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Energy Harvesting and Power Delivery for Implantable Medical Devices

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Abstract

Providing a constant and perpetual energy source is a key design challenge for implantable medical devices. Harvesting energy from the human body and the surrounding is one of the possible solutions. Delivering energy from outside the body through different wireless media is another feasible solution. In this monograph, we review different state-of-the-art mechanisms that do "in-body" energy harvesting as well as "out-of-body" wireless power delivery. Details of the energy sources, transmission media, energy harvesting and coupling techniques, and the required energy transducers will be discussed. The merits and disadvantages of each approach will be presented. Different mechanisms have very different characteristics on their output voltage, amount of harvested power and power transfer efficiency. Therefore different types of power conditioning circuits are required. Issues of designing the building blocks for the power conditioning circuits for different energy harvesting or coupling mechanisms will be compared.

Contents

1

Introduction

Implantable Medical Devices (IMDs) have been used for more than 50 years. The early IMDs dated back to the implantable pacemaker in 1958 [45]. Since then numerous types of IMDs were introduced to tackle different health issues. Implantable cardioverter-defibrillators were developed for detecting cardiac arrhythmia and correcting through electric pulses [61]. Implantable insulin pumps were developed to deliver insulin into the body depending on the blood sugar level of the diabetic patients [82]. These traditional IMDs mainly function by monitoring the local signals and activating certain event for reaction. The required power level ranges from μW to mW. With the advancement in VLSI technology, more sophisticated implantable circuits and systems have been developed that have more sensing capability and stimulation functions. Low power wireless data transmissions are also possible. This creates a new class of IMDs which not only monitor and activate signals in the local region, but also collect data, send it back through wireless channel to a local host to do signal processing and receive commands wirelessly to execute massive stimulation and activation. Examples are the implantable retinal prosthesis devices [50, 89], of which the goal is to restore some vision to people who have degenerative eyesight.

Implants are either on the retina (epiretinal implants) or behind the retina (subretinal implants). Images are either captured by an external camera or the implanted micro-photodiodes. After processing, the signals are either generated locally or transmitted from a host processor through a wireless channel to generate electrical simulation signals to the retina cells. Power hungry circuits such as wireless receivers and electrical stimulators are required. Another example is cochlear implants, which generate electrical stimulation to the auditory system to recover some of the auditory function for the hearing-impaired [23]. Also neural implants are used to directly stimulate the neural cells at the areas of the brain that are dysfunctional due to diseases [80, 31]. Neural implants that have the capability of capturing the activity of the brain and using it for brain–computer or brain–machine interface are also becoming reality. These neural implants require circuits to do electrical stimulation, data capture and also wireless communication, and hence require significant amount of power. Table 1.1 gives a summary of the power requirement of different types of IMDs.

There are many design challenges for IMDs. Power consumption, size, durability, reliability and biocompatibility are some of the key ones. Among them, power consumption is probably the dominant issue as it also affects the other factors. Traditional IMDs such as pacemaker and defibrillator use battery to provide power to the device. Even though the current consumption of the device is in the range of μA, the battery only lasts for a certain period of time (15 years for pacemaker and 7–8 years for defibrillator). When the battery is gone, another operation is required to replace the old device with a new one. For other devices such as neural implants which consume significantly larger power, either a larger battery is used which leads to a larger volume or the frequency of replacement is increased. Both are not desirable

Table 1.1. Power requirement of IMDS.

IMDs	Neural implants	Cardiac pacemaker	Cochlear implants	Retinal implants	Insulin pump
Power required	10 mW ∼200 mW	1 μW ∼10 μW	10 mW ∼100 mW	1 mW ∼100 mW	10 mW ∼50 mW

as we want the IMDs to work perpetually and we want them small. To achieve this contradicting goal, energy harvesting and wireless power delivery methodologies were proposed as the power supply methods for IMDs. Energy harvesting has become popular recently as a strategy to provide power for low power sensors or microsystems used in areas with environmental hazard where it is difficult to recharge or replace the battery [5, 65]. Different types of devices were developed to scavenge energy from the environment. Sources of energy include solar, wind, vibration, radioactivity, ambient RF and heat. Human body, at the same time, is also a great source of energy. Every day for an adult, the average daily diet provides about 10 MJ of energy. Different amounts of power are generated for different daily normal activities, e.g., housekeeping generates 175 W and 81 W is produced during sleeping [84]. Therefore it is tempted to use this as the energy source for IMDs. For the case that we cannot harvest energy from the body, if we can obtain the power wirelessly from outside to power up the implanted devices or recharge the battery, it will remove the requirement of an internal battery or help to reduce its size, and prolong the lifetime of the devices. In this monograph, we will review the recent trends in the research and development of the power provisioning methodologies for IMDs.

We categorize the methods of providing power to IMDs into two types, the "in-body" type and the "out-of-body" type. The in-body energy sources come from the human body. These include the kinetic, thermal, biochemical and direct electrical energy. The movements of the human body or even the internal organs [26] are good sources of kinetic energy. In [60] and [25] it is shown that several μW to mW of power can be extracted from the trunk and the head of the body during walking or running. The inner human body temperature is maintained at a relatively constant value of 37°C and there is a temperature gradient between the inner body, the skin and the air ambience. Exploiting this existing thermal gradient, thermal electric generator (TEG) can be used to generate electric power. Another abundant source of energy inside the body is glucose. Implantable biofuel cells using glucose as a reactant have been investigated and researched for a long time. It has been demonstrated recently that tens of μW/cm^2 power density can be generated constantly for over a month using glucose biofuel cell. Some of our body part is itself a natural electrical battery, e.g., endocochlear potential. If the potential is large enough and the corresponding power condition circuits can be designed to match with the requirement, electrical energy can be harvested directly from this potential. In [58] it has been shown that nW of power can be extracted from the ear of a guinea pig for up to 5 hours.

For out-of-body power delivery, external energy source is used to couple the energy into the IMDs or directly activate the energy harvester implanted inside the body. The external power sources come from magnetic energy, ultrasonic wave, optical wave and the most common one, electromagnetic induction.

The whole implantable energy harvester/receiver consists of three parts (Figure 1.1), the primary energy source, the energy transducer and the power conditioning blocks. The primary energy source is either "in-body" or "out-of-body" source. The energy transducer collects the harvestable energy in a certain form and transforms it into electrical energy. The harvested electrical energy is time varying and usually the output voltage and power levels are low. Therefore power conditioning system is required to regulate the output voltage and deliver the output to the load in the required form. In some energy harvesters, the harvested power varies with the environment and there exist some operation points that the harvested power is maximized. In this situation, the power conditioning block is also required to track and operate the system in the maximum power point (MPP) in order to optimize the power transfer efficiency.

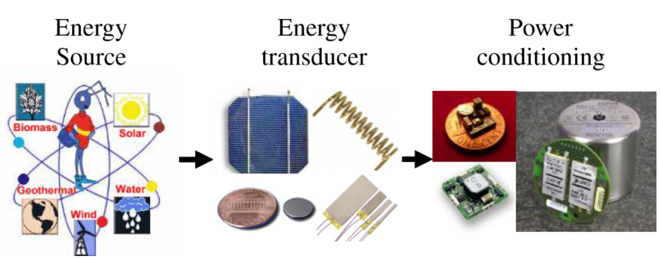

Fig. 1.1 Building blocks of the implantable energy harvester.

The rest of the monograph is organized as follows. Section 2 will discuss different types of energy harvesting sources and wireless power delivery mechanisms. The corresponding energy transducer designs will also be presented and the optimum design strategies will be discussed. The building blocks of the power condition circuits will be presented in Section 3. Detail system and circuit design will also be provided. Conclusions will be given in Section 4.

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