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VIBRATION ENERGY HARVESTING TECHNIQUE: A COMPREHENSIVE REVIEW

Nik Fakhri Nek Daud & Ruzlaini Ghoni*
nickfakhri995@gmail.com

Faculty of Electrical and Automation Engineering Technology, University College TATI, Jalan Panchor, Teluk Kalong, 24000 Kemaman, Terengganu, Malaysia

ABSTRACT

In order to minimize the requirement of external power source and maintenance for electric devices such as wireless sensor networks, the energy harvesting technique based on vibrations has been a dynamic field of studying interest over past years. Researchers have concentrated on developing efficient energy harvesters by adopting new materials and optimizing the harvesting devices. One important limitation of existing energy harvesting techniques is that the power output performance is seriously subject to the resonant frequencies of ambient vibrations, which are often random and broadband. This paper reviews important vibration-to-electricity conversion mechanisms, including theory, modelling methods and the realizations of the piezoelectric, electromagnetic and electrostatic approaches. Different types of energy harvesters that have been designed with nonlinear characteristics are also reviewed. As one of important factors to estimate the power output performance, the energy conversion efficiency of different conversion mechanisms is also summarized. Finally, the challenging issues based on the existing methods and future requirement of energy harvesting are also discussed.

1. INTRODUCTION

The field of power harvesting has experienced significant growth over the past few years due to the increasing desire to produce portable and wireless electronics with extended lifespan[1]. Current portable & wireless devices must be designed to include electrochemical batteries as the power source. The use of batteries can be troublesome due to their limited lifespan, thus necessitating their periodic replacement[2]. In the case of wireless sensors that are to be placed in remote locations, the sensor must be easily accessible or of a disposable nature to allow the device to function over extended periods of time. Energy scavenging devices are designed to capture the ambient energy surrounding the electronics & convert it into usable electrical energy[3]. A number of sources of harvestable ambient energy exist, including thermal energy, sound energy, radio frequency, light, mechanical energy & wind energy.[4]

2. WASTE ENERGY HARVESTING

Waste energy harvesting involves utilizing low - grade energy that would otherwise go to waste, mainly to power electronics with low power requirements. It provides an environmental benefit by doing more useful work with the energy already produced. There are many applications where it is advantageous to not have batteries or wiring – everything from ground sensors to body implants. Innovations such as piezoelectric materials cultivated in the form of virus can help provide scalability to the technology.

A. Radio Frequency Harvesting (RFH)

Radio frequency harvesters use a direct consequence of our current lifestyle. This type of harvesters exploits the electromagnetic waves which are emitted by different sources (antennae, routers, NFC/Bluetooth devices), but largely unused[5]. This is due to the nature of the wireless concept: the location of the receiver is unknown to the emitter and may even be changing. Therefore, to ensure efficient power transmission, RF sources need to emit omnidirectional and only part of the waves is received, all others are lost[6].

Thus, radio frequency harvesting is based on the principle of harvesting these lost waves and transforming them into electrical energy, according to the theory of Maxwell. RFH can be modelled as an AC voltage source and/with a small resistor in series. RFH can harvest up to 50-100 mW from Wi-Fi waves within 1 to 3 meters[1].

B. Optical Harvesting

Optical energy, also referred to as solar energy, covers the spectrum of light - from infrared to ultra-violet - which also belongs to the electromagnetic spectrum. This energy is mainly harvested outdoors where up to $100mW/cm^2$ can be achieved. Indoor harvesting is also possible, but only up to $1mW/cm^2$ can be harvested. Due to the semiconductor nature of solar-cells, they can be modeled by a DC current source in parallel with a diode. Most modern mono-crystalline cells achieve a 30% efficiency in a lab[7].

C. Sound Harvesting

Sound energy is another form of unused energy which can be harvested. Sound energy is almost present continuously & at a considerable level in the environment for e.g. on the railway track, runway, ship yard, or on the road (engine noise of vehicles & horns), loud music played in clubs or parties, at construction sites & other such sources etc. give sufficient sound pressure levels that can be used for EH[8].

D. Vibration Harvesting

Mechanical energy harvesting (MEH) allows converting human daily activities into electrical energy. Different types of convertors can be used: electrostatic, electromagnetic and piezoelectric. Electrostatic converters are based on variable capacitors, electromagnetic converters use Faraday's law and a magnet, and the piezoelectric converter is based on piezoelectric materials[9].

E. Light Energy Harvesting

Light is electromagnetic radiation within a certain portion of the electromagnetic spectrum. Visible light is usually defined as having wavelengths in the range of 400–700 nanometers (nm), between the infrared (with longer wavelengths) & the ultraviolet (with shorter wavelengths)[10]. This wavelength means a frequency range of roughly 430– 750 terahertz (THz)[11]. A comparison of different energy source & their applications is tabulated in Table 1.

Wu et al. proposed the concept of a waste-heat thermoelectric generator, the specific power output of the generator was analyzed & compared with that of Carnot. They concluded that a completely reversible heat engine played a major role in the development of the performance of thermoelectric generators[10].

Rowe et al. investigated the ability to construct a large thermoelectric generator capable of supplying 100 watts of power from hot waste water[12]. The system tested used numerous thermoelectric devices placed between two chambers, one with flowing hot water & the other with cold water flowing in the opposite direction, thus maximizing the heat exchange. With a total of 36 modules, each with 31 thermocouples, 95 watts of power could be generated[13].

A low power thermoelectric generator (micro- thermoelectric harvester) capable of generating tens of microwatts of power (15μW/cm2 from a 10°C temperature differential) out of a device that had previously generated nanowatts with the same size was developed by Stordeur et al. The device was based on thin film thermoelectric materials, consisted of 2250 thermocouples, & operated in temperatures ranging from room to not higher than 120°C[14].

A prototype thermoelectric generator mounted oneself- ignition (Diesel) engine was designed & tested by Wojciechowski et al.[15] The designed model was able to recover even 25kW of heat energy. Assuming the 5% efficiency of the thermoelectric modules it could allow to obtain the maximum electric power of app. 750W. A TEG unit was around the exhaust pipe. The unit was experimentally tested by Birkholz et al. found to generate an open circuit voltage of 22 V & a total power of 58W[16].

F. Vibration Harvesting

A study has been done on energy harvester mounted on sneakers that generated electrical energy from pressure on the shoe sole by Kymissis et al. The first energy harvesters had multilayer laminates of PVDF, the second one contained a PZT unimorph & the third one was a rotary electromagnetic generator[3]. The PVDF & PZT element mounted between the removable insole & rubble sole. The PVDF stack was in the front of the shoe while the PZT unimorph was at the heel.

A mini-scale piezoelectric energy harvester was developed by Roundy et al. which have a similar structure to what have been demonstrated by S. Beeby. The harvester is used piezoelectric instead of silicon wafer as the cantilever beam, & tungsten alloy as the proof mass instead of the magnets[17].

Sodano, Inman, & Park suggested method alters mechanical energy into electrical energy by straining a piezoelectric material. Strain or deformation of a piezoelectric material causes charge separation across the device, producing an electric field & consequently a voltage drop proportional to the stress applied[18].

A mini-scale electromagnetic energy harvester prototype that consists of a coil & a silicon wafer cantilever beam, with four pole magnets as its proof mass was developed by Beeby et al. The harvester was able to produce considerably high power over its size. The mechanical & electrical equivalent of the energy harvester design[9].

A PZT model for harvesting energy from structural sensors on a bridge or global positioning service (GPS) tracking devices was developed by Sodano, Inman et al. They established an experimental method to calculate charge accumulated on the surface of the PZT layer under applied strain[11]. This model in turn simplifies design procedure necessary for determining the appropriate size & vibration levels which is necessary for accurate sufficient energy to be produced & supplied to the electronic devices[19].

This review will not consider the electromagnetic and electrostatic converters; it will only focus on the piezoelectric converter type. A piezoelectric harvester uses a mechanical stress exerted on a material to generate an electrical power. Conversely, an electrical power applied onto this material will lead to resonance[20]. Thus, the principle of MEH thus summarizes as follows: human activities generate vibrations which lead to a stress on the harvester piezoelectric material. This, in turn generates electrical power. For example, 1 to 45 mW can be harvested from motors or vehicles. A piezo harvester can be modeled as an AC current source in parallel with a capacitor[17].

3. DISCUSSION

Choosing the appropriate energy harvesting sources depends on the context, in relation with the constraints imposed by its use and the environment. RF harvesting is usually considered for very low power applications, as the energy source can be found nearly anywhere at any time. Optical energy is, in most applications, dependent on sunshine. At night it cannot be operated and will have well less output on cloudy days. However, it is one of the most productive an easy to use energy sources. Finally, mechanical energy harvesting can be used only in very specific conditions, and the power output is linked to the frequency of the vibration.

4. CONCLUSIONS

As seen previously, there are different types of solutions which allow to harvest free energy, with advantages and drawbacks. Thus, to choose a source, it will be necessary to analyses the needs and context in which the energy harvester will be used[21]. The best decision can be to choose multiple sources, even if it will complicate your circuit and oblige you to develop new components to allow your circuit to accept these sources, But this greater complexity leads to higher energy consumption and again it will be necessary to seek the perfect balance between consumption/optimization and complexity[22].

The concept of energy harvesting may at first glance appear easy. One just needs one a piezoelectric material or an antenna, but energy harvesting is not a straight forward process. One needs to make sure to harvest a maximum of power, for example using the Maximum Power Point Tracking. In certain situations, harmonics created by electronic components, need to be suppressed. This requires dedicated electronics and signal processing.

Table 1: Harvested output power from various waste energy sources

Energy Source	Characteristic	Harvested Power	Applications
Thermal	Human	$60\mu W/cm^2$	Remote Wireless Sensors & Actuators
	Industrial	~1-2	
Mechanical (vibration)	Human	$\sim 4\mu W/cm^3$	Handheld Electronic Devices or Remote Wireless Actuators
	Machines	$\sim 800\mu W/cm^3$	
Sound	Machines	$\sim 10\mu W/cm^3$	Small Handheld Electronic Devices
Light	Outdoor	$100 mW/cm^2$	Handheld Electronic Devices
	Indoor	$100\mu W/cm^2$	
Radio Frequency	GSM 900	$0.1\ \mu W/cm^2$	Remote Wireless Sensors
	WiFi	$0.001\ \mu W/cm^2$	

To achieve fully autonomous sensor nodes, the harvester needs to produce enough energy to power the sensor and its drivers. And so, the device will not need off-chip component to charge itself, thus allowing a gain of space and mobility for the sensor.

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