6.1 Introduction

In most low-power systems, power management is generally thought of as being an ability to switch certain parts of a system off or put them in a low-power state when they are not required, and to manage the charging of a battery. While these are important aspects of low-power electronics powered by energy harvesters, there are much more fundamental reasons for requiring power electronics in an energy-harvesting system than simply managing a battery and conserving energy:

- In order to achieve high-power density from the energy harvester, there should be some form of impedance match between the energy source and transducer and the electrical system. This requires control of the input impedance of the circuit that interfaces to the transducer.
- The output voltage and current from the energy harvester are rarely directly compatible with load electronics and thus some form of voltage regulation is required.
- As discussed in Chapter 7, some form of energy storage is almost certainly required so that the intermittency of the energy-harvesting source does not have a detrimental effect on the continuous operation of the system.

Therefore, the basic power electronics topology for an energy-harvesting system often follows that shown in Figure 6.1.

6.1.1 Interface Circuit Impedance Matching

In a large-scale electrical energy generation plant such as a coal-fired power station, where large amounts of power are produced and where fuel must be purchased, it is important that as much of the energy contained in the original fuel source as possible is converted into useful electrical power. This requires first a high efficiency of conversion of the energy stored in the fuel to a mechanical form, second a high-conversion efficiency of that mechanical energy to electrical energy, and finally a
high efficiency of power transfer from the electrical generator to a load. In order to ensure that the energy produced in the electrical generator is efficiently transferred to the load, there is a well-known and fundamental requirement that the impedance of the load should be significantly larger than the impedance of the generator. However, while this arrangement [Figure 6.2(a)] achieves the maximum electrical efficiency (and prevents the generator from thermal destruction), it does not achieve the maximum power transfer from source to load. Maximum power transfer occurs in the case where the load impedance is equal to the source impedance, as illustrated in Figure 6.2(b). In the case of an AC energy source, the load should provide a conjugate match to the source. If the diagrams of Figure 6.2 were taken as a very basic representation of a conventional electromagnetic electrical generator supplying a load resistance, $R_{Source}$ would represent the generator winding resistance and $V_{Source}$ would represent the EMF produced by time-varying flux linkage with those windings.

In the case of energy-harvesting systems, the fuel supply is effectively free, and this leads to the desire to be able to transfer the maximum power into the load, rather than to accomplish this at high efficiency. In addition, the quantities of power generated are low enough that an impedance match rarely has any thermal implications on the system.

In an energy-harvesting generator, the definition of the impedance of the source to which the load should be matched is not generally as trivial as matching the load to a single electrical impedance. The source impedance will be dependent upon the type of energy harvester used and the conditions under which the harvester

![Diagram](image)

**Figure 6.1** Power electronics topology for energy-harvesting systems.

![Diagram](image)

**Figure 6.2** (a) Maximum efficiency of energy transfer to load and (b) maximum power transfer to load.
is operating. In some circumstances and harvester operating modes, it may not be optimal to match the impedance of the load to that of the source due to other constraints; however, for energy harvesters studied in this chapter, there is always a clearly defined transducer load impedance that results in maximum power extraction from the transducer. It may therefore be more accurate to specify that the input impedance of the interface circuit to the transducer must be controllable, rather than always matched to the source, although in many cases the input impedance of the interface circuit will be set to match that of the source.

The details of source impedance modeling will be discussed in this chapter for each harvester type considered. The source impedance will always be shown as an electrical circuit that will often contain components that represent quantities other than pure electrical ones. As an example, vibration-driven harvesters, discussed in detail in Chapter 4, have a source model that takes into account the mechanical properties of the system such as the mass, the spring, and the vibration characteristics in addition to including the expected electrical resistance of the generator's windings or capacitance. All of these aspects must be included in the source model so that a suitable interface circuit can be designed; otherwise, global system optimization cannot be achieved [1].

### 6.1.2 Energy Storage

The vast majority of energy-harvesting transducers will not be able to supply energy at a constant rate over long periods of time. Clearly, a solar cell can only produce electrical energy when illuminated and a vibration harvester only when it is subjected to acceleration. However, many applications of energy-harvesting technology may require a constant source of electrical energy to supply the load. If the average power consumption of the load is greater than the average power generated by the harvester, it is not possible to provide power continually to the load. However, if the average power generated is equal to or exceeds the average consumption by the load, it is possible to run the load continually. However, in order to achieve this, the addition of a storage device, very likely electrical storage in the form of a battery or capacitor as discussed in Chapter 7, may be required.

### 6.1.3 Output Voltage Regulation

The many different types of energy harvesters produce power at different combinations of voltage and current. Photovoltaic cells and electromagnetic transduction kinetic harvesters tend to produce very low voltages (sometimes significantly less than 1V) while electrostatic devices may produce their output power at over 100V and potentially approaching 1 kV if operated optimally [2]. The output voltage from such devices must therefore be processed before being presented to the load electronics. In addition, if an energy storage element is included in the system, the voltage across that element may fluctuate depending on its state of charge. This effect may be negligible in the case of a storage battery, but may be significant if a capacitor is used as the storage component.
6.1.4 Overview

Often, the most difficult part of the harvester power electronics system to realize is the part that directly interfaces with the transducer (i.e., the part of the system that allows the generator to perform optimally through input impedance control). The implementation of this circuit is the part of the electronics that is most specific to each transducer technology used due to vastly differing voltage and current output combinations provided by the different transduction mechanisms.

The choice of storage, discussed in Chapter 7, and the output voltage regulation circuitry are generally common across all harvester systems with few characteristics being specific to the particular harvester type used. Therefore, the most harvester-specific part of the electronics, the interface circuits with controllable input impedances, will now be discussed.

6.2 Interface Electronics for Kinetic Energy Harvesters

In order to determine an optimal electrical load for a motion-driven harvester, a suitable source model must be developed (i.e., the impedance and output voltage characteristics of the source must be known). All aspects of the energy transfer (from the vibration energy source through to the mass and spring and the transduction mechanism) must be taken into account in the source model. As the overall aim is to provide an optimal electrical load to the system, it is sensible to construct an electrical equivalent model of the generator that takes into account the mechanics of the system as electrical components. Two generic examples of such models are shown in Figure 6.3. A detailed explanation of the construction of these equivalent models is given in [3], and therefore only an overview will be given here.

The circuits of Figure 6.3 show the equivalent circuit models for vibration-driven harvesters using electromagnetic damping and electrostatic damping. The part of the circuit connected to the primary side of the transformer models the mechanical components. In Figure 6.3(a), the current source represents the input energy to the system (i.e., the mechanical vibration), the capacitor, $m$, represents the mass, the inductor, $1/k$, represents the spring, and the resistor, $1/D_p$, represents the parasitic damping. In Figure 6.3(b), the voltage source represents the vibration source, the inductor represents the mass, the capacitor represents the spring, and the resistor represents the parasitic damping. In both cases the transformer represents the coupling from the mechanical domain to the electrical domain through the transducer. In Figure 6.3(a), voltages across components on the left of the transformer represent the velocity of those components, and currents through them represent forces applied to them. The opposite is true for Figure 6.3(b). In both cases, the terminals on the secondary of the transformer represent the physical electrical connections of the transducer to which the interface circuit can be connected (in this case shown as a simple load resistor). The inductor, $L_T$, represents the self-inductance of the coil in an electromagnetic device and $C_T$ represents the terminal capacitance of either the piezoelectric material or the moving capacitor in the electrostatic device. It is important to note that the fundamental requirement for stored energy in these transducers places a limit on the maximum real power that can be transferred to a load resistor (in other words, energy stored in the inductance $L_T$
or capacitance $C_T$). While Figure 6.3(a) is a good model of an electromagnetic harvester and Figure 6.3(b) is a good model of a piezoelectric harvester, neither model is perfect for the electrostatic moving capacitor transducer. This is because Figure 6.3 is a linear circuit and electrostatic transducers are inherently nonlinear systems; their capacitance is nonconstant.

The task, then, in the case of a motion-driven inertial generator, is to connect a value of a load resistance (or much better, a power conditioning circuit feeding a storage element that together emulate a load resistance) that can absorb the maximum amount of energy from the energy source on the left of the transformer.

If we first assume that the storage elements $C_T$ and $L_T$ associated with the transducer have a negligible effect, it is clear from Figure 6.3 that the maximum power can be extracted from the source into the load (shown here as $R$) if the circuit is operated at a frequency where the inductor and capacitor resonate and if the load resistance equals the equivalent resistance of the parasitic damping when referred through the turns ratio. These models are therefore coherent with the analysis presented in Chapter 4, where it was concluded that the maximum power is transferred to the load at resonance and when the electrical and parasitic dampings are equal.

Therefore, in the case of our impedance match for a load to a motion-driven microgenerator, the aim is often to produce a power converter that can feed energy into a storage element while maintaining an input impedance of a resistance $1/D_p$. It should be noted that operating conditions exist where the optimal load resistance that should be presented by the interface circuit is not simply given by $1/D_p$. A different optimal resistance exists if the generator is operating off resonance, and still a different expression can be found for the optimal resistance if the generator’s proof mass becomes displacement limited, which may be the case if the parasitic damping can be made small. A comprehensive derivation of these different constraints is
presented in [4]. However, while the optimal load resistance may change depending on the operating condition, in all these cases we conclude that there is an optimal impedance that should be presented by the power electronics interface circuit (Figure 6.4) to the electrical terminals of the microgenerator’s transducer.

We are now in a position to discuss the specific implementations of electronics to interface with the three different transducer types for kinetic energy harvesters (i.e., electromagnetic transducers, electrostatic transducers, and piezoelectric transducers).

### 6.2.1 Electromagnetic Harvesters

The general requirements for interfacing to an electromagnetic transducer on a vibration-driven microgenerator are:

- Rectification;
- Voltage step-up capability;
- Emulation of a resistive load for the impedance match/impedance control.

The simplest electrical interface for an electromagnetic harvester consists of a step-up transformer that feeds two Schottky diodes (D1 and D2) and a capacitor (C) that acts as a storage component, as shown in Figure 6.5 [5]. Due to the sinusoidal nature of the input vibrations, the output voltage from the electromagnetic harvester is AC. Using the transformer, the typically low transducer output voltage (tens or hundreds of millivolts) is upconverted through the use of the appropriate transformer turns ratio. Rectification of the stepped-up voltage is achieved by diode D1 which conducts during one-half of the AC output voltage, followed by D2 in the other half. This technique of using diodes to rectify the AC voltages from vibration-based energy harvesters is quite common [6–8]. In the configuration shown in Figure 6.5, only one diode conducts during each half cycle of the input vibration when compared to a standard diode bridge, thus minimizing the effect of the diode voltage drop, although this can still pose a problem. This configuration does not perform an impedance match between the electromagnetic harvester’s source impedance and the interface electronics, and therefore the maximum power is not transferred from the harvester to the load. However, the simplicity of the arrangement in achieving rectification and voltage step-up is an advantage of this method.

Alternatively, voltage multipliers such as the Villard multiplier (Figure 6.6) and the Dickson multiplier have been used to boost the voltage from the transducer.
Cascading multiple stages of the Villard multiplier will result in greater step-up ratios on the voltage from the transducer. One benefit of this approach over the previous arrangement is the ability to step up without using magnetic components, which favors integrated fabrication techniques. Again, such an approach fails to provide an impedance match.

Mitcheson et al. proposed a dual-polarity boost converter that interfaces an electromagnetic generator in [1] as a potential solution to provide rectification, an impedance match, and voltage step-up in one circuit, while minimizing diode voltage drops. This converter provides low-voltage rectification of the positive and negative half-cycles of the generated voltage. Two boost converters are activated alternatively to rectify the AC voltage from the harvester’s output. The dual-polarity nature of the converter removes the need for a diode bridge rectifier. Additionally, the circuit fulfills the step-up conversion requirements inherent on the output voltage of electromagnetic energy harvesters. Within the boost converter, the authors recommend the use of synchronously switched MOSFETs or Schottky diodes to reduce the effects of power losses in the converter.

In [10], Maurath et al. reported an adaptive impedance matching technique utilizing switched capacitor arrays. The proposed circuit consumed less than 50 μW (simulated) and was geared towards self-powered applications for energy harvesters. Typically, output currents from microgenerators are quite low (less than 1 mA), which was why an on-chip capacitor-based impedance matching circuit was chosen to interface the generator. If the voltage across the switched capacitor array is half that of the generator’s voltage, an impedance match exists between the generator’s internal resistance and the load. This is an attractive impedance matching technique because it negates the need for current sensing within the power converter. The capacitors in the switched-array are charged to \( (0.5V_{\text{gen}} + \Delta V_{\text{charge}}) \) during a charging time period, and then the switch toggles to the other state whereby the
capacitors will then discharge to a storage capacitor, which feeds a boost converter. At the end of the discharge cycle, the voltage across the capacitor array will decrease to \(0.5V_{\text{gen}} - \Delta V_{\text{discharge}}\). The switching frequency for these capacitor arrays depends on how small the \(\Delta V\)s are required to be and hence is closely linked to the efficiency of the circuit. The control of the circuit is not described in [10] in detail, but it is likely that some open circuit measurement of the transducer open circuit voltage would need to be made during operation as the operating conditions change.

### 6.2.2 Example of a Complete Power Electronics System for a Continually Rotating Energy Harvester

Many examples have been presented in the literature and, indeed, earlier in this book, about vibration powered harvesters. High-performance power electronics with all the functionality of optimal damping control (the impedance match), energy storage, and output voltage regulation have yet to be demonstrated for such systems, mainly because of the difficulty of achieving these functions with such low-power generation capability and the need that these functions must be powered