Low-Power Energy Harvesting Survey

Kendrick Tang, Leo Chen, Yanbo Zou

***Abstract*—As technology trends towards lower-powered and smaller-sized devices, the use of batteries to power these devices becomes more and more impractical. It is not sustainable, especially due to the battery density trends during these last few decades, to use batteries. Due to the mobility and perhaps the location of future devices (sub-dermal, or in inaccessible locations), it also doesn't make sense to use traditional grid power for these devices. One solution may be energy harvesting, which uses the available ambient energy in the environment to provide small amounts of power.**

***Index Terms*—Energy harvesting, low-power, battery.**

I. Introduction

CURRENTLY devices either run on the electric grid, or are battery powered. There are several limitations to these two conventional power sources. The grid can't be used, at least not in a traditional way, for devices with high mobility. The grid also cannot be accessed by devices in remote locations. For now, batteries are a reasonable way to power mobile or remote devices. However, they are made of toxic materials, have low power densities, and low power-cycles. As a result, batteries are not sustainable for the future.

For the increasing amount of personal technology, remote sensor networks, ubiquitous computing, and the internet of things, one potential source of sustainable energy is energy harvesting.

In this paper, we will first provide a general overview of energy harvesting. Then we will discuss ways to harvest three types of energy: mechanical, EM, and thermal. Lastly, we will present current challenges.

II. What is Energy Harvesting

Energy harvesting is a way to generate power from the available environment. This can be done on two scales: macro and micro. On the macro side we have wind power, hydroelectrics, and solar power. These types of energy harvesting have been used to support fossil-fuel plants. On the other hand, there is micro-scale energy harvesting, which is sometimes called energy scavenging. This will be the main focus of this paper.

Energy scavenging currently produces extremely small amounts of power (mirco-, nano-, and pico-watts). Despite these small numbers, low-power energy harvesting has a huge potential in low-power devices. Energy harvesting systems will not need to be replaced nearly as often as batteries, which wastes more and more time and money as the number of devices continues to increase. Due to its longevity, energy harvesting could be one solution for powering the internet of things, small biomedical devices, and sensor networks.

K. Tang, L. Chen, and Y. Zou are all with the University of Washington Electrical Engineering Department enrolled in EE 478 WIN 2015.

Energy is harvested from available sources in the environment, like ambient vibrations, electromagnetics, or heat. The source used for a particular device would have to be application specific, depending on what types of ambient energy is available.

III. Types of Energy Harvesting

Energy can be harvested from a variety of sources, perhaps even at the same time. One traditional source of energy harvesting solar. Since solar energy harvesting has been around for quite some time now, it has significantly improved in terms of cost and efficiency. In this paper, we will focus on more novel types of energy harvesting that currently produce much lower amounts of power. These include mechanical energy, EM energy, and thermal energy harvesting - but this is not an exclusive list.

A. Mechanical Harvesting

Piezoelectric materials could generate electricity when they had been applied with some mechanical stress. According to the piezoelectricity theory, when a stress is applied to a piece of piezoelectricity material, it would generate electrical potential according to the way of stress is applying. The compressed part of the piezoelectric material would generate a negative electrical potential; the extended part would generate a positive electrical potential [1]. As the difference in electrical potential exists, the voltage exists. The unique characteristics of piezoelectric materials make it possible to use them for transferring mechanical energy to electricity. There are couple kinds of piezoelectric materials that had been already in many applications, yet none of them are used in harvesting material. It is because they could not harvest enough energy from mechanical stresses. In other words, the efficiency was too low. Today researchers found the piezoelectric material that could dramatically increase the efficiency and make it possible to use it for electronic devices. A research team in Georgia Institute ofTechnology had found a piezoelectric material that has an energy harvesting efficiency estimated to be 17 to 30% [2]. The material they made was zinc oxide. By using aligned zinc oxide nanowire array, it could uses the coupling of piezoelectric and semiconducting properties of ZnO as well as the formation of a Schottky barrier between the metal and ZnO contact [2]. By using zinc oxide nanowire array, the researchers successfully used it to power a heart pacemaker. The prototype heart pacemaker is powered by heartbeat of human, which is low frequency vibration. Utilizing the characteristics of zinc oxide nanowire array, the heartbeats-powered heart pacemaker could have an output of 25A with 2-3 V output voltage [3]. The zinc oxide nanowire power cell could also be used on other human organs with low frequency vibrations.

The research team also shows the possibility that this material could be used to power wearable devices. They used the same power cell module to power a LCD screen successfully [4]. However, the zinc oxide is not the only material that could be used to covert vibrations to electricity. A research group had developed a piezoelectric power cell using aluminum nitride to convert vibration ranged from 200 Hz to 1200 Hz into electricity. The aluminum nitride piezoelectric cell could have an output of 60 W using an acceleration of 2.0 g and a vibration frequency of 572 Hz [5]. As the technology of piezoelectric materials is developing, commercial products are also manufactured by companies. Philips has a batteryless controller using piezoelectric micro-generators in buttons. As we can see, the market of piezoelectricity powered devices is developing. Sooner or later, we will be able to see all kinds of energy harvesting devices using piezoelectric generators.

B. EM Harvesting

Another exciting source of energy harvesting is ambient radio frequency energy. A French research group from University of Tours has conducted a measurement on the RF power density on different points of an urban environment. Their measurements show that the average RF power density varies on a frequency range of 680 MHz to 3.5 GHz. Within this spectral range, the RF power density varies from 1 nW/m2 to 35.5 W/m2 and it appears to be constant over time [6]. The research team has come up with two systems to harvest RF energy in the environment. The first one is called broadband system. This system aims to recover all the signals available in the environment. In order to do so, it uses a broadband Omnidirectional antenna to capture the signals. The antenna is connected to a rectifier that will convert the RF energy to output a steady DC power. The performance of this system did not quite meet the expectation, mainly because the broadband antenna did not work quite well in recovering all the signals available and extract a large portion of RF energy from them. The output DC power was about 12 pW. The team then came up with the second design to improve the system called narrow band system. This system uses a narrow band antenna that focuses on recovering the RF energy within the frequency range of 1.8 GHz to 1.9 GHz. Within this range the RF power density was found to be the maximum across the spectrum. To better recover the signals, they also designed a matching circuit placed in between the antenna and the rectifier. These changes led to a significant increase on the DC power to about 400 pW. However, one disadvantage of this system is that it is limited by its limit dependency. Professor Parks and Professor Smith from the University of Washington published a new approach to improve the approach of broadband harvesting. Their technique is similar to the one adopted in broadband system. However, the single broadband antenna is followed by several narrow band rectifier chains. Each rectifier chain consists of a band pass filter, a tuned impedance matching network, and a rectifier. A diode summation network will then combine the output power of all the rectifiers [7]. This technique enables a good performance even if there are only a subset of the narrow band rectifiers is excited and thus the system can be used in various urban areas. The advantage of RF energy harvesting is that RF energy is a relative consistent source in the environment, especially urban areas since RF waves are everywhere.

C. Thermal Harvesting

There are two main ways to convert heat into electricity: thermoelectric and pyroelectric. These two mechanisms are fundamentally different and are used in very different applications.

Thermoelectric conversion uses a thermal gradient of free charge-carrying particles to induce a current. Similar to how diodes use density gradients to induce diffusion drift, the differences of temperature within a thermoelectric generator will cause free electrons to flow from the warmer side to the cooler side. As a result, for thermoelectric harvesting to be useful, a persistent and well-defined thermal gradient must be available in the environment. This is usually very difficult to achieve, especially on a small surface. One exception is for wearable technology; there is almost always a very well-defined thermal gradient from body heat to the colder ambient environment.

MIT compared the energy generated by thermoelectric harvesting to the Carnot Cycle, which is the theoretical most efficient way of converting heat into usable energy. The Carnot Cycle showed very low efficiency for reasonable temperature gradients, e.g. 5.5% for $T_L = 20^\circ$ C and $T_H = 37^\circ$ C. The efficiency was even worse for thermoelectric generation. For temperature differences less than 30° F, they found only a 1% efficiency. For much larger temperature differences ($> 200^\circ$), it was still less than 10% [8].

Pyroelectric generation does not need a thermal gradient. Instead, it generates a current when stressed, like piezoelectric generation. Unlike piezoelectric materials, which use mechanical stress to create current, pyroelectric materials use thermal stress to create current. This can be used in environments which fluctuate in temperature to produce AC power. In one demonstration, periodically changing temperature from 295 to 304 K produced 5.8 mV peaks in voltage and 108.5 pA peaks in current [9].

IV. Current Challenges

Even though there have been a lot of applications in using the energy harvesting, there are still a lot of challenges that we currently facing in improving this new arising technology. First major challenge is reliability. Systems powered by energy harvesters sometimes have to work under harsh and unpredictable environments. A good example is the sensor nodes that placed in the bottom of the ocean or in the middle of a rainforest. The unpredictable outer environmental conditions add a significant uncertainty to the performance of the systems. We need to make sure that the systems are able to function regardless of any of the environmental affect. Another major challenge is the size of the system. If we are to power up a biosensor such as heart monitor with energy extracted from the heart beat, and implant it in human body. Beside all the functionality of the monitor, we need to make sure the size of this sensor is small. So the small scale of size of the system is challenging. Lastly, efficiency in energy harvesting needs to improve in order to make it more practical. The conversion rate between RF energy to electrical energy is as low as 0.6% for the narrow band system that discussed earlier [6]. That means we are losing most of the captured ambient energy in the conversion.

V. Conclusion

In summary, we have introduced different parts of the energy harvesting in this paper including what is energy harvesting in concept, what are the popular technologies in energy harvesting, what are the challenges in this field. As a new concept in scientific field, the energy harvesting is now a popular topic among the research teams around the world. In the process of writing this research paper, we can tell there are numerous research teams dedicating themselves making this technology into our lives. As what we presented in this paper are the frontiers in the field of energy harvesting, scientists are now working on harvesting energy from mechanical energy, electric-magnetic energy and thermal energy. However, the development of the energy harvesting is not going to be limited only to these field. As a fact, we have already seen some of energy harvesting products that are now existing on the market, like the solar battery cells. So we can be confident enough with the future of this new technology to conclude that there would be more ways to harvest energy and more products using energy harvesting technologies would be produced and put into our lives in order to reduce the cost of getting energy.

References

[1] G. Gautschi, *Piezoelectric Sensorics*. NY: Springer-Verlag Berlin Heidelberg, 2002.

[2] Z. L. Wang and J. Song, "Piezoelectric nanogenerators based on zinc oxide nanowire arrays," *Science*, vol. 312, pp. 242–246, Apr. 2006.

[3] Q. Zheng *et al.*, "In vivo powering of pacemaker by breathing-driven implanted triboelectric nanogenerator," *Advanced Materials*, vol. 26, no. 33, May 2014.

[4] G. Zhu *et al.*, "Flexible high-outpput nanogenerator based on lateral zno nanowire array," *Nano Letters*, pp. 3151–3156, Jul. 2010.

[5] R. Elfrink *et al.*, "Vibration energy harvesting with aluminum nitride-based piezoelectric devices," in *PowerMEMS 2008 + MicroEMS2008*, Sendai, Japan, Nov. 2008.

[6] M. L. D. Bouchouicha, F. Dupont and L. Ventura, "Ambient rf energy harvesting," in *ICREPQ '10*, Granida, Spain, Mar. 23–25, 2010.

[7] J. R. S. A. Parks, "Sifting through the airwaves: Efficient and scalable multiband rf harvesting," in *IEEE RFID 2014*, Orlando, Florida, Apr. 2014.

[8] T. S. J. A. Paradiso, "Energy scavenging for mobile and wireless electronics," *Pervasive Computing*, pp. 18–27, Jan.-Mar. 2005.

[9] Z. Wang *et al.*, "Progress in nanogenerators for portable electronics," *Materials Today*, vol. 15, no. 12, pp. 532–543, Dec. 2012.