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Energy Harvesting for Sensors: DC Harvesters

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Energy Harvesting for Sensors: DC Harvesters

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10.1 Photovoltaic Energy Harvesting................................................. 10-1
10.2 Thermoelectric Energy Harvesting............................................. 10-7
References...................................................................................... 10-10

Nowadays, photovoltaic (PV) panels and thermoelectric generators (TEGs) constitute the most important direct current (dc) energy transducers that can be used to harvest energy from the environment and power an autonomous sensor node. They generate a direct current and voltage for constant operating conditions. A current–voltage (I–V) curve is defined for each operating condition in which an optimum bias point exists where maximum power is achieved. The voltage at the maximum power point (V_{MP}) depends on the operating conditions and it changes as these conditions vary with time. Several energy conditioners have been proposed and commercialized to transfer the energy to a storage unit or a load. The small magnitudes of the currents and voltages of such transducers constitute the main challenge in the design of these circuits. Ultralow-power consumption energy conditioners have to be designed to make feasible the use of these power sources.

This chapter presents a description of these energy transducers and their associate energy conditioning circuits.

10.1 Photovoltaic Energy Harvesting

PV technology is the most widespread form of energy harvesting because of its availability, low cost, and power density. PV panels generate electric energy when exposed to light irradiance. Consisting of semiconductor junctions (P–N), their operation is based on the photons’ impact ionization effect. Each one of these P–N junctions is known as a PV cell and can be associated in series and parallel to form a PV panel. The generated current (I) depends on the bias voltage (V), the temperature (T), and the light irradiance (G). Figure 10.1 shows the symbolic representation of a PV panel, its equivalent electrical model, and a couple of graphs showing the current dependency on the bias voltage and on environmental
FIGURE 10.1 On the left, the symbolic representation of a PV panel and its equivalent electrical model. On the right, $I$-$V$ curves of a PV panel for several temperatures ($T$) and irradiances ($G$) with operating conditions ($G_3 > G_2 > G_1$ and $T_3 > T_2 > T_1$).

conditions ($G$ and $T$). For a given $T$, the short circuit current ($I_{SC}$) is proportional to the light irradiance. The current $I$ is slightly reduced when the voltage $V$ is below a threshold value and is abruptly reduced above it. Considering a single PV cell, this voltage limit corresponds to the diode threshold voltage in the equivalent model of Figure 10.1. The open-circuit voltage ($V_{OC}$) delimits the maximum voltage range in which the PV transducer provides energy and works as a power source.

As shown in Figure 10.1, the values of $I_{SC}$ and $V_{OC}$ depend on the temperature and irradiance operating conditions. PV panel manufacturers conventionally specify the panel parameters under standard test conditions (STCs) ($T = 25$ °C, $G = 1000$ W/m$^2$ and light spectrum AM 1.5). They usually indicate $I_{SC}$, $V_{OC}$, and the nominal power. Nominal power is defined as the maximum power achieved from the $I$-$V$ curve under STCs.

PV panels can be connected in series or parallel to achieve, respectively, higher voltage or current levels. If all of them have identical operating conditions and performance, the resulting power is scaled to the number of PV panels. Otherwise, for instance, in a shadow projection that produces differences in the light irradiance conditions, the current in a series association is limited by the $I_{SC}$ of the less illuminated PV panel. In the case of a parallel association, the less illuminated PV panel could work as a load reducing the global generated power. To reduce these power losses, a diode can be connected in series with each of the parallel connected PV panels. In the series configuration, an antiparallel diode must be connected instead. Although both solutions can reduce these power losses, identical PV panels and physical orientation are recommended whenever they are connected in series or parallel.

Light efficiency ($\eta_{PV}$) indicates how much light energy is converted to electric energy. The efficiency depends on the PV panel technology and on the light spectrum. Although new technologies such as dyesensitized solar cells are becoming commercially available, silicon PV panels are still the most used because of their low cost and high efficiency. Basically, there are three technologies based on silicon: amorphous, polycrystalline, and monocrystalline PV panels. Each is designed to satisfy a different trade-off between price and efficiency. While amorphous panels have the lowest efficiency (~5%), they are the cheapest ones and are more suited to indoor applications where an artificial light source is used. On the other hand, monocrystalline panels are the most efficient (~20%) for sunlight but they are also the most expensive.

PV energy harvesters can be used to power outdoor or indoor autonomous sensors. Figure 10.2 shows typical irradiance conditions in both environments. In a well-lit office, around 500 lux, the surface of a PV panel would be submitted to a $G$ around 2 W/m$^2$ (for an incandescent light). When using an amorphous panel, the resulting output power density is about 100 mW/m$^2$. The same power levels are much lower than the power of an outdoor monocrystalline panel. In this case, the irradiance varies with the time and can reach 1000 W/m$^2$. Therefore, the output power density could be as high as 200 W/m$^2$. So, the power availability, and thus the design constraints for PV systems, is very different indoors and outdoors.
Design engineers must size PV panels to overcome the average power consumed by the overall sensor node ($P_{I}$), including the energy harvester. If the PV panel works at its maximum power point (MPP), the minimum nominal power under STC ($P_{PV}$) is determined by

$$P_{PV} > \frac{P_{I} \times 1000 \text{ W/m}^2}{\eta_{Tot} \times G \times (1 - \delta_{T} \times (T_{max} - 25 \text{ } ^\circ\text{C}))} \quad (10.1)$$

where $\bar{G}$, $\eta_{Tot}$, and $\delta_{T}$ are, respectively, the average light irradiance on the surface of the PV panel, the overall efficiency of the energy harvesting system, and the temperature degradation factor of the PV power. The temperature $T_{max}$ is the maximum temperature of the PV panel, which will be higher than the ambient temperature. Both external parameters, such as wind speed, and internal parameters of the PV panels, such as the surface protection material, determine the temperature increment. At $G = 800 \text{ W/m}^2$, $20 \text{ } ^\circ\text{C}$ ambient temperature, and wind speeds of $1 \text{ m/s}$, temperature increases up to $42 \text{ } ^\circ\text{C}$ and $48 \text{ } ^\circ\text{C}$ typically.

The optimal size and orientation of an outdoor PV panel is not evident because the Sun position varies with time. The panel surface must be perpendicular to the light rays to achieve maximum irradiance ($G_{opt}$). Figure 10.3 shows the calculation of the irradiance for a surface tilted by angle $\beta$. If $\beta$ is different from the optimum tilt angle ($\beta_{opt}$), the resulting irradiance and generated power is lower. Hence, the sunlight direction must be taken into account to select the panel orientation. On the Earth surface, the sunlight can be split into three components: direct sunlight, diffuse sunlight, and albedo. Diffuse sunlight and albedo are, respectively, the light scattered by molecules and particles in the atmosphere and the light reflected from the Earth surface. Both of them are usually neglected with respect to the direct sunlight to determine the optimal panel orientation. The direction of direct sunlight is described by the Sun position.

The orientation of a PV panel is defined by the azimuth ($\alpha$) and the tilt ($\beta$) angles as shown in Figure 10.4. The azimuth is the angle between the axis of the PV panel and the geographic north direction. The tilt angle is measured between the PV panel surface and the horizontal plane. It can also be defined as the angle between an imaginary line to the center of the Earth and the normal vector of the panel surface.

**FIGURE 10.2** Typical irradiance ($G$) conditions in an indoor and an outdoor application.

**FIGURE 10.3** Calculation of the light irradiance on a surface tilted at angle $\beta$. 

\[ \begin{align*} 
\text{Area} (\beta_{\text{Opt}}) \times G(\beta_{\text{Opt}}) &= \text{Area} (\beta) \times G(\beta) \\
\text{Area} (\beta_{\text{Opt}}) &= \text{Area} (\beta) \times \cos(\beta_{\text{Opt}} - \beta) \\
-G(\beta) &= G(\beta_{\text{Opt}}) \times \cos(\beta_{\text{Opt}} - \beta) 
\end{align*} \]
The PV system of an autonomous sensor is fixed at a given orientation and tilt because the energy benefit from an automatic orientation system does not compensate for the additional power consumption and cost. The optimal fixed azimuths are respectively 0° (toward the south) and 180° (toward the north) in the northern and southern hemispheres. On the other hand, the optimal fixed tilt angle depends not only on the hemisphere where the PV panel is placed but also on the latitude, the season of the year, and the distribution of the power consumption of the autonomous sensor along the time.

Figure 10.4 shows the variation of the direct sunlight direction during the year, described by the declination angle (δ). δ is the angle between the sun’s rays and the equatorial plane. The optimal tilt for the winter solstice is latitude (φ) minus 23.45° at that solstice (i.e., for the winter solstice and in the northern hemisphere, the optimal tilt will be φ + 23.45°). Take into account that both the Summer and Winter solstices take place on opposite dates in both hemispheres and thus, δ has a different sign for the same solstice. φ also has a different sign in both hemispheres.

For long operation periods of the autonomous sensor, the proper tilt angle for the worst-case scenario must be considered. The required $P_{pv}$ for any available tilt angle must be evaluated for each month, using Equation 10.1 and determining the best angle. In this way, an optimum angle and a minimum $P_{pv}$ is determined for each month. The optimum angle for the overall period will be the optimum angle of the month in which maximum $P_{pv}$ is required. In the case of a constant value of $P_{pv}$ along the year, the worst case will be the month with the lowest irradiation, which typically is December and June for the northern and southern hemispheres, respectively. Thus, the proper tilt angle will be $\Phi - \delta$ (±23.45° in the northern hemisphere and $\phi - 23.45°$ in the southern hemisphere). Even so, it is not recommended to use tilt angles lower than 15° to let the water from rainfalls slide and avoid the accumulation of dust.

An energy conditioning circuit is used to transfer energy from a PV panel to a storage unit, that is, a battery or a (super) capacitor. Two types of energy conditioners can be distinguished: the direct coupled and the maximum power point trackers (MPPTs). Figure 10.5 shows these two alternatives by using a battery as the storage unit.

In order to obtain the average light irradiance for a tilt angle and a period of time, meteorological records kept by weather stations all over the world can be used. Although the measurements are mostly limited to a horizontal surface ($G_o$), the irradiance ($G_p$) on a surface tilted an angle $\beta$ can be deduced from $\beta_{opt}$ and the relationship shown in Figure 10.3. The ratio between $G_p$ and $G_o$ is called the tilt factor and depend on $\beta$ and on the latitude of the PV panel. Tilt factor tables [1] or interactive databases such as SoDa [2] can be used to estimate the average light irradiance on a PV surface for any tilt angle and period of time.
The direct coupled connection is the simplest solution because it simply uses a Schottky diode. The diode permits charging the storage unit from the PV panel and prevents its discharge when $V_{OC}$, mostly at low irradiance condition, is below the storage unit voltage ($V_{Bat}$). It is a proper solution for indoor PV panels, where the generated power is very low, because the power loss is limited to that of the diode. Unfortunately, the transducer voltage is fixed by the storage voltage and so, the transducer works outside its MPP. Therefore, Equation 10.1 cannot be used to size the PV panel. Instead, $I_{SC}$ at STC is calculated as:

$$I_{SC} > \frac{P_{L} \times 1000 \text{ W/m}^2}{n_{Tot} \times G \times V_{Bat} \times (1 - \delta_1 \times (T_{min} - 25^\circ \text{C}))}$$

(10.2)

where $\delta_1$ and $T_{min}$ are, respectively, the temperature degradation factor of the $I_{SC}$ and the minimum temperature of the PV panel. In this design condition, $V_{Bat} < V_{MPPT}$ was assumed to approximate the current $I$ by $I_{SC}$. To account for variations of $V_{Bat}$ with temperature and of $V_{MPPT}$ with temperature and irradiance, a conservative (low) value of $V_{Bat} (< V_{MPPT})$ is chosen, which leads to oversizing the PV panel. As $V_{Bat} < V_{MPPT}$, $I_{SC}$ can be used instead of $I$ in Equation 10.2.

In applications where $V_{Bat}$ is so small that significant power losses are caused by the diode voltage drop, a transistor can be used instead. The SPV 1001 of STMicroelectronics is an implementation example of such alternative solution [3].

MPPs are more sophisticated energy conditioners that bias PV panels at their MPP. Although they have been widely used in high-power PV systems [4], their use in low-power panels is recent. To be feasible, the power benefit caused by following the MPP must outperform the power consumption of the power conditioning circuit. Although this design goal can be easily reached for high-power PV panels, it is more challenging for low-power PV panels (<1 W) used in low-power autonomous sensors. High-performance controllers that were used for high-power PV systems, such as digital signal processors (DSPs), are not feasible for small autonomous sensors because of their high cost and power consumption.

An MPP is composed of a dc/dc switching converter and a tracking controller (see Figure 10.6). The converter biases the PV panel to a reference voltage given by the tracking controller. The controller measures the appropriate electrical variables of the PV panel (e.g., $I$ and $V$) to determine the optimal reference voltage that makes the panel work at its MPP.

Switching converters are chosen because of their high efficiencies. Figure 10.7 shows a boost converter that can be used whenever the storage unit voltage is higher than the voltage of the PV panel. The state of
the transistor can be controlled by a pulse width modulator (PWM) or by a pulse frequency modulator (PFM). The traditional PWM used in switching converters is not the most suitable solution in low-power applications. A periodic switching sequence holds the transistor in on state during a portion of the sequence period, called duty cycle. The voltage of the PV panel is adjusted by means of the duty cycle. As the transistor is continuously switching, the resulting power consumption is too high for low-power PV panels (<1 W). Instead, PFM can be used to further reduce power consumption. The converter remains inactive, with low-power consumption, during a long period of time while the capacitor \( C_{in} \) is charged by the PV panel. When the voltage \( V \) reaches a higher threshold value, the converter is activated to discharge the capacitor to a lower threshold value. In this way, \( V \) is held inside a small hysteresis cycle that is centered in \( V_{MPP} \). In [5,6], the authors propose implementations of the PFM switching converter using commercial voltage regulators. There are also commercial MPPT ICs, such as the BQ25504 from Texas Instruments, that uses a PFM switching converter and achieves a current consumption as low as 330 nA [7].

The most popular MPPT tracking controllers are the fractional open-circuit voltage (FOCV) and the perturbation and observe (P&O). The FOCV is an open-loop controller that is based on the empirical relationship between \( V_{OC} \) and \( V_{MPP} \) of the PV panel. The value of \( V_{MPP} \), which varies with the light irradiance and the temperature, is nearly proportional to \( V_{OC} \). Figure 10.8 shows the functional scheme of this controller and the factor of proportionality, \( K \). The PV panel is periodically disconnected and \( V_{OC} \) is captured by a sample and hold (S&H) to obtain \( V_{MPP} \) through the empirical relationship. This is the most usual MPPT controller for low-power PV panels because of its simplicity [7–9].
On the other hand, the P&O is a more sophisticated and accurate tracking controller. It is a closed-loop controller that reaches the MPP by comparing the PV power at two bias points. Figure 10.8 shows the control law that determines if the bias voltage ($V_Q$) must be increased or decreased to reach the $V_{MPP}$. The variation of the PV power ($\Delta P$) is measured between one bias voltage ($V_Q$) and another bias voltage ($V_Q + \Delta V$). Considering a positive perturbation in the voltage ($\Delta V$), the working voltage will be increased if $\Delta P$ is higher than zero. Otherwise, it will be decreased. The SPV1040 from STM microelectronics is an example of a commercial MPP IC that is based on a P&O and is intended for low-power applications, such as small autonomous sensors [10]. Discrete solutions that implement the control law in a microcontroller [6,11] or using discrete analog circuits [5] can also be found in the literature. In all of them, the main design goal is to reduce the power consumption of the controller. A possible solution consists of reducing the activity of the microcontroller by using an ultralow frequency clock [11]. Nevertheless, such slow microcontrollers cannot be used to implement other tasks of the sensor node. Prediction algorithms, such as those proposed in [6], allow the application of dynamic power management techniques that reduce the power consumption, making feasible the use of high-speed microcontrollers.

Another alternative energy conditioning solution is provided by the LT3105 from Linear Technology [12]. The switching converter biases the PV panel to a fixed voltage that is configured in the design process. This is a proper solution if small variations of $V_{MPP}$ are expected.

### 10.2 Thermoelectric Energy Harvesting

TEGs are used to provide electric energy from a temperature difference between a heat source (hot side) and a cold ambient (cold side). The source can be, for instance, a machine, a warm-blooded animal, or a human being whose temperature is different from the environment. Potential applications could be animal monitoring, fire detection, and cars, ships, and aircrafts industry. Besides its applicability in sensor nodes, it can also power small electronic circuits such as the Seiko Thermic, which is a wristwatch driven by body heat [13].

As shown in Figure 10.9, a TEG is implemented with a Peltier cell, which is physically based on the Seebeck effect. The hot side of TEG is thermally connected to the heat source, and the cold side is held.
The temperature gradient produces a heat flow and a temperature drop ($\Delta T_{\text{Pelt}}$) between both faces of the TEG, given by

$$\Delta T_{\text{Pelt}} = \frac{\theta_P}{\theta_{\text{HP}} + \theta_P + \theta_{\text{PA}}} (T_{\text{Hot}} - T_{\text{Amb}})$$  \hspace{1cm} (10.3)

where $\theta_{\text{HP}}$, $\theta_P$, and $\theta_{\text{PA}}$ are, respectively, the thermal resistances between the heat source and the TEG, between both faces of the TEG, and between the TEG and the environment.

The electrical behavior can be approximated by a T evenin equivalent circuit. T evenin voltage ($V_T$) is proportional to the TEG temperature drop ($\Delta T_{\text{Pelt}}$). T evenin voltage is given by

$$V_{\text{T}} = N \times (S_P - S_N) \times \Delta T_{\text{Pelt}}$$  \hspace{1cm} (10.4)

T evenin resistance ($R_T$) depends on the cross area and length of the thermocoupled unions and on their electrical resistivity.

Nowadays, the thermocoupled unions are built with bismuth telluride (BiTe) that has a Seebeck coefficient of 0.2 mV/°C ($S_P - S_N$). An example of a commercial Peltier cell that could be used as a TEG is the MPG-D751 from Miropt GmbH [14]. It is formed by 540 thermocoupled unions ($N$) in an area around 14 mm². Despite its small area, the thermal resistance is as small as 12.5 °C/W. T evenin resistance is around 300 Ω and the voltage $V_T$ increases 140 mV/°C at 23 °C. A practical way to increase the generated voltage and power per area consists of using thinner thermocoupled legs. Unfortunately, the industrial technology of BiTe TEG is near its miniaturization limits and it is not possible to decrease the cross section without decreasing their length [15]. An alternative feasible solution consists of using multistage Peltier cells. T ey consist of using two or more stages of Peltier cells that are thermally and electrically connected in series. For the same number of thermocoupled unions, the area will be divided by the number of stages and so, higher $V_T$ will be achieved. Figure 10.10 shows the T evenin voltages for two stages of TEGs thermally connected in series. Considering $\theta_P$ much lower than $\theta_{\text{HP}} + \theta_{\text{PA}}$, the resulting voltage is doubled from a single stage. Nevertheless, the resulting voltage is not doubled if both TEGs are connected thermally in parallel and electrically in series. As the thermal resistances are connected in parallel, the temperature drop is reduced by half and $V_T$ is hardly incremented.

The size and cost design constraints of TEG usually lead to low generated voltages and power levels. In [16], voltages ranging from 150 to 250 mV with a maximum current of 18 mA are achieved with a TEG coupled to a human hand. Such low voltage levels constitute the main challenge when designing a

FIGURE 10.9 TEG implemented with a Peltier cell connected between a heat source and a heat sink. Equivalent thermal and electrical models are shown, respectively, on the left and on the right.
FIGURE 10.10 Comparison between two TEGs thermally connected in series with a parallel connected configuration. To calculate the generated voltage $V_{TH}$, it was taken into account that both TEGs are electrically series connected and $\theta_p \ll \theta_{HP} + \theta_{PA}$.

A power conditioning circuit for the TEG. The minimum start-up voltage of conventional boost (step-up) dc/dc converters is limited to above 0.7 V by the threshold voltage of transistors. If lower input voltages have to be processed, special low-threshold transistors or special power conditioning architectures must be used. An example is the charge pump S-882Z from Seiko that employs silicon on isolation (SOI) transistors with low threshold voltages [17]. The minimum start-up voltage is 300 mV and the quiescent current is 0.6 $\mu$A but the power efficiency is below 20%. The manufacturer recommends using S-882Z with a boost switching converter to improve the overall efficiency. The S-882Z is used during the start-up to charge a capacitor until the minimum start-up voltage of the switching converter is reached. The capacitor powers the control circuit of the boost and is charged by the output of the converter through a diode once it starts working. Figure 10.11 shows a scheme of the power conditioning circuit and the evolution of the main electrical variables.

An alternative solution to step-up of such low input voltage consists of using an electromagnetic transformer [18]. The induced voltage on the secondary is equal to the voltage in the primary multiplied by the turns ratio. Therefore, the primary voltage will be stepped-up if high turns ratio is selected. Unfortunately, electromagnetic transformers can just step-up an ac voltage source and TEG provides a dc voltage. To overcome this problem, an ac voltage is generated by an oscillator. The oscillator is formed by a JFET transistor that is fed back by a coupled solenoid of the transformer (see Figure 10.12). A JFET transistor is selected instead of bipolar or a MOSFET enhancement-mode channel transistor because it provides a modulated conduction channel from zero input voltage ($V_{IN}$). Therefore, the oscillator can start working from very low input voltages and a sinusoidal voltage is induced in the secondary ($V_s$). The output capacitor is charged from $V_s$ through a rectifier diode and powers the control circuit of a boost converter ($V_{DP}$).

Similar starter circuits are also used by commercial power conditioning ICs such as the LTC3108 from Linear Technology [19]. It is operative from 20 mV input voltage for a 1:100 turns ratio.
Another commercial IC converter, specifically the BQ25504 from Texas Instruments, tracks the MPP of TEGs. As it is based on PFM converter controlled by a simple FOCV, it has an ultralow current consumption that makes feasible to work for such low-power sources. TEGs, as well as PV panels, hold an empirical relationship between the $V_{oc}$ and MPP, and so, the FOCV technique can also be applied. Taking into account that the electrical behavior can be modeled by an equivalent T even in source, $V_{MPP}$ will be the half value of $V_{oc}$ ($K = 0.5$).

References