An Investigation of Energy Harvesting System for WSN Nodes

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Abstract

WSN nodes are termed wirelessly connected sensor networks which are applied in the tough physical conditions of the environment for assembly and arrangement of data gathered from this open environment. WSN nodes are placed in different and worst atmospheres for the collection of data related to minerals, temperature/heat, sound, wind, water, sunlight, and so on. But since the lifetime of these WSN nodes directly depends on their power supply that is a battery but in these difficult environmental conditions it is a great challenge to replace/recharge their battery manually, so there comes the need for energy harvesting systems which uses the natural energy sources available in an open environment. In this paper, such energy harvesting techniques are discussed which uses natural energy sources openly available in the environment and the WSN nodes with these energy harvesting models are known as Self powering WSN nodes. The main structure of these self-powering WSN nodes is divided into two parts first is the sensor part and the other part is the energy harvester. These energy harvesters may use one energy source or these might be hybrid which means it uses more than one energy source. In the end of the paper some important conclusions are made based on the comparison on energy harvesting models.

Keywords: - *WSN Node, Energy Harvesting System, Natural Energy Sources*

INTRODUCTION

WSN node is generally a small-sized device that is operated using a battery and due to its small size, the battery capacity is also very low thus, efficient hardware implementations are required either at the operational level or network level. But applying these hardware changes also consumes energy that cannot be fulfilled by the battery as it is beyond the battery's capacity. Thus, the need for self-powered WSN nodes arrises which have an energy harvesting system inside it. This energy harvesting system harvests energy from the open environment on which they are applied. This technique also replaces the need for replacing or changing battery manually which increases the eternal life of the WSN node.

Energy can be harvested using different sources of energy for example solar energy, RF (Radiofrequency) energy, thermal energy, wind energy, acoustic energy, water energy, and so on. But some of these energy sources are not fully dependable as solar energy can only be harvested in the day time, RF energy can only be harvested in areas where tv tower or radio towers are available and for thermal energy harvesting through TEG (Thermal Electric Generator) a great temperature difference is required which might not be available in some areas. Since the lifetime of WSN nodes very much depends on their battery capacity which is the prime factor for the lifetime of WSN node and another factor on which the lifetime of WSN node depends is the applied load across the battery. So the lifetime of the WSN node can be calculated by the formula given below:

$$Lifetime = \frac{Battery\ Capacity(mAhr)}{Current\ Consumption\ on\ load(mA)} \qquad (1)$$

Another important factor on which its lifetime depends is its duty cycle which is the portion of time for which it is in an active state. From [1] it is seen that the WSN node became active for 500ms for a time frame of 5 minutes and in this period it performs all of its operations. Considering [1], the required current usage for 24hrs came out to be 8.14mAh.

$$E_{24\,hr} = 8.14mAh \times 3600\frac{s}{hr} = 105.5J \qquad (2)$$

From equation (2)(taken from [1]), it is seen that for a 3.6V Li-ion battery, the energy consumption of the node for 24hrs is 105.5J. So this comes out to be the target value for any energy harvesting technique to fulfill this much energy need for a WSN node to function for 24hrs.

In this paper, considering the above challenges, energy consumption, and some standard parameters like hardware design, efficient architecture, and energy consumption different energy harvesting techniques are discussed to uninterruptedly power the WSN nodes as for increasing WSN lifetime one must understand the energy harvesting patterns.

TYPES OF ENERGY HARVESTING SYSTEMS

Several different energy harvesting systems are available for extracting energy from natural sources of energy which constitutes solar energy, wind energy, acoustic energy, RF energy, thermal energy, water energy, etc. In WSN nodes energy is stored in a battery in electrical form and this energy is used in performing its functionalities. The different energy harvesting techniques from which energy is harvested are briefly explained and compared with each other in the next sections. After explaining these energy harvesting systems some important observations are made which will help in finding an optimized solution for powering the WSN nodes to increase their lifetime.

SOLAR ENERGY HARVESTING SYSTEM

The energy that can be extracted from the solar light that is sunlight is called solar energy and this solar energy is harvested by using PV(photovoltaic) cells. The basic principle behind the PV cell is a photovoltaic effect which states that when PV material is exposed to sunlight voltage and current is generated which can be stored in a battery in electrical form. From sunlight only 7% visible rays are emitted which can be used in the conversion of energy from light energy to storable electrical energy and the energy density of this visible radiation spectrum, which can be transformed into storable electrical energy is about 1120W/m^2.

The material of the solar cell is a prime factor in the extraction of energy as the current generated very much depends on the type of material. Materials like indium, gallium, and nitrogen can be used to convert the spectrum of visible light into storable electrical energy. Some important comparison on the material of the photovoltaic cell is shown in Table 1, this comparison is done based on key parameters such as Maximum module efficiency percentage, research cell percentage, the area required per kW in m^2.

Table 1: Types of PV cell material

Imp. Parameters	Max Module Efficiency (%)	Research cell (%)	Area Required per kW (m^2)
Monocrystalline	21	25	9-8
Polycrystalline	16	20.4	7
Amorphous	8	13.4	16
CdTe	11	18.7	12
CIS/CIGS	12	20.4	11

From Table 1, Taken from [1] shows tshat from monocrystalline, polycrystalline, amorphous, CdTe, and CIS/CIGS Monocrystalline has the Maximum Module Efficiency. The VOC that is the open-circuit voltage can be calculated by the formula given in equation (3) which is also the voltage across the photovoltaic cell which directly depends on I_n that is solar intensity as mentioned below:

$$\text{Voc} = \frac{nKT}{q}\ln\left(\frac{Idn \times Isc}{Io}\right) \qquad (3)$$

In the equation (3), 'n' is the constant whose value for Ge is 1 and for Si, it is 2, I_{sc} is the short circuit current, I_n is the solar intensity, K represents the Boltzmann constant whose value is 1.38×10^{-23} m^2 kg s^{-2} K^{-1}, 'Q' represents the electronic charge that is 1.6×10^{-19} C and 'T' represents the temperature in kelvin.

In [2], the authors developed a solar power harvesting model that stores the harvested energy in the battery and it also maintains the record of the energy stored in a battery. The authors analyzed the model using Heliomote. 80%-84% of efficiency was obtained.

In [3], the author presented a solar energy harvesting model for Wireless sensor nodes. The node gas detection sensor was applied and analyzed along with the Xbee and CC2420 and all processing was done using the ARM cortex. From the model, it has been analyzed that by varying sleep and wakeup approaches the lifetime of the sensor node can be increased. The authors of [4] designed a model that uses a 34W fluorescent lamp as a source. The model was made in such a way that the energy was stored in the ultracapacitors. They showed that a lot of energy is wasted in the OFF state in the results.

The authors of [5] showed a hybrid energy harvesting system that uses both the battery and supercapacitor in combinations. In this, the supercapacitor charges the battery when the battery level gets down to a specific threshold.

THERMAL ENERGY HARVESTING SYSTEM

The thermal energy can be harvested using the TEG that is a thermal electric generator that works on the principle of Seebeck effect which states that the difference in temperature between two thermoelectric materials generates a voltage. The formula for calculating the total power generated using the TEG is shown in equation (4).

$$P = Q \times A \qquad (4)$$

In equation (4), 'P' represents the total generated power, 'Q' represents the radiation flux and 'A' is the area in m^2.

$$\eta_{TEG} = \frac{\Delta T}{T_H} \times \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_C}{T_H}} \qquad (5)$$

$$Z = \frac{\sigma S^2}{k} \qquad (6)$$

In equations (5) and (6), ‘Z’ is the figure of merit, 'ΔT' is the temperature difference between the hot and cold side, 'S' is the Seebeck coefficient, ‘k’ is the thermal conductivity, ‘σ’ is the electrical conductivity, ‘T’ is 27k and ‘'η'’ is the efficiency. To increase the converter efficiency blend of material like Bi_2Te_3 and PbTe etc are used.

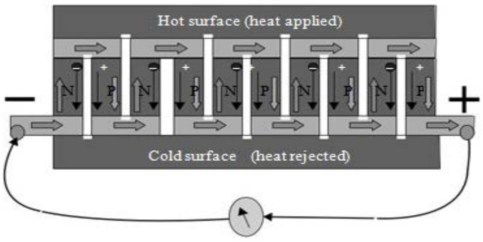

Figure 1: TEG diagram

The Fig.1 is taken from [1], which shows the TEG diagram. In [6] the author's used telluride superlattice thermocouple in the model with efficiency of 2% and at a temperature difference of 20°C. The authors in [7] designed a model that uses a variation in temperature using a heat storage unit that is HSU. It was used for aircraft health monitoring and using HSU 13J of energy is generated. The authors in [8] used about 1000 couples to activate pulse oximeter. The device was small size of the size of a small watch. In [9] the authors used a boost converter to control micropower. They used a DC-DC convertor to transform 35mV to a higher voltage level optimized for the perfect use.

WIND ENERGY HARVESTING SYSTEM

Wind energy is a type of energy source which is only available in open areas as it can only be harvested using a windmill which requires a large area to plant. The basic factor behind this energy harvesting is wind speed. Wind speed is the rate of flow of air in a particular space or area above the ground level. Wind speed very much depends on different atmospheric factors such as temperature, pressure, etc.

$$\text{Wind Power} = F(v^3) \quad \text{or} \quad W = 0.5\times pAv^3 \qquad (7)$$

In equation (7), 'F' is force, 'p' is the atmospheric pressure, 'A' is the cross-section area of the turbine, 'v' is the velocity of the wind. From equation (7) it can be seen that velocity is the prime factor in the calculation of wind power.

$$W = (0.652v^3)\frac{W}{m^2} \qquad (8)$$

In equation (8), it ‘W’ is wind power density in W/m2 and this equation shows the turbine's area is also an important parameter in modeling a wind energy harvesting system. The equation shows that the turbine's area is also an important parameter in modeling a wind energy harvesting system. Table 2 taken from [1], shows the comparison between different turbines based on key parameters.

The authors in [10] developed an airflow energy harvester equipped wireless network. They used 3 microturbines for a network of 24sensor nodes for 1 year. They found out that it recovers the power loss made due to inactivity that is 0.1V in 33 minutes at a wind speed of 7m/s. In the model of [11], they used 4 blades and a rotor diameter of 10cm to achieve an output of 8mW of power at power density equal to 0.1 mW/cm2. Whereas in [12] they used 12 blades and a rotor diameter of 10.2cm to achieve power equal to 5mW at a wind speed of 4.4m/s but in [13] the authors used 3 blades and 4.2 cm rotor tip to achieve 130mW of power at a wind speed of 11.8m/s which is great. Table 2. Taken from [1] (same chapter) shows the comparison of the work done on different models with key parameters.

Table 2: Comparison between Turbines

Turbine Characteristics	*Turbine Radius (cm)*	*Maximum Power (mW)*	*Wind Speed (m/s)*	*Efficiency (%)*
3-Blade (KMAC 2012)	16	200	5.4	2.5
Piezoelectric windmill (ISHM 2012)	6.5	5	4.5	0.7
Vertical-axis wind turbine (VAWT)six blades (Rice et al. 2010)	6	45	5	0.5
Wind turbine (Hankuk 2012)	3	24	4.5	14.9
Wind turbine with maximum power point tracking (MPPT) (Hankuk 2012)	3	7.86	3.62	9.4
Horizontal-axis wind turbine (HAWT) (Tan and Panda 2011)	7.5	243	5	16.3
VAWT (Tan and Panda 2011)	19	83	5	8.2

ENERGY HARVESTING USING LIQUID FLOW

A liquid is a substance that has a definite volume that can move freely in any direction and have properties similar to oil or water. Energy harvesting using liquid flow can be done using a dynamo over a mechanical structure or by applying pressure over a piezoelectric material. The basic principle behind it is that voltage is generated across a conductor when it moves in a magnetic field and when the load is applied across the conductor current also starts flowing.

$$P_o = \frac{pZ}{A} \times \Phi N \times \frac{2\pi A}{pz\Phi} \times \frac{Im}{r} \times \frac{d(2(P_S - P)/\rho)}{dt} \qquad (9)$$

$$P_o = 2\pi N \times \frac{Im}{r} \times \frac{d(\,2(Ps - P)/\rho\,)}{dt}$$

In equation (9), 'P_o' is the output power, Ps is the stagnation pressure, P is the static pressure, ρ is the density of water, I is the current in the conductor, A is the count of parallel paths, Z is the count of conductors, N is the speed of the rotating part. are the rotor diameter d and l are the machine's length and breadth respectively in meters, Φ is the flux and Im is the moment of inertia. This equation (9) shows that the output power very much depends on the dynamic and static pressure and density of the fluid.

The authors of [14] showed that the kinetic energy from the liquid can be generated using vortex shedding and in the result, about 0.18 μW of power was generated with an efficiency of 4.4% at a liquid flow speed of 6.8m/s. The authors of [15] use some water droplets of diameter equal to 4mm and used their kinetic energy created by wind flow at 0.5m/s which is then converted into electrical energy. In this, they used the basic principle of electromagnetic induction for energy harvesting. In [16] the authors used domestic pipelines for energy harvesting and took some observations at a liquid flow speed of 20L/min and they achieved a power output of about 720mW whereas at a liquid flow speed of 3L/min they achieved a power output of about 2mW. In the model of [17] the authors used an energy harvesting system that uses piezoelectric material. In this liquid vibrations were used for energy harvesting and at a liquid flow speed of 20L/min a power output of 20mW was achieved.

ACOUSTIC ENERGY HARVESTING

Acoustic energy is a type of energy which can be generated using a different type of materials like solid, liquid, some gases, sound, ultrasound, etc. It is generated using vibrations inside the particles of the matter. As shown in figure 1. current can be generated by applying pressure on the pressure sensor or on any transducer and using the Thevenin's equivalent circuit this current can be calculated.

Volage also can be generated on the load resistance applied across the piezoelectric material by applying a force or pressure on it.

$$P = 0.5 \times |I^2| \times R \qquad (10)$$

In equation (10), 'P' is the power obtained across the load, 'I' is the load current and 'R' is the load resistance.

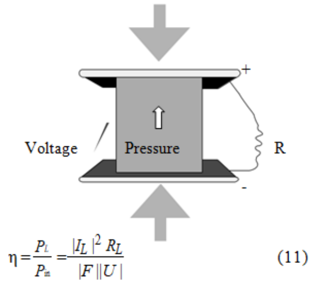

Figure 2 Electrical energy generation using pressure

$$\eta = \frac{P_L}{P_{in}} = \frac{|I_L|^2 R_L}{|F||U|} \qquad (11)$$

Fig.2. is taken from [1], which shows Electrical energy generation using pressure. In equation (11), power efficiency (η) is calculated where 'F' is the force applied, 'U' is the displacement 'I_L' and 'R_L' are the load current and resistance respectively.

The authors of [18] developed an energy harvesting model using acoustic energy as an energy source of aeroacoustic. In this, at a sound pressure level (SPL) of about 149dB, a power output of 0.34 μW/cm^2 was achieved. The authors of [19] used the sol-gel fabrication technique in the fabrication of the membrane of the piezoelectric material and using this sol-gel fabricated PZT membrane at a resonant frequency equal to 16.7 kHz and 100dB SPL a power output of 140 pW was achieved. In [20] the authors developed an acoustic energy harvesting model using the sonic crystals and a piezoelectric material. A power output of 40 nW was generated using the 45dB SPL, 4.2 kHz resonant frequency, and a load resistance of 3.9 kΩ.

RADIO FREQUENCY ENERGY HARVESTING

RF energy is generated by radiofrequency waves. These waves are generally found near radio towers. An electrical circuit consisting of an antenna and a rectifier known as Rectifying Antenna is used to convert RF waves into DC voltage. Incident power density, power conversion efficiency, and size of the antenna are the main factor in the generation of energy. The formula used for the calculation of the Incident power density from the electric field is shown in equation (12).

In equation (12), 'E' is the electric field intensity, and 'Z_o' is the Impedance. Using Friis transmission equation far-field region's power can be extracted as shown in equation (13).

In equation (13), 'P_t' and 'P_r' are the transmitted and received power respectively, 'G_t' and 'G_r' are the transmitted and received gain respectively, λ represents the wavelength, and'd' shows the distance between harvester and source.

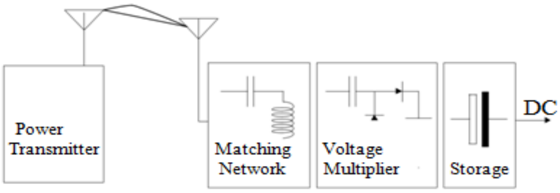

Figure 3 Block diagram of RF energy harvester

Figure 3 is taken from [1] represents the block diagram of the RF energy harvester. For an impedance matching network is used, the power transmitter represents the Tv or radio tower that is the source, for minimum working potential voltage multiplier is used and in the last block, a supercapacitor is used as a storage device and then output DC power is obtained.

CONCLUSIONS ON REVIEWED ENERGY HARVESTING SYSTEMS

- Using the duty cycle of any process is the key factor in developing an efficient energy harvesting system but it is still a challenge for the researchers.
- Designing an optimized energy harvesting model for WSN is difficult for researchers because of their small and compact size and small battery capacity.
- The main focus of researchers in designing an energy harvesting model is the lifetime of the WSN nodes and better-optimized use of the hardware.
- It is easier to design energy harvester for a high power consumption device as compared to the low power consumption devices such as WSN nodes. This is the main issue faced by researchers.
- In the process of energy harvesting using the solar cell that is PV cell, a great amount of energy is harvested in the day time but no amount for energy could be harvested in the night time as there is no sunlight.
- In the process of energy harvesting using acoustic energy as the main source, a continuous vibration in particles is required but this would need full mechanical machinery.
- In thermal energy harvesting, the main challenge faced by the researchers is that TEG requires a great temperature difference which cannot be maintained in some areas.
- For the energy harvesting system using the wind energy the issue occurred is that it would need a large area for setup as it requires high wind speed for better results.
- The RF energy harvesting system is the most popular one as power can be transmitted over a long area wirelessly. The energy is generated when the receiver transforms the RF wave into electrical energy and this electrical energy can be easily stored into the battery.
- From all the above points it can be concluded that these energy harvesting techniques can be used for the everlasting life of the WSN nodes.

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