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Requirements for Power Electronics used for Energy Harvesting Devices

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Abstract

The output of a vibration-based energy harvester generally is an AC-voltage, whereas the input to an electronic load should be a certain DC-voltage. A voltage regulator circuit is therefore needed to provide the correct voltage. In this contribution, the main requirements for such a voltage regulator are given. Different design options are discussed: linear voltage regulators, classical switching techniques and switched-capacitor regulators. Pros and conts of each configuration are discussed, thereby concluding that the best design option is highly dependent on the output characteristics of the energy harvester.

Keywords: Voltage regulator, power electronics, energy harvester

1 INTRODUCTION

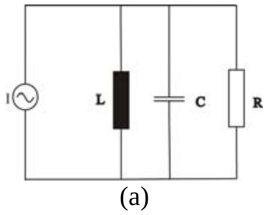
Autonomous devices such as sensors for ambient intelligence need a long battery lifetime in a small volume. The battery size can be reduced by incorporating micro-power generators based on ambient energy, so called energy harvesters or scavengers. Vibrational energy can for example be used as an energy source. Different types of these vibrational energy harvesters are currently developed. Their working principle can be based on electrostatic [1], [2], and electromagnetic principles [3], [4], while others are made of piezoelectric material [5]–[7]. As most of the time the output power of these generators is an AC voltage, it is not immediately feasible to drive an electronic device. A power conditioning circuit is needed to condition the output of the energy harvester: it has to rectify the output voltage and convert it to a useful level, e.g. 1V DC, with a limited voltage ripple.

In this contribution, the requirements of such power conditioning circuits are discussed. The first section deals with the resonance behaviour of vibrational energy scavenger with non-linear loads. Section 2 discusses the importance of matched capacitances of a power conditioning circuit to a harvester device with capacitor as output impedance. The following section discusses a few possible conditioning circuits: linear voltage regulators, classical switching regulators and switched-capacitor regulators. The conclusion is given in the last section.

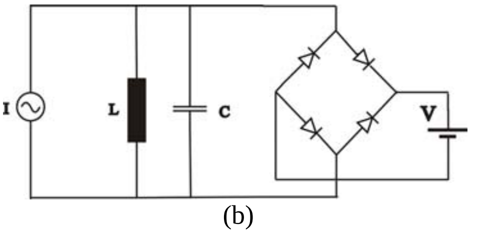
2 RESONANCE BEHAVIOUR

To extract as much energy as possible out of the environment, the working principle of most of the vibrational energy harvesters is based on resonance behaviour. For every load, there exists a certain resonance frequency at which the output power of the harvester device is maximal. To model this behaviour, a resistor is usually taken as load, but a power conditioning circuit generally does not act as a linear load to the harvesting device. To make sure that the connection of non-linear loads to the device does not change anything to the resonance behaviour, the behaviour of a simple resonant structure (fig. 1a) was investigated. The peak output power of this basic circuit is obtained at following resonance frequency:

$$f_{resonance} = \frac{1}{2\pi\sqrt{LC}} \qquad (1)$$



(a)



(b)

Figure 1. Basic resonance structure with (a) linear load and (b) non-linear load.

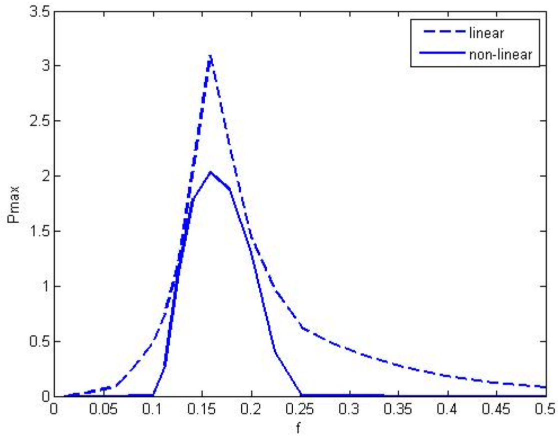


Figure 2. Maximum load-voltage versus frequency of the resonance structure.

The output of a vibrational harvester is an AC voltage, whereas the desired output of the power conditioning circuit is a DC voltage, meaning a rectifying circuit is needed. A diode bridge is the simplest and most used rectifier, though its behaviour is not at all linear. If this non-linear load is connected to the simple resonant structure (fig 1b.), the resonance frequency of the structure does not change (fig 2.). In other words, the modelling of a harvester device, with only linear loads taken into account proves sufficient. On the other hand, the damping of the system gets higher, hence the power output of the system is decreased.

3 MATCHED CAPACITANCE

Electrostatic or piezoelectric vibrational energy harvester devices are usually modelled with a capacitance as output impedance [1,5]. The output power of these devices is characterized by a relatively high output voltage with large ripples and a low output current. To filter these ripples out of the voltage output, a capacitor is usually connected to the device, after the rectifier circuit. Storage devices, for example a battery, can also be seen as a large capacitor. The power transfer of the harvester device to this capacitor can be very inefficient. Consider the circuit in fig. 3., where the output capacitor C_{output} of the harvester is connected to a filter capacitor C_{filter} through an ideal switch S. The initial energy (when the switch is open) of this system is U_0.

$$W_0 = \frac{C_{output} U_{output,0}^{\ 2}}{2} + \frac{C_{filter} U_{filter,0}^{\ 2}}{2} \qquad (2)$$

Initial voltage $U_{filter,0}$, of C_{filter} is zero. After the closing of the switch, and after transient effects, both capacitors have the same voltage. It can be shown that the final energy $W_{f,tot}$, stored in the system is:

$$W_{f,tot} = \frac{C_{output}}{C_{output} + C_{filter}} W_0 \qquad (3)$$

Final energy transferred to the conditioning circuit is the final energy present on C_{filter}:

$$W_{f,filter} = \frac{C_{filter} C_{output}}{\left(C_{filter} + C_{output}\right)^2} W_0 \qquad (4)$$

A maximal amount of energy is transferred when C_{filter} equals $C_{output.}$ Half of the initial energy is then lost, although we have an ideal circuit without any resistance taken into account. This lost energy can be seen as energy needed to build up the electromagnetic field in C_{filter}, and is emitted through electromagnetic radiation. While designing a power conditioning circuit for an energy harvester with capacitive output impedance, this effect is very important and has to be taken into account. To optimize the power output of the total design, the capacitance of the conditioning circuit has to be chosen very carefully, it has to 'match' the harvesting device's impedance. It is not recommended to choose a very small filter capacitor value, although the total energy content of the system is large, no energy is transferred to the conditioning circuit.

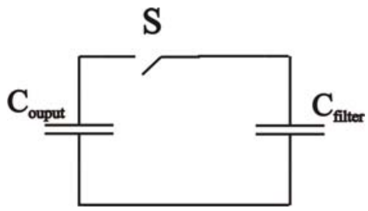


Figure 3. Connection of two capacitors.

4 CONDITIONING CIRCUITS

4.1 Linear voltage regulator

Only a few power conditioning circuits are found in literature. The circuit that is mostly used, is a linear voltage regulator. This circuit is used to convert a DC voltage to a reference value. If the output of the harvester device is an AC voltage, a rectifying circuit is still needed. The basic structure of a series voltage regulator is given in fig. 4. A parallel linear regulator is also possible, its working principle is analogous.

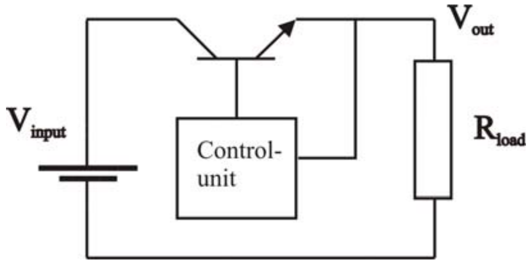


Figure 4. Series linear voltage regulator

The regulator mainly consists of an active element, generally a transistor, operating in its 'linear region', thus acting as a variable resistor. The transistor can be seen as the first half of a voltage divider. To control the output voltage, a feedback circuit compares output voltage with a reference value. The input to the transistor gate is adjusted to keep the voltage output equal to the reference. This regulation circuit is very inefficient, because the transistor works as a resistor, energy is dissipated as heat. The maximal theoretical efficiency of a series linear voltage regulator is:

$$\eta_{\max} = \frac{V_{out}}{V_{in}} \qquad (5)$$

Another reason why linear regulators are not the most convenient conditioning circuits for harvesting devices is the fact that we have to deal with a variable resistor. According to section 2, a certain input vibration frequency leads to resonance only with a certain load connected to the device. Even more important is the fact that due to a changing load, a change of vibration amplitude of the vibrating mass in the harvester is expected. The vibration amplitude of this mass has a maximum, collisions with the ‘walls’ of the harvester device must be avoided. Achieving optimal load conditions with a linear regulator is therefore hardly possible. Another remark is that the output voltage of a linear regulator is always lower than the input voltage, if a higher output is desired, other regulation techniques have to be used. The great advantage of linear regulators is their low complexity, the control circuit is also very straightforward.

4.2 Classical switching regulators

A second class of voltage regulators that can be used as power conditioning circuit for harvester devices are the classical switching regulators. A few examples are found in literature, for example: using a buck converter [7], and using a fly-back converter [8]. A great advantage of these systems is that they do not suffer from inherent low efficiencies as linear regulators do. To have a ‘matched load impedance’, i.e. the optimal load where resonance occurs (see section 2), the duty cycle of the switching element can be adjusted, according to [7]. The switching regulator provides the optimal load for the harvester, whatever the end-user load is.

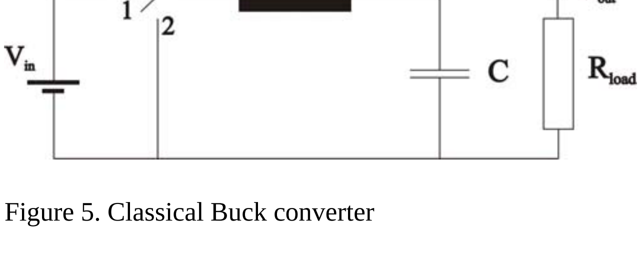


Figure 5. Classical Buck converter

A classical switching regulator always contains at least one inductor or transformer. In fig. 5, a buck converter is given as basic example. The output voltage of the harvester is down converted to the desired output, control is achieved through the adjustment of the duty cycle of the switch. In a buck-converter the inductor serves as low-pass filter element to eliminate the switching frequency components in the converter output. The switching frequency $f_s=1/T_s$ and the maximal desired output current ripple Δi_L determine the size of the inductor, according to (6). D is the duty cycle of the switching element.

$$L = \frac{V_{in} - V_{out}}{2\Delta i_L} D T_s \qquad (6)$$

Usually a current ripple of 10-20% of the DC component of the output current is desired. The output power range of an energy harvester device generally lies in the µW to mW range. Output voltages of the vibrational harvesters are usually some Volts, the desired regulator output is for example 1 V. The Δi_L-term in equation (6) is very small (µA- mA), therefore a large inductor value is needed (mH to even H). The inductor becomes a very large, bulky component of the total device. Moreover, inductors of these magnitudes are difficult to produce if a sufficiently high quality factor has to be achieved. The value of the inductor can be decreased, if very high switching frequencies are used. On the other hand, switching frequencies in the order of 100 kHz to 1 MHz imply high switching losses. In other words, the use of classical switching technologies as regulator circuit is not always an efficient choice, as it highly depends on the output characteristics of the harvester device.

4.2 Switched-capacitor regulators

Switched-capacitor regulators, also known as ‘charge pumps’, are another possible type of regulation circuit [9]. This type of regulators only uses capacitors as magnetic energy storage element, as opposed to the classical switching regulators where an inductor is used. Therefore, the inductor sizing problem can be avoided, which already is a great advantage of switched capacitor regulators. In section 3 is stated that an energy loss occurs if two capacitors, with different initial energy, are connected. The same effect occurs in switched-capacitor circuits. A careful design is therefore definitely needed to avoid such energy losses. In an ideal design, capacitors are only connected if they have the same initial voltage.

The simplest configuration is the switched-capacitor (SC) circuit where only one switching capacitor provides the up- or down conversion of the voltage (fig. 6). To increase the voltage conversion number, the amount of capacitors has to increase. The most common topologies of SC-regulators are the ‘series-parallel’, to step-up the voltage, or ‘parallel-series’, to step-down the voltage, configurations (fig 7).

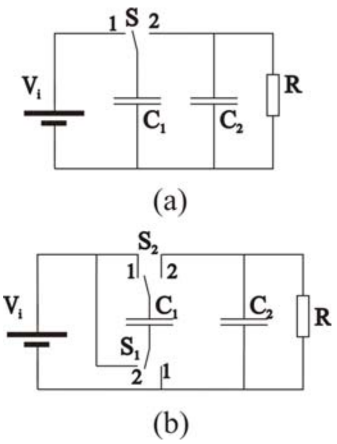


Figure 6. Step-up (a), and step-down (b) charge pump circuit

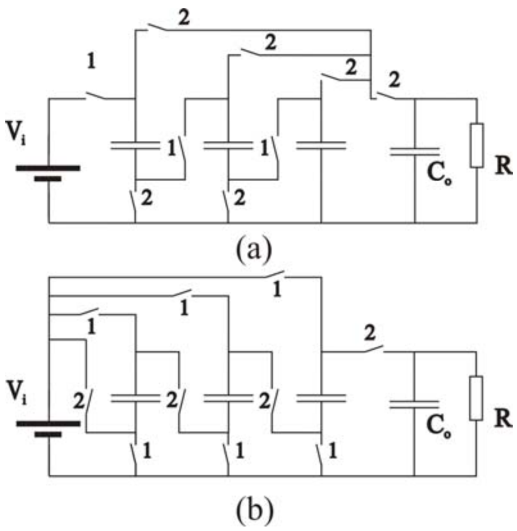


Figure 7. Series-parallel (a) and parallel-series (b) configuration.

A disadvantage of switched-capacitor regulators is the fact that the conversion number is fixed, it depends on the amount of capacitors, and the used configuration. The regulator circuit is not very flexible. This may pose a problem if the energy harvesters are used in an environment with a high variation of vibration amplitudes and frequency. This high variation possibly provides an input that is too divers to be efficiently regulated by the switched-capacitor circuit. They therefore definitely need a complex control circuit.

5 CONCLUSION

Possible circuit configurations are highly dependent on the output characteristics of the harvester device: vibration frequency, output power, and output voltage. Resonance behaviour of the harvester device restricts possible configuration options. Main conclusion is that the design of an efficient power conditioning circuit for energy harvester devices is not at all straightforward, a general solution is hardly possible, because specifications are too divers.

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