract more energy from the material by using switched inductors. These inductors build a resonance circuit with the internal capacitor of the piezoelectric material. The non-linear techniques are also explained in Chapter 9.

Another task of the power management is the charge regulation and protection of the energy storage elements in the energy harvesting system. This can be done by charge regulators if large load or charge currents are present, which might damage a battery or a capacitor if not carefully adjusted. Most often, in energy harvesting system, the currents are so small that only simple voltage regulators are needed for energy storage elements. Battery monitoring in terms of calculation the remaining charge in a battery can also be done in the power management unit. Here counting the charge flowing into and out of the battery can be used as well as simple voltage measurement.

1.6 Load Device

The electrical power obtained from an energy harvesting system is very small (1 $\mu W/cm^3$ to 100 mW/cm^3) and that is why only low-power loads can be supplied with energy harvesting generators. A typical electronic load consists of a sensor, a microcontroller, and a wireless transceiver (see Fig. 1.3). Table 1.11 shows some current consumption values for those components differentiating between ultra-low-power and conventional components.[43]

During transmission, the power consumption is approximately between 50 to 100 mW depending on the transmission range.[44] The consumed power is much higher in almost all the cases than the available harvested power. The energy present in the environment that can potentially be harvested is mostly discontinuous in nature.

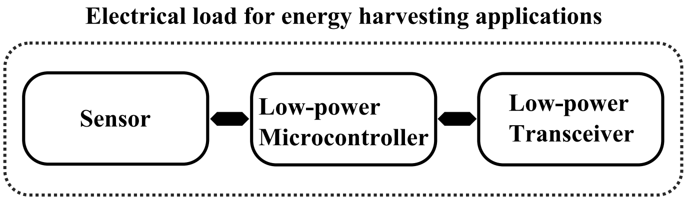

Figure 1.3 Block diagram of a general load: sensor, microcontroller, and wireless transceiver.

Table 1.11 Characteristics of low-power loads

Device	Ultra-low-power	Conventional
Microcontroller	160 μA/MHz	500 μA/MHz
Sensor	120 μA	> 1 mA
Transceiver	3 mA	15 mA
Transceiver	120 μA	70 mA

Consequently, there must be an element to store the energy at periods with high ambient power to guarantee an operation at times with low ambient power. This storage element can be a capacitor, or a secondary battery.

So, the harvested energy is accumulated in a storage element and the sensors, microcontroller, and RF transceiver can work in a low-power or standby mode or are totally powered off until there is enough energy accumulated to sense, process, and transmit the data. The next subsection goes deeper into this topic.

1.6.1 *Continuous and Discontinuous Load Operation*

The discontinuous nature of ambient energy sources has consequences on the way in which electronic devices powered by energy harvesting power supplies are operated. In principle, we can distinguish between two situations in which an energy storage element is necessary:[45]

(1) The average power consumption of the electronic device is lower than the average power provided by the energy

transducer. In this case, the electronic device may operate continuously.

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

The electronic device is able to operate only when there is enough energy in the energy storage element. Figure 1.4 shows the two cases. The energy storage element is necessary to provide energy during the moments where transiently the provided power is lower than the power consumed by the load. A special case would be if the device is operated exclusively during the time when there is electrical power generated, and the power consumption is at all times smaller than the generated electrical power (Fig. 1.5). In this case, the energy storage element is not necessary, although voltage regulation is.

In the general case of discontinuous operation (Fig. 1.4b), energy is a more relevant magnitude than power for energy harvesting systems because the electrical energy generated determines when an operation can be done and also the time between operations of the load. The power requirements of the load in active mode will determine the energy storage element to select and the power profile of the load. The power consumption of the load in active mode is fixed by its electrical components and the supply voltage. Moreover, the components also determine the enable times needed to enter different power consumption modes.

The eZ430-RF2500[46] is a state-of-the-art wireless transceiver system that combines a MSP430 microcontroller with a CC2500 2.4 GHz wireless transceiver. The ultra-low power consumption of both components is ideal for its utilization in energy harvesting applications. Figure 1.6 shows the current profile of the eZ430-RF2500 as a transmitter and Fig. 1.7 shows the current profile of the acceleration sensor when it does four measurements and the current profile of the eZ430-RF2500 that transmits the data employing a piezoelectric energy harvesting supply.

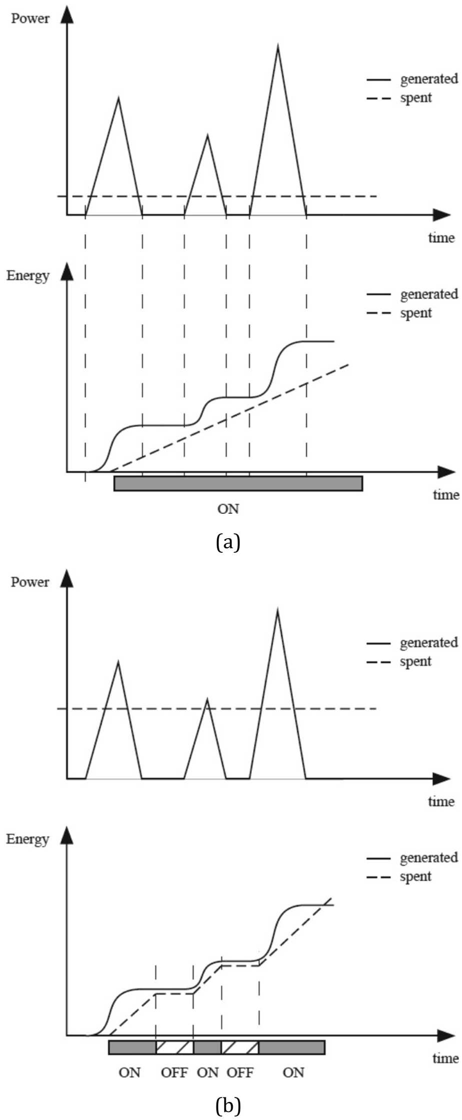

Figure 1.4 Case of continuous (a) and discontinuous (b) load operation. In the case of discontinuous operation, the device must be turned off until enough energy is collected in the storage element.[45]

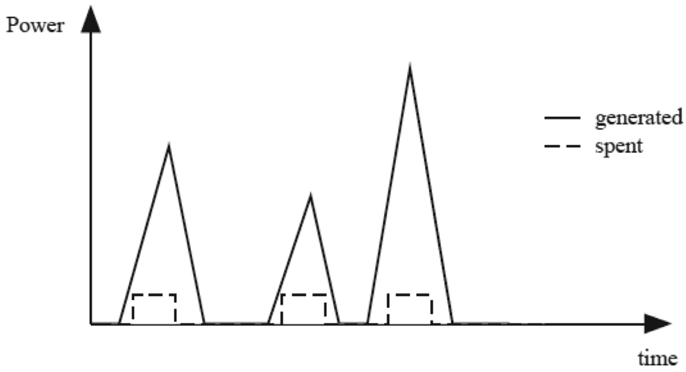

Figure 1.5 Generated and spent power when the device operation is only at times when there is energy generation.

The active time needed by a wireless transceiver for sending a certain amount of data is calculated with Eq. (1.2):

$$T_{\text{active}} = \frac{1}{\text{data rate} \times \frac{1\text{ byte}}{8\text{bits}} \times \frac{1}{\lceil \frac{D}{n} \rceil \text{packet length}}} \tag{1.2}$$

where data rate is the transmission speed in Kbps, D are the data bytes to transmit, n are the data bytes of one packet and packet length is the number of bytes that are transmitted.

Only a minimum current is required in standby mode of most RF transceivers since nearly all the blocks are turned off. In the synthesizer mode, only the blocks associated with the synthesizer (like the crystal and PLL) are turned on. During the transmit and receive mode, all the blocks that are necessary for a transmission and reception are turned on.

When the application requires to transmit data several times per second, Eq. (1.3) is employed to calculate the average current needed by the wireless transceiver.

$$\langle I \rangle = \frac{\left(I_{\text{sleep}} T_{\text{sleep}} + I_{Tx} T_{Tx}\right)}{T_{\text{sending}}} \tag{1.3}$$

where I_{sleep} is the current consumed by the transceiver in sleep mode, T_{sleep} is the time that the transceiver is in sleep mode, I_{Tx} is the current consumed during a transmission and T_{TX} is the time required to send the data and T_{sending} is the period of the

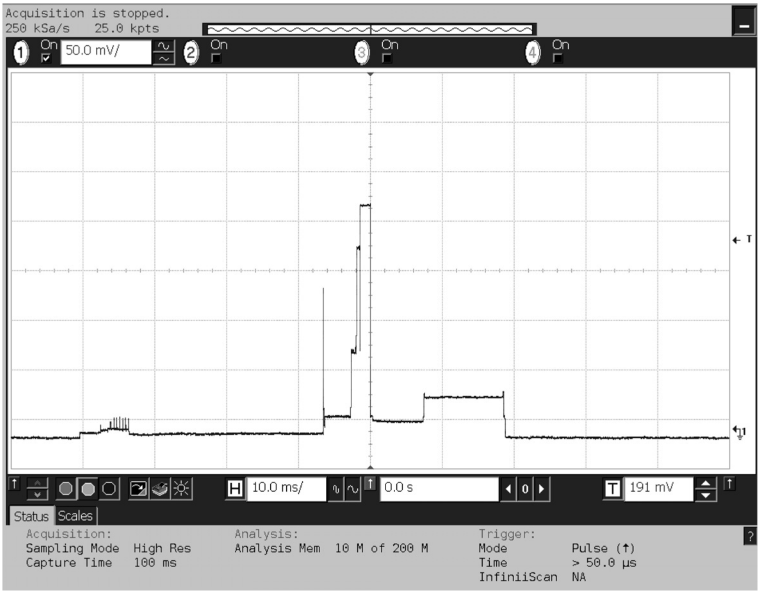

Figure 1.6 Current profile of the eZ430-RF2500 as a transmitter.

transmissions. Thus,

$$T_{\text{sleep}} = T_{\text{sending}} - T_{TX} \tag{1.4}$$

The previous calculus can also be done fixing the average current necessary to power the wireless transceiver and generated by the power converter of the energy harvesting power supply and obtaining the period between transmissions. This case is more realistic that the previous one for energy harvesting applications since it does not imply a redesign of the transducer nor the power management unit to increase or decrease the value of $\langle I \rangle$.

1.6.2 *Low-Power Sensors*

Important parameters to take into account in the selection of sensors for energy harvesting applications are the current consumption both in active and power down modes and the enable response time. The mean power provides the information about the energy consumed by the sensor. The minimum voltage supply and current

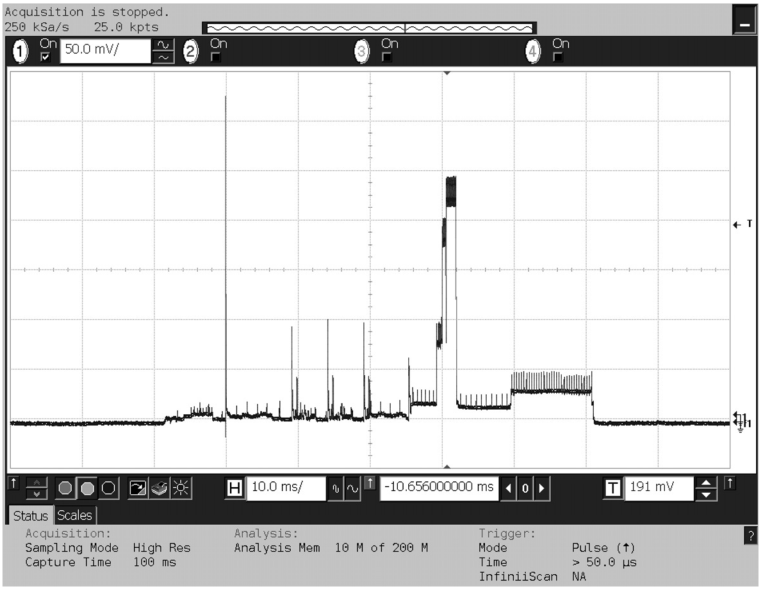

Figure 1.7 Current profile of the eZ430-RF2500 as a transmitter in combination with an accelerometer sensor.

consumption in active mode are fixed parameters that provide the power consumption in active mode. Nevertheless, the time that the sensor is in power down mode changes the total energy required by the sensor. Sensors with low current consumption values in power down mode and low enable response time are the best suited for energy harvesting applications. The enable response time is the time needed to obtain valid data once the low power down mode has been left. Thus, this time extends the time that the sensor will be in active mode.

Sensors can provide analog, digital or both kinds of output. When the output data is available through an I^2C/SPI interface, it has a direct interface for its connection with a microcontroller.

The sensitivity of a sensor is the amount of change in the output signal for the change in the measured parameter. For the case of analog passive sensors, the output signal is expressed in volts and for the case of a digital passive sensors, the output signal is expressed in number of bits. The sensitivity of a sensor will be between the

Table 1.12 Characteristics of body sensors

Signal	Sensitivity	Number of samples per time	Data rate
Heart rate	8 bits	10 samples/min	80 bits/min
Blood pressure	16 bits	1 sample/min	32 bits/min
Temperature	16 bits	1 sample/min	16 bits/min
Blood oxygen	16 bits	1 sample/min	16 bits/min

minimum and maximum values given by the manufacturer on the datasheet for a certain temperature, usually 25°C. Thus, a calibration of the sensor is necessary in order to obtain accurate results. The sensitivity changes versus temperature and this variation is expressed in %/°C.

A conditioning circuit is required to obtain a voltage response from active sensors. Conditioning circuits for resistive, capacitive and electromagnetic sensors are explained by Pallàs et al.[47]

The resolution is the smallest change of the measured quantity that can be detectable by the sensor.

The bandwidth response of a sensor is expressed in Hertz and it is the maximum frequency at which the sensor can make measurements. The data rate is expressed as well in Hertz and corresponds to the frequency at which the measured data is captured.

In wearable applications, sensors measure vital parameters as heart rate, blood pressure, temperature or oxygen in the blood. Table 1.12 presents the required sensitivity, number of samples per time and data rate for some body sensors. Yeatman[48] reports that a total power consumption for a load of 1 μW is a realistic value for body sensors.

Torfs et al.[49,50] adapted the design of a pulse oximeter to have a low-power consumption device that uses an average power of only 62 μW when a measurement is done every 15 s. Figure 1.8 shows the percentage of power consumption of all the components that compose the pulse oximeter device.

The load with lower power consumption is composed by a sensor, an analog to digital converter (ADC) and a transmitter. Yates et al.[51] expose that the power consumption of an ADC with a data rate of 1 Kbps would be 104 nW and that the power consumption of

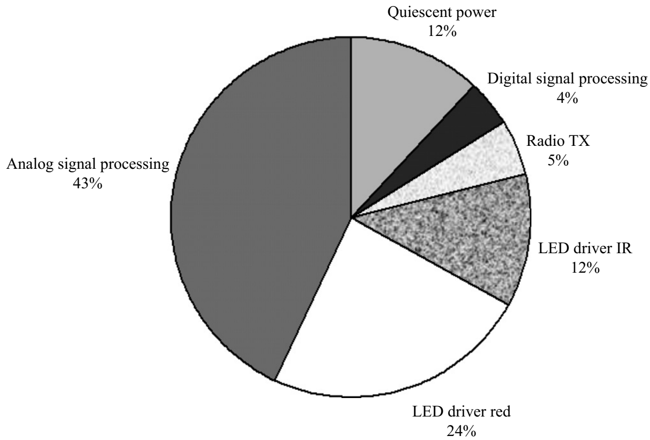

Figure 1.8 Power consumption of the different components of the pulse oximeter device.

a transmitter with the same date rate would be 300 nW. The ADC is operated with a duty cycle of 0.26% and if the temperature sensor MAX6613, which has a power consumption of 20 μW, is operated also with the same duty cycle it has an average power consumption of 5.2 nW. Therefore, a total power consumption of 456 nW for a 1 kbps is required for the sensor, ADC and the transmitter.

1.6.3 *Low-Power Microcontrollers and Transceivers*

Low-power microcontrollers have different operation working modes associated with different current consumptions. In the active mode, the current consumption is the highest and all the clocks are active, whereas in the low-power modes the CPU and some of the internal clocks are disabled. Figure 1.9 shows a generic block diagram of a low-power microcontroller.

Data rate, preamble cycles, and packet length determine the active time needed for the transmission of the data in transceivers. Figure 1.10 shows the typical current profile of a wireless transceiver. In an energy harvesting application, the transceiver is in standby mode most of the time to keep the average power consumption at a minimum level. When the sensed data has to be transmitted, first, some time is needed to enable the synthesizer

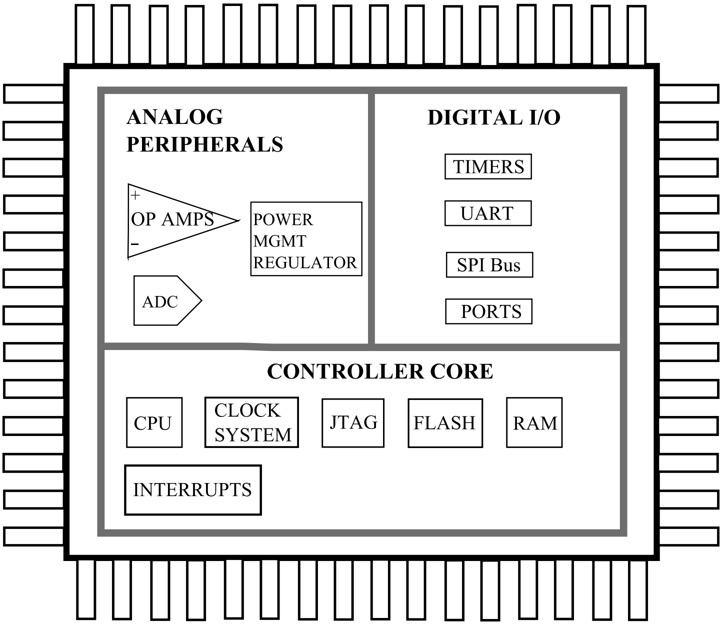

Figure 1.9 Block diagram of a low-power microcontroller.

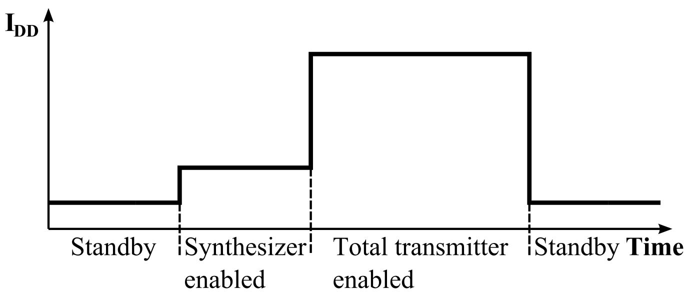

Figure 1.10 Current profile of a transceiver.

and afterward the data is sent. Each of the different modes has its associated current consumption value.

Figure 1.11 shows a block diagram of a generic low-power RF transceiver.

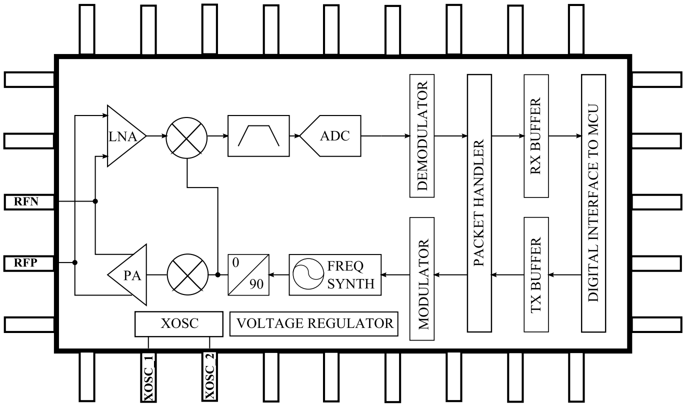

Figure 1.11 Block diagram of a low-power RF transceiver.

1.7 Energy Storage Element

Energy harvesting transducers such as thermogenerators and piezoelements provide only small amounts of electrical power. Moreover, the size and thus the price of the transducer are always related to the power output. Additionally, energy harvesting transducers exhibit large internal resistances, not able to provide large currents without a drop in their output voltage. Finally, typical application scenarios such as the human body or buildings exhibit only small ambient energy sources. In contrast to that, common electronic devices used in energy harvesting systems, especially wireless transmitters, operate in burst mode, transmitting data only during a small period of time and thus require pulse currents during these transmission bursts. Also, microcontrollers are often operated between a full-performance mode, active mode, and a low-power, sleep, or stand-by mode, leading to a pulse current profile of the typical application device. Finally, the application itself, such as sensor data measurement of temperature, moisture, heart rate, etc., is done only during short periods of time, because the interesting physical parameters do not change that frequently to ask for a permanent measurement.

To match the low power output of the transducers with the pulse current requirement of the application, energy storage elements are always needed in energy harvesting systems. These might be rechargeable batteries or capacitors, each having its advantages and downsides.

Regarding volume and weight related to energy content, which is more precisely called gravimetric and volumetric energy density, batteries are superior compared to capacitors. The downside of batteries is their aging depending on application temperature and number of charge and discharge cycles. With that aging comes a reduced maximum capacity and an increased internal resistance, leading to larger voltage drop. Leakage current of both types have to be considered very carefully, since energy harvesting systems collected minimum currents, which might be in the range of these leakage currents. These leakages are of course temperature dependent. Problem with capacitors is their linear decrease of output voltage during discharge. This means, a fraction of the energy cannot be used, because of the minimum supply voltage of the application. A solution that should be investigated very carefully is using boost or step-up converters, because of their own power consumption. In contrast to capacitors, batteries have a flat voltage profile between 80% and 20% of their capacity, making it more easy to use the most of their energy without special means. Moreover, their operating voltage range does not go below a certain voltage such as 3 or 2 V. All these values depend on the technology and manufacturer chosen. The temperature range is another parameter that helps decide one of the two alternatives of energy storage. Batteries usually work from -20 to $+50°C$, which is a range for charging starting at $0°C$. Below that level, the capacity droops significantly. Capacitors are superior regarding this issue. Batteries as well as capacitors will be explained in Chapter 11.

1.8 Combination of Several Input Energies

There are a lot of application environments where several ambient energy sources are available for powering electronic circuits. If the power budget of the electronic consumer is critical and price or board space is not an issue, a simultaneous operation of several energy transducers makes sense. Especially, when using light, there is often also a thermal gradient introduced, which can be employed for additional electrical power generation. At the human body environment, motion, and heat could be used with a combination of piezoelectric films and thin-film thermogenerators. Machines and large motors exhibit heat besides vibrations; thus, a combination of both principles will be promising to increase the available power. Also, the building environment offers the use of a combination of energy transducers such as solar cells and thermogenerators. Furthermore, mobile applications, where the environment is changed by movement such as human beings, animals, and vehicles, can be stuffed with different kinds of energy transducers. Such combination of energy transducers can guarantee a self-powered operation regardless of the situation.

New research approaches try to combine several kinetic energy transducer principles in on system.

Owing to the different nature of the outputs from the different transducers, there will be always a dedicated power management required for each transducer. Thermogenerators exhibit large currents at small voltages, whereas piezoelectric transducers generate larger alternating voltages at small currents compared to TEGs. Electrodynamic and electro-static converters also produce alternating currents but at a smaller voltage level.

1.9 Energy Neutral Operation

The amount of available power in a system that employs an energy harvesting power supply is limited and it is not constant with time.

It is desirable to have equal amounts of the energy harvested by the generator and the energy consumed by the load to assure an energy neutral operation, in other words, to guarantee that there will always be sufficient energy available to supply the load. This is the same as stating that the average power in the time interval generated and spent must be the same for energy neutral operation.

In Section 1.6.1, the two operation modes of an electronic load powered by an energy harvesting generator are explained: continuous and intermittent. An energy storage element is not necessary if the power consumption of the electronic device is

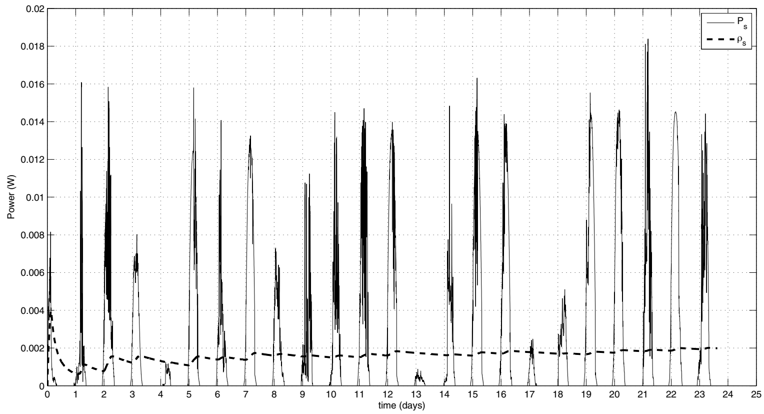

Figure 1.12 Power P_s delivered by a portable panel to an energy storage element as a function of time as a function of time and calculation of its mean power ρ_s.

always lower than the power generated by the energy harvesting generator and is only operated when there is power generated. For the rest of the cases, an energy storage element is necessary, which could be, for example, a battery.

The application and the harvested and consumed energy will determine the operating mode to select. The objective of this section is to present a way to calculate the initial charge of the storage element before starting operation as well as the maximum quantity of energy that is necessary to store. The method is based on the works made by Kansal et al.[52,53]. This technique consists of a model to characterize environmental sources and electronic loads that allows to determine the size of the energy storage element employed as a function of the power consumption profile of the load to assure energy neutral operation.

First of all, it is necessary to define the energy delivered by the transducer to the energy storage element and the energy consumed by the load in a mathematical way. Figure 1.12 shows the power P_s delivered by a portable solar cell with an open circuit voltage of 1.89 V and a short-circuit current of 12.6 mA at a location 42.78°N, 73.85°N[54] to an energy storage element as a function of time. The mean power ρ_s is defined as:

$$\rho_s = \frac{1}{T}\int_T P_s(t)dt, \tag{1.5}$$

where T is the interval of time considered for the calculations that gives an error of $\pm\Delta$.

The difference between the last maximum and minimum of the mean power delivered by the energy harvesting transducer to the energy storage device is called Δ this means that the error to calculate the energy neutral operation point is $\pm\Delta$. The value of Δ in Fig. 1.12 after 10 days of measurements is 109 μW. This value is reduced to 54 μW after 23 days of measurements. This method is feasible for periodical or quasi-periodical energy harvesting sources where the value of the maximum and minimum mean power provided by the transducer to the storage element converges but not for non-periodical input energies. Kansal et al. developed this method for solar panels in outdoors applications where there is power available only under sunlight and the cycles of converted power caused by day and night alternation are quasi-periodic.[52,53] Nevertheless, this behavior is not limited to solar energy since mechanical energy sources or thermal energy sources can also be periodical or quasi-periodical.[13]

If it is assumed that $T_{\text{lows}-i}$ is the i-th contiguous time duration for which $P_s(t) \leq \rho_s(t)$, then σ_d is defined as the maximum deficit of energy of the energy harvesting transducer (see Fig. 1.13).

$$\sigma_d = \max_i \left\{ \int_{T_{\text{lows}-i}} \rho_s - P_s(t)dt \right\} \tag{1.6}$$

If it is assumed that $T_{\text{highs}-i}$ is the i-th contiguous time duration for which $P_s(t) \geq \rho_s(t)$, then σ_e is defined as the maximum excess of energy of the energy harvesting transducer (see Fig. 1.13).

$$\sigma_e = \max_i \left\{ \int_{T_{\text{highs}-i}} P_s(t) - \rho_s dt \right\} \tag{1.7}$$

The energy harvested by the transducer and delivered to the energy storage element will be inside a certain margin limited by E_{smin} and E_{smax}:

$$E_{\text{smin}} \leq \int_T P_s(t)dt \leq E_{\text{smax}} \qquad \forall\, t \tag{1.8}$$

where E_{smin} is the lower limit and E_{smax} is the upper limit of the energy delivered by the energy harvesting transducer to the energy

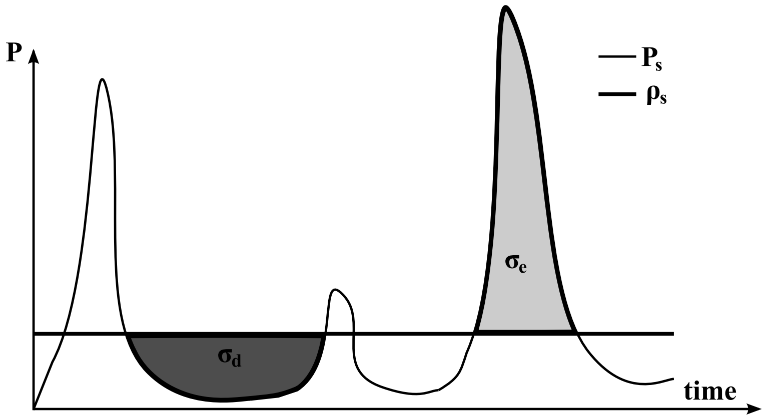

Figure 1.13 Power delivered by the energy harvesting transducer to the energy storage element as a function of time.[13]

storage element. $E_{\text{smin}}(T)$ and $E_{\text{smax}}(T)$ are piecewise functions defined as

$$E_{\text{smin}}(T) = \begin{cases} \rho_s T - \sigma_2 \frac{T}{T_{lows-i}} & \forall T \leq T_{\text{lows}-i}, \\ \rho_s T - \sigma_2 & \forall\, T \geq T_{\text{lows}-i}. \end{cases} \quad (1.9)$$

$$E_{\text{smax}}(T) = \begin{cases} \rho_s T + \sigma_1 \frac{T}{T_{\text{highs}}} & \forall\, T \leq T_{\text{highs}-i}, \\ \rho_s T + \sigma_1 & \forall t \geq T_{\text{highs}-i}. \end{cases} \quad (1.10)$$

Figure 1.14 shows the power consumption of an electronic load P_l as a function of time. ρ_l is the average power consumption of the

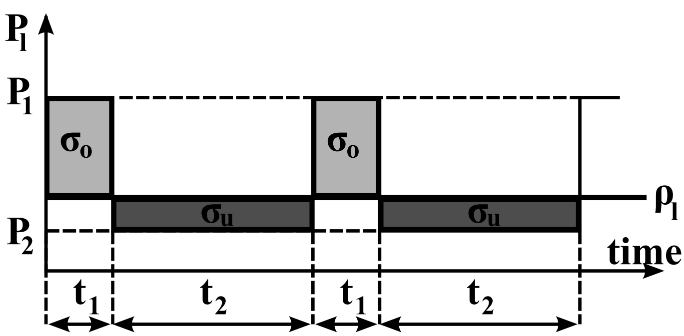

Figure 1.14 Power consumption of the load as a function of time.[13]

load. P_1 is the power consumption of the load in the highest power consumption mode (e.g., transmission mode in a communication module) and it takes place during a time interval t_1. P_2 is the power consumption of the load in the lowest power consumption mode (e.g., standby mode in a communication module) and it takes place during a time interval t_2. Therefore, the electronic load consumption can be defined as a function of the parameters (ρ_l, σ_3, σ_4).

$$\rho_l = \frac{1}{T} \int_T P_l(t)dt \tag{1.11}$$

If it is assumed that $T_{\text{highs}-i}$ is the i-th contiguous time duration for which $P_l\,(t) \geq \ \rho_l\,(t)$, then σ_o is defined as the maximum over-consumption of energy made by the load (see Fig. 1.14).

$$\sigma_o = max_i \left\{ \int_{T_{highl-i}} P_l(t) - \rho_l dt \right\} \tag{1.12}$$

If it is assumed that $T_{\text{lowl}-i}$ is the i-th contiguous time duration for which $P_l\,(t) \geq \ \rho_l\,(t)$, then σ_u is defined as the maximum under-consumption of energy made by the load (see Fig. 1.14).

$$\sigma_u = \max_i \left\{ \int_{T_{\text{lowl}-i}} \rho_l - P_l(t)dt \right\} \tag{1.13}$$

The lower and upper limits of the energy consumed by the electronic load are:

$$E_{\text{lmin}}\,(T) = \begin{cases} \rho_l T \ - \sigma_4 \frac{T}{T_{\text{lowl}-i}} & \forall\, T \leq T_{\text{lowl}-i}, \\ \rho_l T \ - \sigma_4 & \forall\, T \geq T_{\text{lowl}-i}. \end{cases} \tag{1.14}$$

$$E_{\text{lmax}}\,(T) = \begin{cases} \rho_l T \ + \sigma_3 \frac{T}{T_{\text{highl}-i}} & \forall\, T \leq T_{\text{highl}-i}, \\ \rho_l T \ + \sigma_3 & \forall\, T \geq T_{\text{highl}-i}. \end{cases} \tag{1.15}$$

1.9.1 *General Conditions for Energy Neutral Operation*

When a wearable device, e.g., a node of a WSN, employs an energy harvesting system to be powered, the objective is to eliminate the need to replace or recharge its battery. Thus, it is necessary to assure energy neutral operation or in other words, to assure that the battery will contain always the energy required by the electronic device. Therefore, the energy storage element is defined by two parameters that are its initial charge when it is connected to the energy harvesting system, B_0, and the amount of energy that can be stored, B. The values of both parameters are calculated in this section.

In order to achieve energy neutral operation, the total energy in the system, ΣE, has to be always greater than zero since the energy from the harvesting transducer, E_s, plus the initial energy stored in the battery, B_0 has to be greater than the energy consumed by the electronic load, E_l. Moreover, it is desirable in an energy harvesting system to assure that no energy is wasted or that the battery is damaged due to overcharge. These two conditions can be expressed as:

$$\Sigma E \geq 0 \tag{1.16}$$

$$\Sigma E \leq B. \tag{1.17}$$

The available energy in the system is equal to the initial energy stored in the battery plus the energy harvested by the transducer minus the energy consumed by the load and minus the leakage energy due to the energy storage element.

$$\Sigma E = B_0 + E_\mathrm{s} - E_l - \int_T P_\mathrm{leak} T\,dt, \tag{1.18}$$

where P_leak is the leakage power of the energy storage element.

The value of B_0 can be calculated using the condition expressed by Eq. (1.16). This condition is evaluated when the worst case takes place, that is, when the provided energy from the harvesting transducer to the energy storage device is minimum, E_smin, and the energy consumed by the electronic load is maximum, E_lmax.

$$B_0 + E_\mathrm{smin} - E_\mathrm{lmax} - \int_T P_\mathrm{leak} T\,dt \geq 0 \tag{1.19}$$

The above condition can be expressed as:

$$B_0 + E_\mathrm{smin} - E_\mathrm{lmax} - \rho_\mathrm{leak} T \geq 0, \tag{1.20}$$

where ρ_leak is the mean leakage power of the energy storage element.

In a similar way, the value of B can be calculated using the condition expressed by Eq. (1.17). This condition is evaluated when the worst case takes place, that is, when the generated energy by the harvesting transducer is maximum, E_smax, and the energy consumed by the electronic load is minimum, E_{lmin}. In this case, the energy storage element will have at its maximum capacity.

$$B_0 + E_{\text{smax}} - E_{\text{lmin}} - \int_T P_{\text{leak}} T\,dt \leq B \tag{1.21}$$

The above condition can be expressed as:

$$B_0 + E_{\text{smax}} - E_{\text{lmin}} - \rho_{\text{leak}} T \leq B \tag{1.22}$$

If the value of T tends to infinity for the two conditions expressed by Eqs. (1.20) and (1.22), the following is obtained:

$$\rho_s - \rho_l - \rho_{\text{leak}} \geq 0 \tag{1.23}$$

$$\rho_s - \rho_l - \rho_{\text{leak}} \leq 0 \tag{1.24}$$

Equations (1.23) and (1.24) can be simplified as:

$$\rho_s - \rho_l - \rho_{\text{leak}} = 0 \tag{1.25}$$

Substituting in Eq. (1.20), the value given for E_{smin} and E_{lmax} by Eqs. (1.9) and (1.15), respectively, and taking into consideration the previous expression, the following is obtained:

$$\begin{gathered} B_0 - \sigma_2 \frac{T}{T_{\text{lows}}} - \left(\sigma_3 \frac{T}{T_{\text{highl}}}\right) \geq 0 \\ \forall\, T \leq T_{\text{lows}} \text{ and } \forall\, T \leq T_{\text{highl}} \end{gathered} \tag{1.26}$$

$$\begin{gathered} B_0 - \sigma_2 \frac{T}{T_{\text{lows}}} - (\sigma_3) \geq 0 \\ \forall\, T \leq T_{\text{lows}} \text{ and } \forall\, T \geq T_{\text{highl}} \end{gathered} \tag{1.27}$$

$$\begin{gathered} B_0 - \sigma_2 - \left(\sigma_3 \frac{T}{T_{\text{highl}}}\right) \geq 0 \\ \forall\, T \geq T_{\text{lows}} \text{ and } \forall T \leq T_{\text{highl}} \end{gathered} \tag{1.28}$$

$$\begin{gathered} B_0 - \sigma_2 - (\sigma_3) \geq 0 \\ \forall T \geq T_{\text{lows}} \text{ and } \forall T \geq T_{\text{highl}} \end{gathered} \tag{1.29}$$

There are two conditions that give as a result the worst scenario and therefore, the minimum value of B_0. One of these conditions occurs when T is equal to T_{lows} and this value is greater than T_{highl}.

The second condition occurs when T is equal to T_{highl} and this value is greater than T_{lows}. For both cases, the same expression is obtained:

$$\begin{aligned}&B_0 \geq \sigma_2 + \sigma_3\\ &\forall\, T = T_{\text{lows}} \text{ and } \forall\, T \geq T_{\text{highl}}\\ &\forall\, T = T_{\text{highl}} \text{ and } \forall\, T \geq T_{\text{lows}}\end{aligned} \tag{1.30}$$

When the conditions given by Eqs. (1.30) and (1.25) are accomplished, the energy harvesting system can operate forever.

The conditions to avoid overcharging the energy storage element are obtained substituting in Eq. (1.22), the value given for E_{smax} and E_{lmin} by Eqs. (1.10) and (1.14), respectively, a piecewise expression is obtained:

$$\begin{aligned}&B_0 + \sigma_1 \frac{T}{T_{\text{highs}}} - \left(-\sigma_4 \frac{T}{T_{\text{lowl}}}\right) \leq B\\ &\forall\, T \leq T_{\text{highs}} \text{ and } \forall\, T \leq T_{\text{lowl}}\end{aligned} \tag{1.31}$$

$$\begin{aligned}&B_0 + \sigma_1 \tfrac{T}{T_{\text{highs}}} - (-\sigma_4) \leq B\\ &\forall\, T \leq T_{\text{highs}} \text{ and } \forall\, T \geq T_{\text{lowl}}\end{aligned} \tag{1.32}$$

$$\begin{aligned}&B_0 + \sigma_1 - \left(-\sigma_4 \frac{T}{T_{\text{lowl}}}\right) \leq B\\ &\forall\, T \geq T_{\text{highs}} \text{ and } \forall\, T \leq T_{\text{lowl}}\end{aligned} \tag{1.33}$$

$$\begin{aligned}&B_0 - \sigma_2 - (\sigma_3) \leq B\\ &\forall\, T \geq T_{\text{highs}} \text{ and } \forall\, T \geq T_{\text{lowl}}\end{aligned} \tag{1.34}$$

The maximum amount of stored energy B will occur when the maximum delivered energy by the transducer and the minimum spent energy by the load are coincident in time. In this case, the following expression is obtained:

$$B_0 + \sigma_1 + \sigma_4 \leq B \tag{1.35}$$

Combining Eqs. (1.30) and (1.35), it is deduced that

$$\sigma_1 + \sigma_2 + \sigma_3 + \sigma_4 \leq B \tag{1.36}$$

When this condition is accomplished, no waste energy is produced from the energy harvesting transducer since all the energy generated can be stored in the energy buffer.

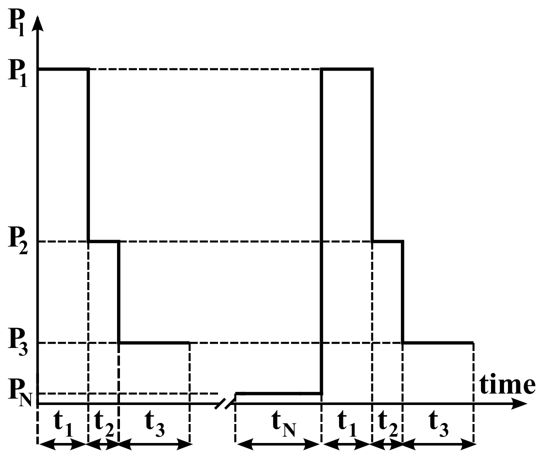

Figure 1.15 Power consumption of the load as a function of time.[13]

1.9.2 *Conditions for Energy Neural Operation with* N *Power Consumption Modes*

Figure 1.15 shows a load with N different power consumption modes. P_N is the lowest power consumption mode, whereas P_1 is the highest power consumption mode. The rest of the power consumption modes between these two values increase consecutively their power consumption from P_N to P_1. When this assumption is accepted, for the general case of N different consumption modes, it is calculated that

$$\tau = \sum_{i=1}^{N} x_i \tau, \tag{1.37}$$

where τ is period of the power consumed by the load and x_i is the percentage of τ where the power consumed by the load is P_i.

$$\rho_l = \sum_{i=1}^{N} P_i x_i \tag{1.38}$$

The expressions for σ_3 and σ_4 are

$$\sigma_3 = \tau \left((P_1 - \rho_l) x_1 + \sum_{i=2}^{N-1} \langle P_i - \rho_l \rangle x_i \right) = \tau \sum_{i=1}^{N} \langle P_i - \rho_l \rangle x_i \tag{1.39}$$

$$\sigma_4 = \tau\left((\rho_l - P_N)\,x_N \sum_{i=2}^{N-1} \langle \rho_l - P_i \rangle\, x_i\right) = \tau \sum_{i=1}^{N} \langle \rho_l - P_i \rangle\, x_i \quad (1.40)$$

The addition of σ_3 and σ_4 gives the following as a result:

$$\begin{aligned}\sigma_3 + \sigma_4 &= \tau\left(\sum_{i=1}^{N} \langle \rho_l - P_i \rangle\, x_i + \sum_{i=1}^{N} \langle P_i - \rho_l \rangle\, x_i\right)\\ &= \tau\left((P_1 - \rho_l)\,x_1 \sum_{i=2}^{N-1} \langle \rho_l - P_i \rangle\, x_i\right.\\ &\quad \left.+ \sum_{i=2}^{N-1} \langle P_i - \rho_l \rangle\, x_i + (\rho_l - P_N)\,x_N\right)\end{aligned} \quad (1.41)$$

$(\rho_l - P_N)\,x_N\tau$ can be expressed as a function of the rest of the power consumption modes:

$$\begin{aligned}(\rho_l - P_N)\,x_N\tau &= \rho_c T\left(1 - \sum_{i=1}^{N-1} x_i\right) - P_N x_N T\\ &= \left(\sum_{i=1}^{N-1} (P_i - \rho_c)\,x_i\right)\tau\end{aligned} \quad (1.42)$$

Therefore, substituting the above expression in Eq. 1.41, the following is obtained:

$$\sigma_3 + \sigma_4 = 2\tau \sum_{i=1}^{N-1} \langle \rho_l - P_i \rangle\, x_i \quad (1.43)$$

Therefore, the conditions to be fulfilled for energy neutral operation by an electronic load with N consumption modes are summarized here employing Eqs. (1.30) and (1.36).

$$\sigma_2 + T \sum_{i=1}^{N-1} \langle P_i - \rho_l \rangle\, x_i \leq B_0 \quad (1.44)$$

$$\sigma_1 + \sigma_2 + 2T \sum_{i=1}^{N-1} \langle P_i - \rho_l \rangle\, x_i \leq B \quad (1.45)$$

1.10 Conclusion

The different parts that compose an energy harvesting system are presented and general information about each of them is given. This information is extended in the following chapters of the book. Moreover, it is explained which blocks are optional and why.

The concept of continuous and discontinuous load operation has been introduced. In an energy harvesting system, the key approach is to energy and not to power since the input energy sources are not present all the time and will probably not deliver the required power to let the load operate in active mode all the time. Thus, it is desirable to achieve the energy neutral operation in an energy harvesting system since it assures that the energy requirements of the load can be achieved.

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