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A REVIEW ON PIEZOELECTRIC ENERGY HARVESTER AND ITS POWER CONDITIONING CIRCUIT

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ABSTRACT

The application of batteries as the main portable power sources is not applicable any longer as it has limited lifespan. This paper presents the recent concern on the power requirements of Wireless Sensor Nodes and the studies on the development of energy harvesting system using piezoelectric devices. Ambient Energy harvesting is one of the alternatives in replacing the use of batteries and wiring where small amounts of energy from environmental sources such as solar, air flow or vibration is harvested to form an electrical energy. Numerous studies have shown that power density of energy harvesting devices is in the range of hundreds of microwatts, while from the literature study it reveals that power requirements of most of electronic devices are in the range of milliwatts. Therefore, a key challenge for a successful deployment of energy harvesting technology remains, in many cases, the provision of adequate power. General discussion on two types of rectifier; full-wave bridge rectifier and voltage doubler also presented at the end of this paper.

Keywords: energy harvesting, wireless sensor network, piezoelectric, power conditioning circuit.

1. INTRODUCTION

There are generally two types of energy sources; primary and secondary energy sources. Primary sources of energy are fossil fuels, wind, hydro, solar, nuclear fuels and kinetic or vibration where this energy is renewable and occurs naturally. For the secondary energy, it is generated by using the primary resources. Thus, electricity is secondary energy sources. Electricity is a form of energy that humans are very dependent on. As the population, industrialization and technology have been growing rapidly, global demand for the electricity also keeps increasing. These issues raise concern on the availability of energy sources and the environmental effects of using them.

Recently, the whole world is more interested to explore for alternative energy sources as we are moving towards the green technology energy sources. Windmills [1], watermills [2], geothermal [3] and solar [4] energy are the examples of the alternative energy whereby the concept of converting these renewable resources into electricity is known as energy harvesting technology. This technology has becoming an active research area especially the vibration ambient energy harvesting. This is due to the largely use of semiconductor devices in microelectromechanical system (MEMS). Besides, forth industrial revolution is the current trend of automation where communication in exchanging data between one devices to another are using cloud computing which mostly known as Internet of things (IoT) [5]. As it is expected to be connected to the internet, wireless sensor network (WSN) is the key enablers for IoT [6].

Conventionally, electronic devices and wireless sensor nodes are power up by using batteries or wired to power outlet. However, batteries have a finite lifespan and not easy to maintain as WSN are normally implant at unreachable area. This system will become much more reliable if it is compact in size and self-powered without the use of batteries and wiring. Many researchers did a study on ways to recharge or replace them [7], [8]. Energy harvesting has become a promising solution to overcome this limitation as compared to batteries, as it presents a potentially infinite source of energy for powering wireless sensor nodes.

The rest of the paper is arranged as follows. Section II provides the fundamental and overview of the power requirement of the Wireless Sensor Network. Section III presents various energy sources available for powering low-power application devices followed by Section IV which briefly discusses on the Kinetic Energy. Next, Section V presents the fundamental knowledge's on Piezoelectricity. In Section VI, studies on the past research is presented. Section VII discusses on the power conditioning circuits for energy harvesting and lastly section VIII concludes the paper.

2. WIRELESS SENSOR NETWORK

2.1 Overview of power requirements

Wireless sensor network (WSN) can be defined as a group of devices that communicate to one another through multiple nodes wirelessly. The WSN is built of several nodes where each node is connected to one or more sensors. Those sensors nodes typically composed of several parts; radio transceiver, microcontroller and power sources [9]. A functional block diagram of a typical wireless sensor node is shown in Figure-1.

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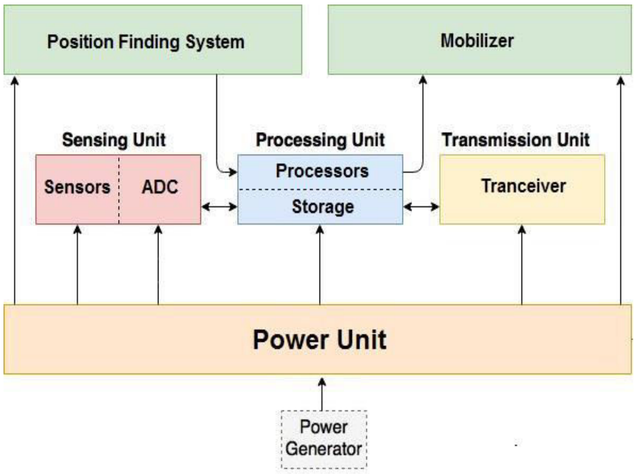

Figure-1. Wireless sensor nodes architecture [10].

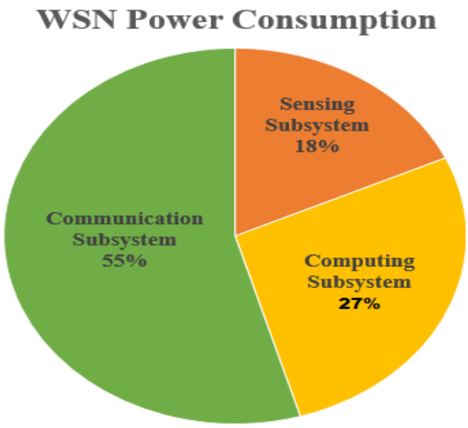

Figure-2. Wireless sensor nodes power consumption distribution [10].

WSN normally powered up by using batteries. The working period for the WSN is depend on the lifespan of the batteries which have limited power sources. The size of the battery limits the size of the node. This becomes a challenged in WSN nodes designing process as it needs to carefully consider the issues on the efficient energy use to prolong the life of the network as much as possible [11] - [13]. Renewable energy sources can overcome this limitation in enhancing the system reliability and there are many researchers already pursuing towards self-powering WSN using energy harvesting technology. According to [10], a sensor node architecture usually composing of four subsystems of sensing, processing, communications and power supply.

2.1.1 Sensing subsystem

A sensing subsystem links the node to the outside world. It consists of a group of sensors and an analog to digital converter (ADC) that responsible to capture and convert any physical phenomenon into digital form signal. Energy consumption can be reduced by using low rate power components and saving power during idle time.

2.1.2 Processing subsystem

A processing subsystem composed of a microcontroller unit, MCU and other supporting components that computing various operating modes for managing power consumption, including Active, Idle and Sleep modes. It controls all sensor node activities and responsible for implementation of communication protocols.

2.1.3 Communication subsystem

The communication subsystem comprised mainly of a short range radio transceiver (RF transceiver) with the amplifiers that communicate and transmit the processed sensor data with the neighboring nodes. Most radios that operating in Idle mode results in significantly high power consumption, almost equal to the power consumed in the Receive mode. In Figure 2, shows that this subsystem has the highest power consuming rate compared to the other subsystem. It is important to completely shut down the radio instead of putting it in the Idle mode when it is not receiving or transmitting for saving power.

2.1.4 Power supply subsystem

A power supply subsystem consists of batteries and DC-DC converter that supplies power to the node. The operation of batteries depends on battery dimensions and type of material used by the electrode. WSN current consumption is often exceed the rated capacity of the battery causing it to die faster as high current is drawn from it for a long time. In order to prolong the lifetime of a battery, the WSN needs to reduce the current consumption or always switch off if no operation required.

3. ENERGY SOURCES

3.1 Batteries

Emerging to this era, despite the rapid development of portable devices and smart technology, they are still limited by power. The energy storage system can be a battery or a super capacitors depends on the application. Unfortunately, the progresses in battery development are gradually increasing for almost a decade after the emergences of rechargeable lithium-ion battery system [14]. This improvement is slow compared with other areas of electronics [15] and this cannot satisfy all the demands for low volume, low weight, long lifespan and limited environmental impact.

Nowadays, supercapacitor has overcome the limitation of batteries and thin-film technology. The typical characteristics of battery and supercapacitor technologies are illustrated in Table-1. Compared to batteries, super capacitor technology is a best candidate for WSN system due to its advantages on the lifecycles and efficiency [16]. The use of conventional batteries for WSN system nowadays seems impractical anymore. Hence, an alternative type of energy source to conventional batteries must be considered. Scavenging energy from ubiquitous energy has becoming a promising solution for battery alternatives. This technology which known as energy

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harvesting (EH), captures the ambient energy of natural external sources and converts it.

Table-1. Characteristics of batteries and super capacitors.

Storage technology	Life cycle	DC-DC efficiency	Time scale
Flow Battery	10,000 cycles	75~80%	Minutes-Hours
Lithium-ion	3000 cycles	97%	Seconds-Minutes
Sodium-Sulfur (NaS)	2250 cycles	89%	Minutes-Hours
Supercapacitors	10^6~10^8 cycles	86~98%	Seconds-Minutes

3.2 Ambient energy sources

Into usable electrical energy, normally in alternating current (AC). These renewable sources exhibited in the form of thermal, wind, hydro and vibration energy help in providing unlimited energy for the lifespan of the electronic devices.

Energy harvesting can be classified on the basis of the form of energy the system used to scavenge the power. These renewable sources exhibited in the form of thermal, wind, hydro and vibration energy help in providing unlimited energy for the lifespan of the electronic devices. Having advantages on renewability, this technology also has their own limitations as its required specific environmental conditions. For instance, solar panels demand sunlight to operate; clearly it would not function during the night.

Table-2. Characteristics of typical energy harvester [17].

Energy sources	Characteristics	Efficiency	Harvested power
Light	Outdoor Indoor	10~25%	100 mW/cm^2 100 µW/cm^2
Thermal	Human Industrial	~0.1%	60 µW/cm^2 10 mW/cm^2
Vibration	~Hz-human ~kHz-machines	~3%	4 µW/cm^2 800 µW/cm^2
Radio frequency	GSM 900 MHz WiFi 2.4GHz	25~50%	0.1µW/cm^2 0.01µW /cm^2

4. KINETIC ENERGY

All moving things have kinetic energy which is possessed by an object due to its motion or movement. In general, motions and vibrations are the most ubiquitous ambient source available It exists in the surrounding all the time compared to solar, which only possible during the day. This form of mechanical energy can be used to generate electricity using energy harvesting method. According to [18], [19], there are three types of mechanisms used for translating this type of energy; piezoelectric, electrostatic and electromagnetic.

This paper only focuses on the piezoelectric energy harvesting and the basic components of power management system involved with this transducer. Referring to Figure-3, the number of publication of Scopus regarding piezoelectric technology is relatively twice the publication of other transducers. Compare with electrostatic and electromagnetic methods, scavenging energy with piezoelectric materials able to provide higher energy density and easy to be embedded into a system [20].

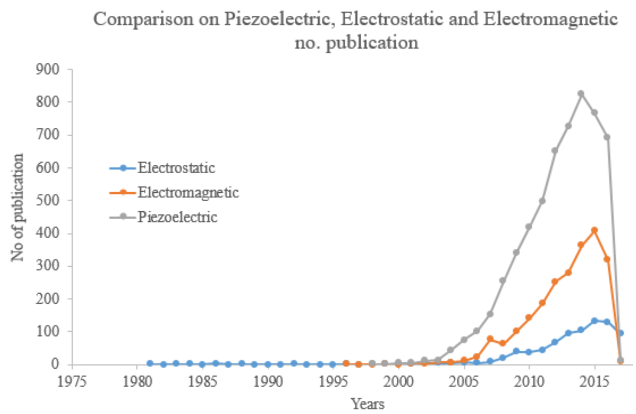

Figure-3. Number of publication in Scopus in comparing three mechanical transducers.

5. PIEZOELECTRIC ENERGY HARVESTING

5.1 Discovery of Piezoelectric

The piezo word is derived from the Greek "piezein", which means to squeeze or to press. In the more modern terminology, it also knows as the effect of intermingles electric and elastic phenomena. It was first discovered by Pierre and Jacques Curie in year 1880 [21]. They found that that in certain materials such as zincblende, turmalin, signet salt, topasz and quartz,

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mechanical stress was accompanied by macroscopic polarization and hence the production of electric surface charges. This effect was named as “piezoeffect” or mostly known as “direct effect”, electricity generated by mechanical pressure was called “piezoelectricity”, and materials that having this phenomenon called as “piezoelectric”.

The theory of electric voltage enclosed in piezoelectric material would cause mechanical pressure and elastic deformations was known beforehand by G. Lipmann in 1881 [22]. Curie's brothers proven this basis experimentally and named the phenomenon as “return piezoeffect” or familiar with the name of “converse effect” following Lippmann's work [21].

Paul Langevin, a French mathematician and physicist, applied the foundation of piezoelectric to develop an ultrasonic detector in detecting underwater objects; iceberg after the sinking of Titanic in 1912. Figure-4 shows the cross-sectional view of a quartz transducer designed by Paul Langevin. A quartz plates with a resonance frequency of 50kHz were built between steel overlays to acts as a projector and receiver of ultrasonic signals [23]. The device transmitted a high-frequency chirp signal into the water to measure the depth by timing the return echo. Successive development of their sonar transducer, piezoelectric application such as microphones, accelerometers, phones and many more were developed and commercialized later on.

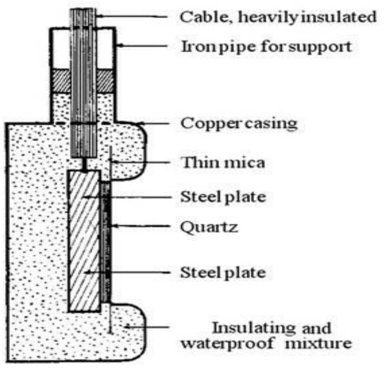

Figure-4. Cross-sectional view of a first ultrasonic detector by Paul Langevin [23].

5.2 Piezoelectric materials

The principle behind the kinetic energy harvesting is the mechanical deformation of structures of the energy harvesting devices. This displacement or deformation is converted into electrical energy by a piezoelectric material that exhibits the piezoelectric effect. These materials normally are the crystal that exists naturally on nature such as quartz, tourmaline and sodium potassium tartrate.

Other than the crystals mentioned before, an important group of piezoelectric materials is the piezoelectric ceramics, Lead ZirconateTitanate (PZT) for example. This type of crystal has been used a lot nowadays as it is considered as one of the transducer that shows a high efficiency in converting mechanical stress into electrical energy [24]. Each piezoelectric property differs depending upon the direction of forces and orientation of the polarization and electrodes as it has an anisotropic characteristic [25].

6. EVOLUTION OF PIEZOELETRIC ENERGY HARVESTER

Scavenging energy from surrounding has been used around the world for over decades now [26]. The research on this area has been conducted tremendously as world nowadays is moving toward Industry 4.0 where the uses of WSN are becoming a trends and these nodes will become useless if its run out of power; normally batteries. Numerous studies have been done around the world from 19th centuries up until now. The awareness on this area rapidly increases as illustrated by the line graphs in the Figure-5 with 5164 publications in 2016. This data analysis is collected from publication of this topic indicates that this research area is actively scrutinizing.

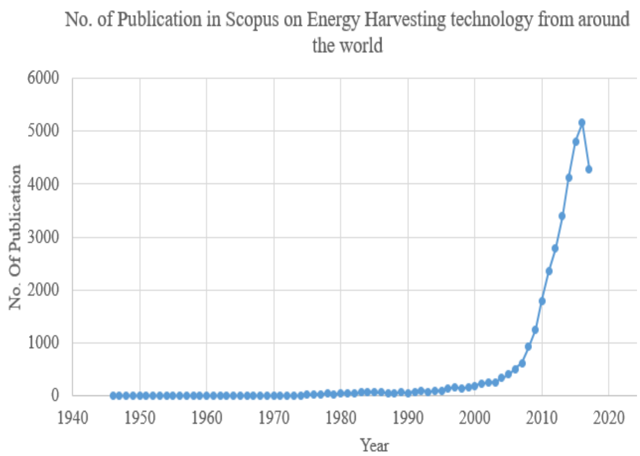

Figure-5. Number of publication in scopus on energy harvesting technology.

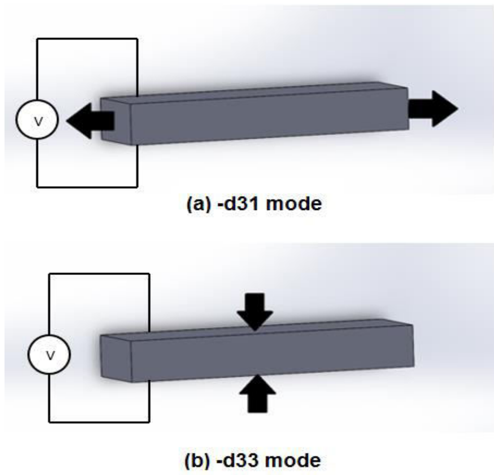

Figure-6. Mode operation for piezoelectric material (a)-d31 mode (b)-d33 mode [20], [39].

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The study on the piezoelectric was started in early 19th after Curie brothers, Pierre and Jacques Curie, [21] discovered the production of electrical surface charges by deforming the physical of the crystal in 1880. In 1920, the first generation application of natural crystals was megacycle quartz resonators where it is used as frequency stabilizers for vacuum-tube oscillators [27]. Based on this finding, studies on the piezoelectric materials and its characteristic have been done around that year. The first ever paper was published in 1925 on the uses and possibilities of piezoelectric oscillators [28] which had led to the development of microphone, accelerometers, ultrasonic transducers, and many other applications that keeps evolving until now.

In most cases, piezoelectric generates electricity under the influenced of mechanical pressure; impact or vibration, which deformed their physical characteristic [29]. Basically, the electrical power from the piezoelectric transducer can be obtained by reaping it in two modes of operation; impact or bending. The widely used piezoelectric modulus are d_{33} and d_{31} modes, which is also familiar with the name of piezoelectric charge constant. Whereas d_{15} is related to shear stress which it is impractical to use for scavenging energy [20]. Studies on the mechanical impact type have been performed by numerous methods; free-fall test [30]-[36], shoes implant [37], road implant [38]–[40], rotating gear [41] and etc. While for mechanical vibration technique, ordinarily piezoelectric cantilever beam is attached to the exciter with one free end that vibrates accordingly to the vibration source [42].

In 1996, [43] studies the energy resulted from the human body motion. They did mention that the power generates by the body heat, breath or motion theoretically capable to power up the computer devices without the use of any electrical outlet. From the calculated results; with the human weight of 68kg and 2steps/sec with the displacement of heel impact of 5cm, the estimate output power that can be generated from walking can reach up to 67 Watts. This technique may be achieved by collecting the impact force exerted by the human strike during walking using shoe-embedded piezoelectric energy harvester. Two years later, [37] had implemented this technique by using three strategies where different device; PZT (Thunder), PVDF stave and rotary magnetic generator is used. These transducers were placed neatly in the insole of the sneakers at the corresponding locations. The outcome of this study found that the magnetic rotary generator is not practical to use for extracting the power from the pressure of the heel to spin the flywheel using the electromagnetic by walking. On the other hands, the performances of both Thunder and PVDF stave had given positive results where it able to generate nearly 80mW and 20mW for the peak power with 150V and 60V for the peak voltage respectively.

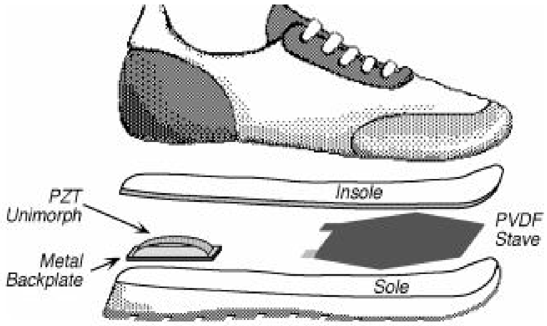

Figure-7. Exploded views on integration of piezo shoe [37].

The motivation on experimenting direct impact free-fall test according to [32] is because of normal vibration frequency in nature is below 100Hz and cantilever beam's resonant frequency normally higher than 100Hz. To overcome this limitation, numerous studies on the impact testing using free-fall or drop test have been done in [30] - [36], [44]. This test is performed to determine the energy absorbed or the energy required to fracture a unit under test. A free-falling object is called like so as it is falling upon only by the force of gravity that does not encounter air resistance and accelerates downwards with a rate of 9.8m/s/s. When an object with mass, *m* is drop vertically from point A to point B with *h* height, the kinetic energy of the mass is:

$$K = \left(\frac{1}{2}\right) mv^2 \quad (1)$$

and the gravitational potential energy of the mass is,

$$U = mgh \quad (2)$$

The expression (1) and (2) yields to

$$\left(\frac{1}{2}\right) mv^2 = mgh \quad (3)$$

$$v = \sqrt{2gh} \quad (4)$$

The basic physics of an impact is further discussed in [30] approximated to the actual phenomenon. The initial reported work that discussed on this type of approach is [45], applying the concepts of the Newton's law physics discussed before with piezoelectric transducer by dropping a 5.5-gram rigid steel ball from the height of 20mm vertically towards unimorph piezoelectric transducer with specification of 19mm x 0.25mm piezoelectric ceramic with a brass disc of 27mm x 0.25mm. The resulted electrical output is measured and it has the efficiency of 9.4% with the 10kΩ as the resistive load. This is very inefficiency as most of the energy produced from the steel ball being returned back in the form of kinetic energy when it bounces on the plate after the initial impact. [45] also introduced the uses of equivalent circuit model in order to estimate the resulted

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energy produced by making amendment on the variables in the systems.

Another drop weighted impact technique has been implemented by [31], but more focusing on the effect of dimensional size of uncapped piezoelectric ceramic on the output characteristics. Hard and soft kinds ceramics body each coded with QB and KA respectively were used in this study. The characteristics for both types at 1kHz have been tabulated in Table 3 and 6 samples of piezoelectric disc shapes is used with different dimensions and capacitance. Through a steel guide, 16.5 g steel ball was dropped with displacement of 5 to 50mm. The generated output voltage for soft type body is nearly doubled the hard type voltage. With same direct impact forces, altering the piezoelectric characteristic; thickness, dimension, and size, resulted in producing higher output voltage with increasing of material density.

[46] doing progressive studies on the metal end-cap Cymbal transducer with the same concept used by [31]. It concludes that, the generated output voltage produced by the Cymbal transducer is much higher than the uncapped piezoelectric disk in [31] where with the same piezoelectric parameters; the uncapped one produced nearly 10V compared to 160V to 220V when capped with a geometric Cymbal.

Based on [32], a cube-shaped mechanical impact piezoelectric energy harvester was developed in 2010. Six-sided wall made by the piezoelectric plate is harvested using free moving ball that hit the cube faces as the structure vibrates. This concept is the prior to the theory of free-fall experiments; single collision and two dimensional experiments; multiple collision. From a particular height, a 2mm steel ball was dropped vertically on the piezoelectric plate that mounted along two edges. The bouncing ball concept was extended to a two-axis energy harvester for a multiple-collision test on the piezoelectric transducer with a four-sided piezoelectric walls. The average output produced were in millivolts mV ranges for both experiments but had enough power to turn on micro powered devices. However, when the real product is tested whether in 1:1 or 1:10 ratios, the output power generated is a decade lower from the single and multiple collisions tests. The same concepts were used in [44], [47] later on. Triaxial ball-impact piezoelectric energy harvester in Figure-8 attached to human heel able to produce 16mW on a 1-kΩ resistive load.

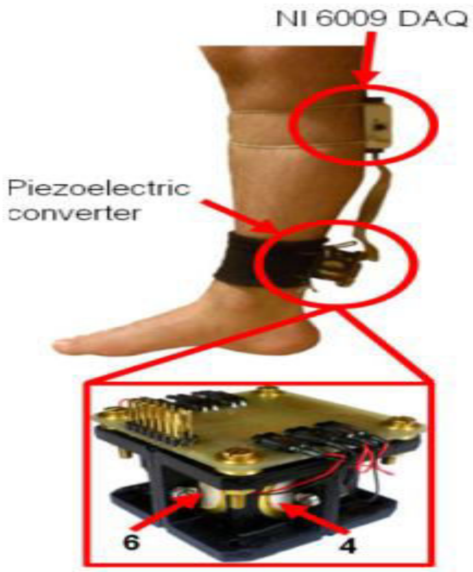

Figure-8. Conceptual illustration of missile-impact energy harvester [44].

[34], [48] present an equivalent circuit model for an impact-based piezoelectric energy harvester. According to [49], [50], piezoelectric harvester is generally represented by the sub-circuit of mechanical; L_m, C_k, R_{d1} and electrical; R_{d2}, C_p in Figure 10 that was first introduced by [51]. The extracted power from the piezoelectric energy harvester is not sufficient enough to directly connected to the loads. To overcome this limitation, a conversion circuit; rectifier is proposed to be interfaced between the harvester and the loads. The schematic in Figure-9 composed of a cantilever beam with each end mounted along a proof mass and a free moving ball that seats in an aluminium housing at other end. This architecture used frequency-up converting topology that significantly increases the generated frequency signals impacted from low-frequency vibrations with higher efficiency.

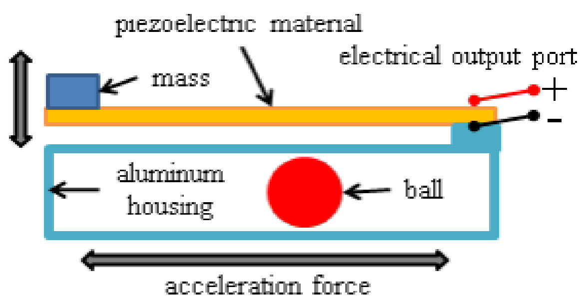

Figure-9. Frequency-up converting piezoelectric energy harvester [48].

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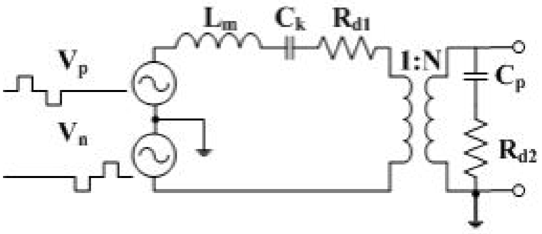

Figure-10. Equivalent circuit model of targeted energy harvester [48].

The study by [35] introduced an analytical model of a cantilever beam with two piezoelectric patches that cover both surfaces of the beam completely; bimorph. The transducer is made of porous piezoelectric material, a composition of air and piezoelectric material which claimed to offers a good control on capacitance [52], [53]. A single-degree-of-freedom cantilever beam is modelled using a non-linear spring derived from a *Hertian Contact Law*. This beam impacted by a spherical ball that is characterized with respect to the geometrical properties of the beam. Studies found that the generated power produced by high porosity percentage beam is lower compared to the one with higher piezoelectric material. It is also reported that, for off-resonance base excitation frequency, impact-based energy harvester has higher efficiency in generating more power.

[36] conducted a research on weight-drop experiment on piezoelectric discs on two different types of setting base; a flat iron base and a setting base with hole. The diameter of the hole is designed to support only the brass of the discs, leaves the piezo materials free from being supported by the base. The purpose of this study is to evaluate the response of changing the parameters of the device; stiffness, velocity and mass, on the generated output power. The steel balls with4-g and 8-g mass are dropped from different height tested by using different setting base. The results of using setting base with hole able to produce additional 200mW output power which increased the efficiency of the device as the stiffness of the device has been reduced.

Energy extracted from human can also be used as piezoelectric energy sources such as breathing and heart rate [54], limb motion or shaking [44], [47] and foot pounding [38]-[40]. In 2009, [55] developed one dimensional collision energy harvester based on the impact of a missile on piezoelectric beams. From Figure 11, the proposed harvester basically is a frame of two piezoelectric beams at each opposite. It was tested by strongly shaking the prototype attached to the hand of a person with estimated frequency of 10Hz at the amplitude of 10cm. The missile in the housing slides through the guiding channel impacted the beams accordingly able to generate 600µW at the maximum.

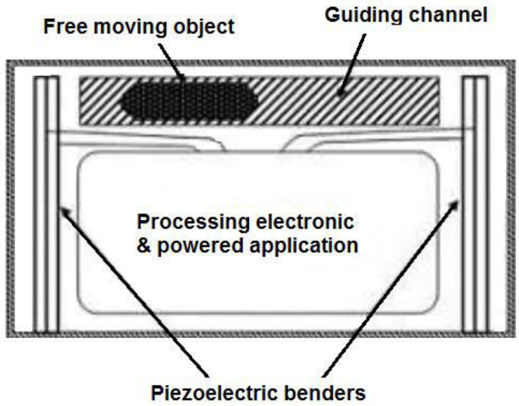

Figure-11. Conceptual illustration of missile-impact energy harvester [55].

[38]- [40] developed a road-implant energy harvester by collecting energy from human foot strike on the pavement. A prototype of bus stand lamp with piezoelectric energy harvester placed on the floor was developed by [38]. A total of 81 piezoelectric discs was connected in parallel to enhance the generated output current. A weight drop analysis was done to simulate the human strike based on weight and displacement. From the finding, higher voltage was produced when greater force applied to it and the highest amount of voltage and current produced were 35.9V and 0.389A respectively, which depends on the number of piezoelectric pounded by the weight of 3.75kg at 8cm height.

[41] proposed a piezoelectric MEMS scavenger system that harvests energy from a rotating gear driven by a motor gearbox. A silicon tip was fabricated at the backside of the cantilevers free end with the height of 240µm while the other one fixed to the wall as in Figure 12. The tip was designed to fit the spaces between the 16 gear teeth. When the motor starts rotating the gear, this tip will collide with those spaces that eventually drive the cantilever beam into motion. The generated power is observed by varying the depth of the tip into the gearbox from 20-100µm. A highest output power and voltage was measured at 100µm; 1.26µW and 9.01V respectively. Reported that as the depth of the tip increased from 60µm to 100µm, the output power produced increased more than 10 times.

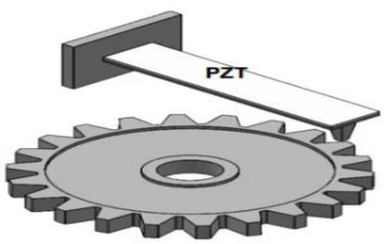

Figure-12. Schematic diagram of rotating gear energy harvester concept [41].

Another principle of piezoelectric energy harvester is bending or vibration technique which

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normally used a cantilever beam. This type of vibration energy harvesting technique used a very simple structure of piezoelectric transducer that can produce a large deformation under vibration. Normally, a plate-type piezoelectric transducer is anchored to a fixed end; shaker with the other free end that vibrate accordingly to the frequency of the vibration source. Two types of cantilever design that commonly utilized in the studies of piezoelectric energy harvesting; unimorph and bimorph. Unimorph as the named implied, it has only one active piezoelectric layer while for bimorph structures, it is designed by bonding two thin layers of piezoelectric material to a metallic electrode layers.

[56] theoretically and experimentally designed a wireless self-powered strains sensor using a polyvinylidene fluoride (PVDF) films from a simple beam bending technique. A (28x23x40) µm PVDF beam is used to generate sufficient energy to charge a capacitor with a predetermined value of 1.1V. A switch was used to separate the connection between the capacitor with the transmitter. Accumulate energy from PVDF that stored in the capacitor will turn on the switch when reached the agreed value before discharged and power a transmitter that could send a signal in 2m transmission range.

[57] investigated on the array energy harvester produced from rail vibration using three plates piezoelectric disk diaphragm connected in parallel. The voltage produced is maintained and current is increased for parallel connection [38]. The maximum output power for each piezoelectric plate is 6.5mW, 8.5mW and 7.5mW at 150Hz resonant frequency. With a pre-stress value of 0.8N, maximal output powers of 21.4mW and 17V output voltage was measured at the resistive load of 11kΩ. Noticed that, the maximum output power of parallel array produced is roughly the summation of the total power of those three plates. The exploratory results show that the array energy harvester can attain remarkably cumulative energy compared with the use of a single plate.

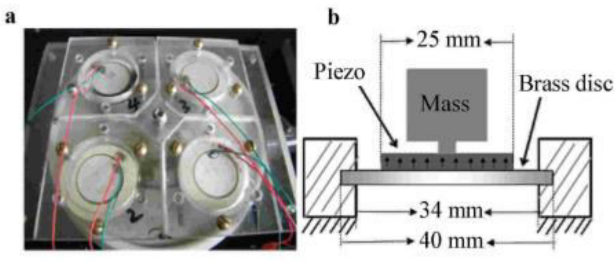

Figure-13. The structure schematic of the array harvester: (a) The top view of the array structure of multiple circular diaphragm piezoelectric harvesters; (b) The detail of single circular diaphragm piezoelectric harvester [57].

Combination of bending and impact-mode power harvester was reported by [58]. Both d_{31} and d_{33} modes of PDVF were utilized in the proposed device as shown in Figure-14. The combination of this two modes was realized when the top PDVF cantilever that excited by using an external vibrating source eventually hit the bottom PDVF membrane by using the proof mass. The results obtained was compared with [59], [60] which also performed experiment on d_{31} and d_{33} respectively. It shows that this type of harvester possesses the advantage of low resonant frequency of d_{31} and high generated voltage of d_{33} where it enables the device to generate high output voltage at low frequency.

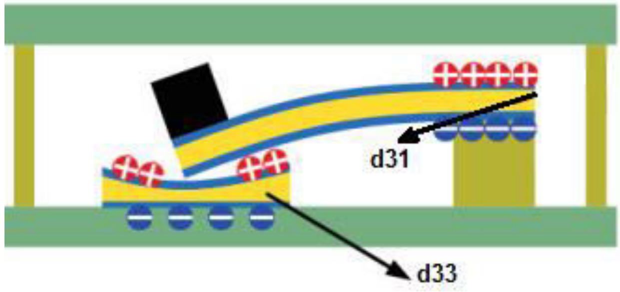

Figure-14. Illustration of d_{31} and d_{33} operating modes of the devices [58].

7. POWER CONDITIONING CIRCUIT

Energy density exerted by the piezoelectric energy harvester normally can be hundreds of microwatts (µW). How- ever, the power requirements for an electronic device available in market are in the range of milliwatts (mW) [61]. Not to mention, piezoelectricity needs to be rectified first as the resulted energy normally in alternating signals. Thus, the employment of power conditioning circuit for kinetic energy harvesting application is needed to provide efficient and optimal rectification and amplification. Furthermore, electronic devices come with a specific charging rate, thus, it is essential to provide a smooth and regulated output voltage to the electronic devices [62].

As mentioned before, in order to utilize the generated power from piezoelectric energy harvester, alternating output produced need to be converted first into a direct one. The reason is because, most electronic devices requires a regulated dc input voltage that can be achieved by using a rectifier. There are many types of rectifiers topology, but the most easiest to use is by using diode [63], [64].

Basically, there are three types of rectifiers that will be discussed in this paper; full-wave bridge rectifier, and three types of voltage doubler rectifier circuit.

The simplest configuration to rectify AC to DC is half-wave rectifier as it consists only one diode. However, as illustrated by the waveform in Figure-15, the conduction of current only able to flow for the top half of a complete cycle resulted in unstable DC output signal.

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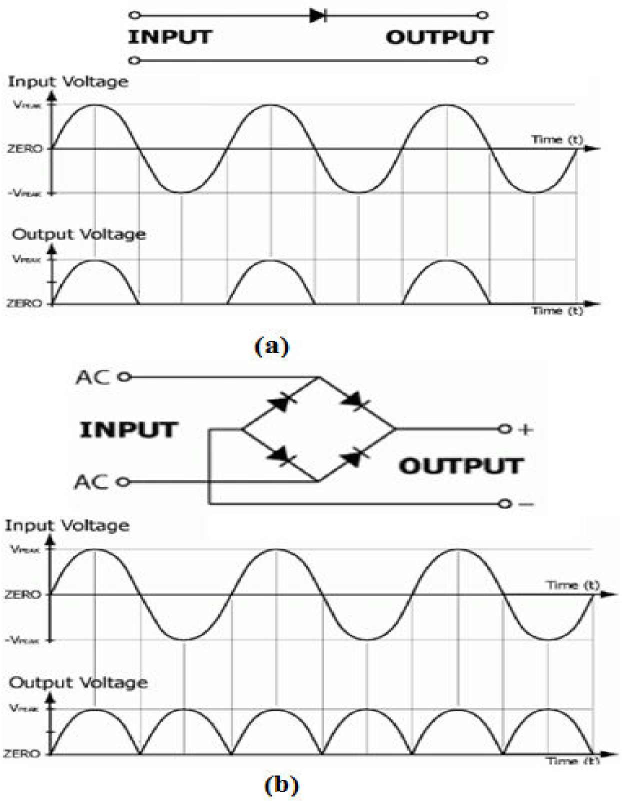

Figure-15. Rectifier configuration (a) Half-wave rectifier, (b) Full-wave bridge rectifier [65].

In order to acquire full-wave rectification of piezoelectric energy harvester, it is essential to use full-wave bridge rectifier. A full-wave rectifier allows current to flow during both the positive and negative half cycles and the output frequency is twice the input frequency signal [65]. According to [66], this passive rectifier is the most common circuit used in energy harvesting. In term of efficiency, this kind of topology is considered low compared to special rectifier configuration; voltage doubler [67], [68]. The main sources of power losses are normally from the leakage currents and the forward voltage drops during reverse biased.

Voltage doubler or voltage multiplier is a special type of diode rectifier circuit that have higher potential to generate an output voltage twice the applied input voltage. This type of rectifier is very useful to be applied where it is necessary to have a very high DC voltage generated from a relatively low AC supply. The difference between this type of rectifier with the switching converter is that, switching converter is composed of one or more inductors whereas, voltage doubler not using any inductors. This type of rectifier was first introduced by Greinacher in 1914.

The concept of voltage doubler is almost similar to the working principle of the standard full-wave bridge rectifier. The only different are, instead of just having rectifier diode, it is also comprised with additional capacitors that potentially producing high DC voltage from a lower AC source. This type of rectifier can be categorized in three different configurations; half-wave series multiplier, half-wave parallel multiplier and full-wave series multiplier. According to [69], it was concluded that the full-wave series multiplier [70], [71] was the best for integrated circuits in term of efficiency and uniform stress. The reason is because it has significant parasitic capacitance for its capacitors and switching devices.

Piezoelectric devices need to operate within its resonant frequency in order to obtain optimum energy transfer from piezoelectric to the load. [72] discussed on the performance of various type of rectifying circuit by using different types of diodes consisting of Zener diode, silicon diode (1N4001), Schottky diode and Metal-Oxide Semiconductor Field-Effect Transistor (MOSFET). These diodes are used to construct a full-bridge wave rectifier and the best diodes was selected to develop a voltage multiplier architecture. Schottky diode is chosen in terms of higher efficiency and output voltage with 99% and 6.54V respectively.

A discussion on the performance on the full-bridge rectifier and voltage doubler rectifier can be reviewed in [73]. The proposed circuit were consisting of voltage doubler rectifier, a step-down switching converter and an analog controller after considering the facts that full-bridge rectifier needs external sensing feedback and needs a complex electronic interface. The number of full-bridge used is twice the requirements of voltage doubler which is the major reason why it has greater power dissipation. The drawback of the propose circuit is that it is not efficient for power less than 0.5mW and it requires a higher voltage level of filter capacitor which is much more expensive than full-bridge rectifier filter capacitor.

[74] presented three types of voltage multiplier circuit used to convert sources from AC to a stable DC voltage sources that can generate two times the output magnitude of rain energy harvester. The voltage multiplier is categorized into standard voltage doubler, Cockcroft-Walton cascade voltage doubler (CWCVD) and Karthaus-Fischer cascade voltage doubler (KFCVD). By comparing the simulation results of these three converter circuits with single piezoelectric connection, KFCVD provided the highest recorded voltage of 11.025V, current of 1.1A and generated power f 12.16W which used as the reference value. Another type of configuration of using two series three parallels (2S3P) piezoelectric is compared to determine the most suitable circuit converter for the harvester. With 2S3P circuit, voltage doubler followed by KFCVD provided the highest output current of almost 2.36A, twice the resulted reference value.

In order to drive the load successfully, the weak harvested energy should be accumulated in the energy storage element for some period of time as WSN requires higher peak power than a piezoelectric micropower generator can produce. According to [75], the most frequently used energy storage devices in energy harvesting system nowadays are Lithium-ion (Li-on) Batteries, supercapacitors and some corresponding Integrated Circuits (IC).

Comparing the credibility of the Li-on batteries with the supercapacitors in terms of energy density and

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cycling stability, both have their pros and cons. Generally, the energy density for Li-on batteries (200Wh/kg) is higher than the energy density of supercapacitor (8Wh/kg). However, in terms of cycling stability, supercapacitor performance of 500,000 times longer than the Li-on batteries of 500 times with the multiplication of a thousand [75], [76].

[77], [78] proposed a power storage device that using supercapacitors to replace the uses of batteries. The supercapacitors are chosen because it enables an efficient use for short power output [79]. They studied on the rechargeable batteries, capacitors and the components that influence the charging and discharging process. According to [78], leakage resistance of the energy storage device was found as one of the factors that affect the process. To optimize the system, this supercapacitor should be disconnected from the load during the charging process to prevent the energy leakage to the load. It supposed to be connected to the load only if the accumulated energy is large enough to drive it.

A new promising energy storage system known as battery supercapacitor hybrids (BSHs); a combination of supercapacitor with batteries as the secondary storage has been done [80]. This system is constructed by using high-capacity battery type electrode and a high-rate capacitive electrode. BSHs structure consists of supercapacitors electrode which is the key for the energy storage mechanism and must be distinguished from a battery electrode. This device claims to surpass the energy density of conventional supercapacitor and could overcome the power density limitation of batteries due to the arguments with each other.

8. CONCLUSIONS

With the advances in semiconductor technology pursuing forth industrial revolution, batteries still remain as the main power resources to supply energy remotely. However, battery has a drawback as it needs to be replaced or recharged periodically. One possibility to overcome this power limitation is by scavenging energy from the environmental sources. Piezoelectric energy harvesting has become an active research area lately on investigating a number of techniques to capture energy from the surrounding and power the low-power electronic devices such as Wireless Sensor Network. Numerous studies focusing on improving the efficiency of piezoelectric power harvesting devices through physical and geometrical configuration, as well as adaptive circuitry of power conditioning circuit have been presented in this paper. Various techniques of piezoelectric energy harvesting from impact and vibration has been reviewed in this paper based on direct and converse piezoelectric effect. It is found that although cantilever beams is highly responsive to small vibrations, but the energy produced is not as efficient as the impact-based techniques. The application of power management circuit of energy harvesting system can help to increase the extracted output power by using supercapacitor as the energy storage.

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