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Energy Harvesting Alternatives for Powering Critical WSN-Based and Autonomous Monitoring Systems

Fidelis C. Obodoeze[1], Ndidi Fidelia Ugwoke[2], Edith Angela Ugwu[3]

[1]Department of Computer Engineering Technology, Akanu Ibiam Federal Polytechnic, Unwana, Afikpo, Nigeria
[2]Department of Computer Science Michael Okpara, University of Agriculture, Umudike, Abia State, Nigeria
[3]Department of Computer Science, Enugu State University of Science and Technology, Enugu, Nigeria

ABSTRACT

Wireless Sensor Network (WSN) applications in the industry, domestic and commercial sectors are becoming quite interesting and exciting. For instance, since January 2005, major International Oil and Gas companies (IOCs) operating in Nigeria Niger Delta region have made wireless sensor network the defacto monitoring system for their vast oil and gas pipelines, oil wells and other facilities. This is because wireless technology has vast advantages over their wired counterpart. Despite the interest generated by the varied advantage of wireless sensor nodes in the oil and gas industry and other sectors, the biggest challenge lie in the limited battery energy of these tiny wireless sensor nodes. Battery energy of the wireless sensors are so limited that it will take maximum of one year to deplete and that will require massive replacements of the batteries so that the network will still be functional. This is almost impossible or very costly for a field of thousands or millions of wireless sensor nodes. This paper will examine the possibility of harvesting ambient or environmental energy sources such as RF, solar, piezoelectric, thermal etc to store and power these wireless sensor nodes so that the need for massive battery replacements will be avoided and costs saved.

KEYWORDS: *WSN, energy harvesting, battery, OIC, Niger Delta, battery energy, wireless sensor network. Piezoelectric, TEG, solar, kinetic, super capacitor, thin film battery, vibration, harvester, Power harvester*

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1. INTRODUCTION

A key requirement for Internet-of-Things, M2M, WSN-based remote monitoring and autonomous systems is the ability of the battery power to sustain the life span of the monitoring device or system. The key issues are the installation of power distribution wires, or in the case of battery use, the battery life or the life span of the battery energy or the time period for battery replacement. The energy of the battery power is highly limited that despite energy-saving optimizations and schemes, the maximum period battery energy can last is at most 2 years. A prototype of wireless sensor nodes (vMBusX-SP) deployed in January 2005 by an IOC operating in Niger Delta region of Nigeria (Shell Petroleum Development Company (SPDC) to monitor her over 1000 oil wells and pipelines is depicted in Fig.1.1.

Fig1.1: A prototype of battery-powered wireless sensor node (vMBusX-SP) deployed by IOCs operating in Nigerian Niger Delta region in 2015 to monitor vast oil wells and pipelines[1]

There won't be any problem in replacing about 10-20 batteries, but the challenge comes when there is need to replace batteries of about 10,000 to millions of wireless sensor nodes in a difficult terrain or environment such as swampy terrain or in an enemy territory.

The challenge lies in the maintenance costs accruable from replacements of batteries, maintenance visits and the difficulty in accessing thousands or millions of wireless sensor nodes in a difficult terrain or enemy territory. This is the major reason why dissemination of wireless sensor terminals in several sectors has become a concern.

1.1. WAYS TO SOLVE THE BATTERY PROBLEM IN WIRELESS SENSORS

There are three ways to address the problems of powering emerging autonomous wireless technologies:-

1. Improve the energy density of storage systems
2. Develop novel methods to distribute power to the sensor nodes, and
3. Develop technologies for wireless sensor nodes to generate or scavenge its own power.

1.2. AIM OF THIS PAPER

In this paper we will dwell mostly on the third option, energy scavenging or harvesting for wireless sensor nodes from its ambient environment. This is because there is sufficient ambient energy in the environment to tap from. Secondly, the energy in the environment cannot exhaust and it can easily be stored in lithium batteries and supercapacitors.

1.3. ENERGY HARVESTING DEFINITION

Energy harvesting/scavenging is a process of receiving green energy sources (such as Solar, Radio Frequency (RF), thermal, wind, kinetic energy (piezoelectric sources), etc. which are free and plentiful in ambient, and converting them into electrical power for electrical devices such as wireless sensors and autonomous monitoring systems to power up. Recent developments in microelectronic and energy harvesting technologies and also growing industrial demands in wireless devices, led to a technological break-through in terms of self-powered autonomous systems. Two of the most popular methods for harvesting energy consist of the application of piezoelectric and pyroelectric materials in scavenging energy from vibration and thermal gradients, respectively [2].

Energy-harvesting technology stems from a simple observation. Where measurable sensor values reside, ambient energy exists sufficient to power sensor radio communications. For example, when a switch is pressed, temperature changes or luminance level varies, energy is produced. These rudimentary operations generate enough energy to transmit radio signals that are useful in terms of sustaining wireless communications between sensors, switches and controls within a building automation system. Instead of batteries, EnOcean-based controls use miniaturized energy converters and capacitors that supply power to building energy management devices. The bottomless power generation (or energy conversion, to be more precise) stems from various sources of ambient power: linear motion converters, solar cells and thermoelectric converters as depicted in Fig. 1.2.

Fig.1.2: Radio & Energy Harvesting Modules—Radio modules powered by ambient sources of energy

Energy harvesting process using energy sources from the ambient environment to convert to electricity via energy harvesters to power wireless sensor nodes is shown in Fig.1.3.

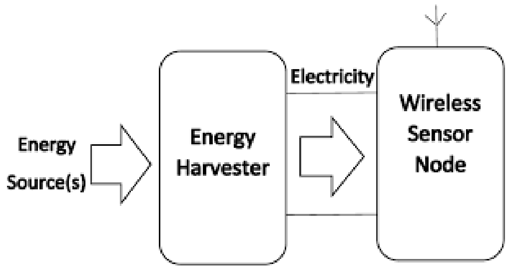

Fig.1.3: Energy harvesting process for WSN node

2. THE BUILDING BLOCKS OF AN ENERGY HARVESTING SYSTEM

The process of energy harvesting takes different forms based on the source, amount, and type of energy being converted to electrical energy. In its simplest form, the energy harvesting system requires a source of energy such as heat, light, or vibration, and the following three key components. Fig.2.1 shows the basic components of an energy harvesting or scavenging system.

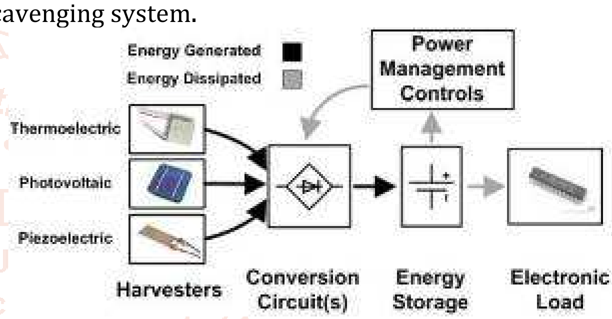

Fig.2.1: Basic components of an energy harvesting system [3]

This paper we will dwell mostly on the third option, energy scavenging or harvesting for wireless sensor nodes from its ambient environment. This is because there is sufficient ambient energy in the environment to tap from. Secondly, the energy in the environment cannot exhaust and it can easily be stored in lithium batteries and super capacitors.

- **Transducer/harvester**: This is the energy harvester that collects and converts the energy from the source into electrical energy. Typical transducers include photovoltaic for light, thermoelectric for heat, inductive for magnetic, RF for radio frequency, and piezoelectric for vibrations/kinetic energy.
- **Energy storage**: Such as a battery or super capacitor.
- **Power management**: This conditions the electrical energy into a suitable form for the application. Typical conditioners include regulators and complex control circuits that can manage the power, based on power needs and the available power.

Figs. 2.2 and 2.3 show the super capacitor and thin film lithium battery respectively, the storage elements for harvested energy from the ambient environment.

Fig.2.2: Super capacitor for storing large energy density charges from energy harvesting

Fig.2.3: Thin film Lithium Nanotech rechargeable battery

Fig.2.4 depicts the flowchart of energy charging methodology in batteries and capacitors.

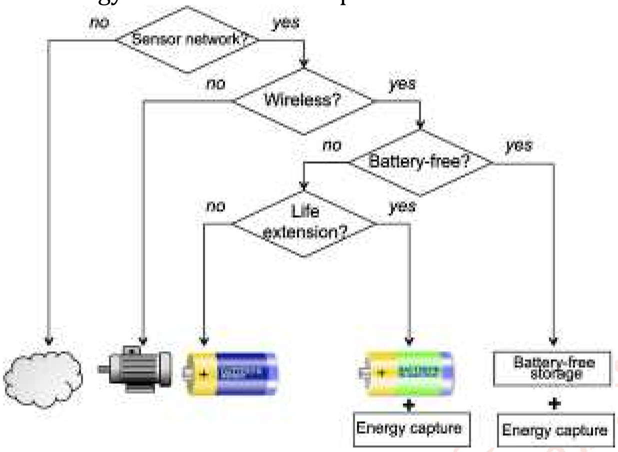

Fig.2.4: Flowchart for energy harvesting process in Wireless Sensor node

Flowchart in Fig.2.4 depicts the energy harvesting process in wireless sensor nodes. Here, a check is made on the battery energy level to determine whether it needs a recharge or not. If battery energy is not full (battery-free), then there is no for battery life extension or recharge. If the battery is rechargeable (Life extension==true), then energy capture (energy harvesting) is activated from the ambient or environmental source. On the other hand, if the battery energy is full (battery-free==true), the excess energy is stored in the battery for future usage.

2.1. COMMON SOURCES OF ENERGY

Energy sources abound in the immediate or ambient environment. Some of the most common sources include:-

- Light energy: From sunlight or artificial light.
- Kinetic energy: From vibration, mechanical stress or strain.
- Thermal energy: Waste energy from heaters, friction, engines, furnaces, etc.
- RF energy: From RF (Radio Frequency) signals.

Fig.2.5 shows the comprehensive sources of energy harvesting for wireless sensor network.

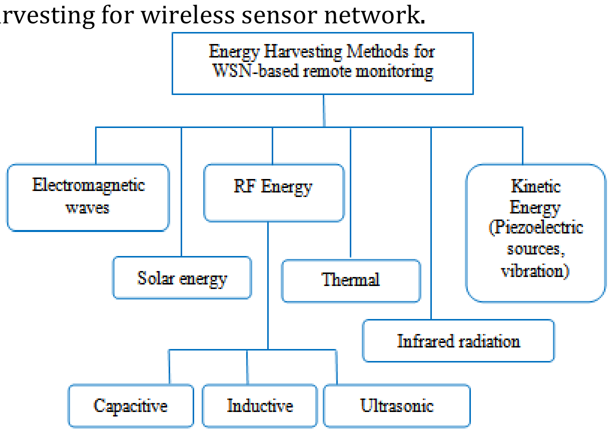

Fig.2.5: Comprehensive energy harvesting sources for Wireless Sensor node

2.2. ENERGY HARVESTING TECHNOLOGIES

Harvesting electrical power from non-traditional power sources using thermoelectric generators, piezoelectric transducers, and solar cells still remains a challenge. Each of these requires a form of power conversion circuit to efficiently collect, manage, and convert the energy from these sources into usable electrical energy for microcontrollers, sensors, wireless devices, and other low-power circuits.

2.3. RELATED WORKS

In this study conducted by [4], an energy harvesting chip manufactured by CMOS-MEMS processes was developed to enable sensor nodes to use energy scavenged from solar cells. The power supply module consists simply of a solar cell, a capacitor, and an energy harvesting chip to provide a battery-less solution, and it is expected to be a sustainable and renewable power source for WSNs. The sensor nodes equipped with the chip based power supply were fabricated for performance tests, including sensor accuracy, response time, and signal deliveries of wireless communication. According to the test results, the feasibility of a "deploy and forget" system was investigated. The WSNs powered by energy scavenging were deployed in a convenience store as a case study. Based on a self defined protocol, the signal deliveries of wireless communication were tested in a real environment.

In another work as depicted in Fig.2.6, a magnetic force is employed to induce the desired amount of magnetic stiffness into the system, thereby altering the device resonance frequency. This technique was previously presented along with experimental validation by [5]. While the resonance frequency tuning technique can be employed on any structure, here a cantilever beam with tip mass is considered as the vibrating structure. Magnets are placed at the top and bottom of the cantilever beam at the tip, such that they are aligned with the magnets on the device enclosure and arranged such that either a magnetic force of attraction or repulsion can be applied. The distance between the magnets dictates the amount of magnetic force exerted on the cantilever beam, which thereby would induce an additional magnetic stiffness in the system and hence alter the resonance frequency of the device. The mode of magnetic force determines the type (positive or negative) of magnetic stiffness induced on the cantilever beam; a magnetic force of attraction would induce a negative stiffness and thus lower the device's natural frequency, whereas a magnetic force of repulsion induces a positive stiffness that increases the total stiffness in the device and hence increases the device's resonant frequency. The technique allows one to tune the resonance frequency of the beam to match both lower source frequencies and higher source frequencies by simply applying the desired mode of magnetic force.

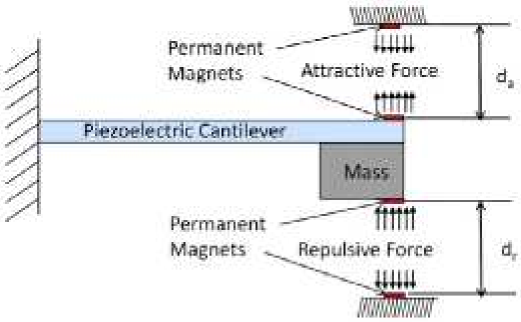

Fig. 2.6: Schematic of the variable magnetic stiffness resonant frequency tuning technique[5]

3. METHODS OF HARVESTING AMBIENT ENERGY SOURCES

This section deals with the various methods of harvesting the ambient energy sources such as kinetic, wind, solar, thermal, RF, etc. to power critical WSN based monitoring systems.

3.1. HARVESTING PIEZOELECTRIC OR KINETIC ENERGY

Piezoelectric transducers produce electricity when subjected to kinetic energy from vibrations, movements, and sounds such as those from heat waves or motor bearing noise from aircraft wings and other sources. This converts mechanical stress into electrical signal. The charge gets accumulated in solid materials due to application of mechanical strain. The reverse of this i.e. mechanical strain gets induced due to subject of electric field on such solid materials will also occur. The common sources which can be exploited in piezoelectric energy harvesting are low frequency vibrations, acoustic noise, human motion etc. These sources can be harvested by piezoelectric materials.

Example of thermoelectric energy harvesting/harvester:

- Piezoelectric floor tiles
- Car tyre pressure sensors or monitors
- Battery less remote control

Fig. 3.1 depicts the working principle of piezoelectric energy harvesting.

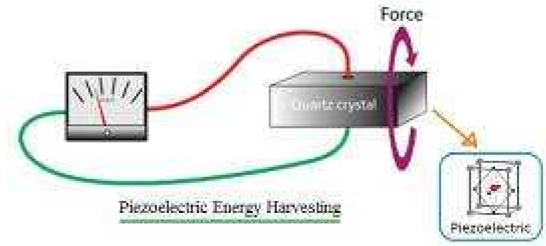

Fig.3.1. Piezoelectric Energy Harvesting

The transducer converts the kinetic energy from vibrations into an AC output voltage which is then rectified, regulated, and stored in a thin film battery or a super capacitor as shown in Fig. 3.2.

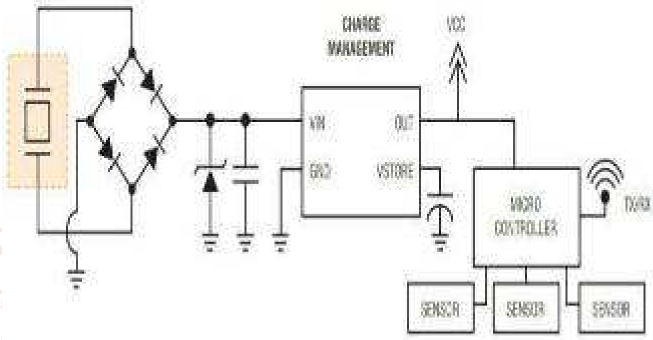

Fig.3.2. Piezoelectric Energy Harvesting Circuit [6]

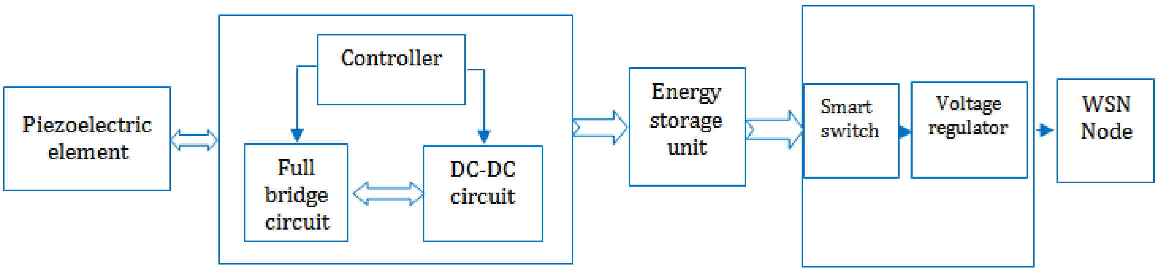

Fig.3.3: Schematic of the energy harvesting system for WSN using piezoelectric element

Fig.3.3 shows the schematic diagram of piezoelectric energy harvesting circuit. Potential sources of kinetic energy include motion generated by humans, acoustic noise, and low-frequency vibrations. Some practical examples are:

- A batteryless remote control unit: Power is harvested from the force that one uses in pressing the button. The harvested energy is enough to power the low-power circuit and transmit the infrared or wireless radio signal.
- Pressure sensors for car tires: Piezoelectric energy harvesting sensors are put inside the car tire where they monitor pressure and transmit the information to the dashboard for the driver to see.
- Piezoelectric floor tiles: Kinetic energy from people walking on the floor is converted to electrical power that can be used for essential services such as display systems, emergency lighting, powering ticket gates, and more.

3.2. HARVESTING RF, WIRELESS OR ELECTROMAGNETIC ENERGY

This involves converting energy available in electromagnetic waves transmitted from various radiating sources (e.g. TV, radio, cellular towers) into equivalent electric current. This method utilizes ambient EM (Electro Magnetic) waves available due to radiations from cellular base stations, satellites, TV and radio broadcasting stations. These RF harvesters convert RF energy into DC energy for storage. It does this using matching and rectifier circuits. The architecture of RF energy harvesting is such that an RF power receiving antenna collects the RF energy signal and feeds it to an RF transducer as show in Fig.3.4.

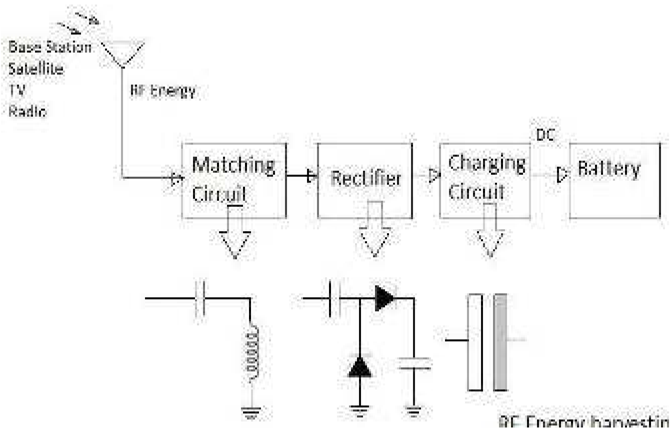

Fig.3.4: RF energy harvesting system [7]

An example of RF transducer or harvester is the Power cast's P2110 RF Power harvester (Kingatua, 2016) as depicted in Fig.3.5.

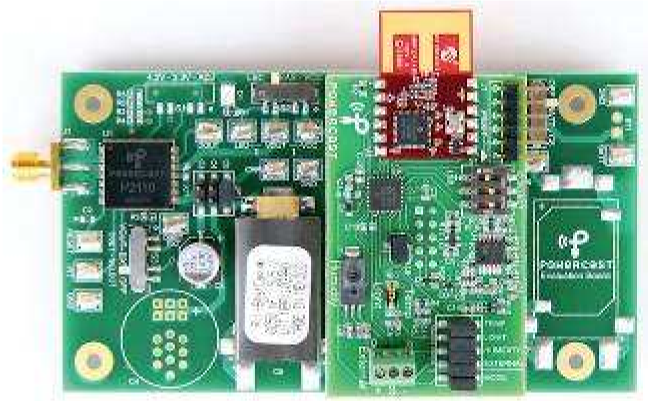

Fig.3.5: A P2110 Power harvester receiver evaluation board[7]

The Power harvester converts the low-frequency RF signal to a DC voltage of 5.25V, capable of delivering up to 50mA current. It is possible to make a completely battery-free wireless sensor node by combining sensors, the P2110, a radio module, and a low-power MCU.

Typical applications for these types of sensors include building automation, smart grid, defense, industrial monitoring, and more. Fig.3.6 shows the block diagram of a Power cast P2110 RF energy harvesting used to power a WSN module 100% without battery.

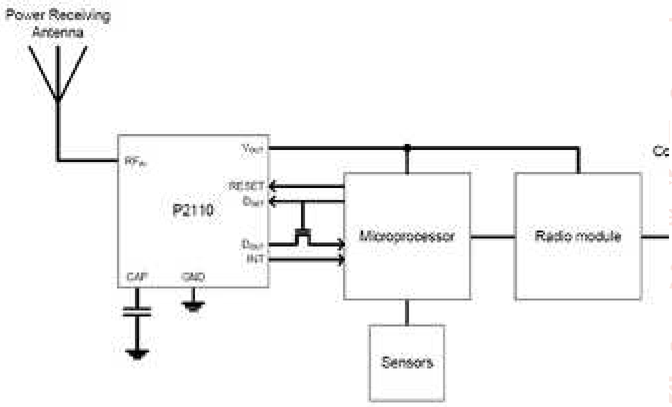

Fig.3.6: Power cast P2110 RF energy harvesting for a battery less wireless sensor [8]

3.3. HARVESTING SOLAR ENERGY

Small solar cells are used in industrial and consumer applications such as satellites, portable power supplies, street lights, toys, calculators, and more. These utilize a small photovoltaic cell which converts light to electrical energy. For indoor applications, light is usually not very strong and typical intensity is about 10 µW/cm^2. Fig.3.7 shows a Smablo TM solar harvester with external cell and battery backup.

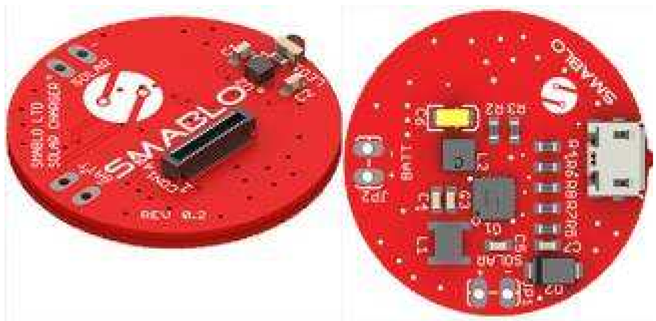

Fig.3.7: Solar harvester with external cell and battery backup [9]

The power from an indoor energy harvesting system thus depends on the size of the solar module as well as the intensity or spectral composition of the light. Due to the intermittent nature of light, power from solar cells is usually used to charge a battery or super capacitor to ensure a stable supply to the application.

3.4. HARVESTING THERMAL OR PYROELECTRIC ENERGY

Thermoelectric or pyroelectric energy harvesters rely on the Seebeck effect in which voltage is produced by the temperature difference at the junction of two dissimilar conductors or semiconductors (or crystal materials). When the temperature of crystal material changes it induces electric charge. No charge is generated when temperature remains constant. This method is used in certain sensors. Similarly, the energy harvesting system can consist of a thermoelectric generator (TEG) made up of an array of thermocouples that are connected in series to a common source of heat. Typical sources include water heaters, an engine, the back of a solar panel, the space between a power component such as a transistor and its heat sink, etc. The amount of energy depends on the temperature difference, as well as the physical size of the TEG. Fig.3.8 shows a typical Thermo Electric Generator (TEG) from Marlow, Ferrotec Corporation, RMT Ltd., Alphabet Energy, Inc. (http://legmannews.com).

Fig.3.8: Thermo Electric Generator (TEG) [10]

The TEGs are useful in recycling energy that would otherwise have been lost as heat. Typical applications include powering wireless sensor nodes in industrial heating systems and other high-temperature environments.

3.5. HARVESTING WIND ENERGY

Wind turbines are used to harvest wind energy readily available in the environment in the form of kinetic energy to power the low power electronic devices such as wireless sensor nodes. When air flows across the blades of the turbine, a net pressure difference is developed between the wind speeds above and below the blades. This will result in a lift force generated which in turn rotates the blades. Similar to photovoltaic's, wind farms have been constructed on an industrial scale and are being used to generate substantial amounts of electrical energy.

Similarly energy of vibration from winds depends on amplitude and frequency. Mass of harvesting device is equivalent to vibrating mass. Vibration or wind is typically made up of number of fundamental frequencies and their harmonics. This phenomenon is utilized in different ways to convert vibration or wind energy into electrical form. The methods include piezoelectric conversion (commonly used materials are PZT, BaTiO3, PVDF etc.), electrostatic conversion (using parallel plate capacitor) and electromagnetic conversion (using magnetic fields and coil).

3.6. HARVESTING ENERGY FROM MULTIPLE SOURCES

Several microchip manufacturers such as Maxim, Texas Instruments and Ambient Micro have developed some integrated circuits with the ability to simultaneously capture different types of energy from multiple sources. Combining multiple sources has the benefit of maximizing the peak energy as well as providing energy even when some sources are unavailable.

An example of a circuit that harvests energy from multiple sources is as shown in Fig.3.9.

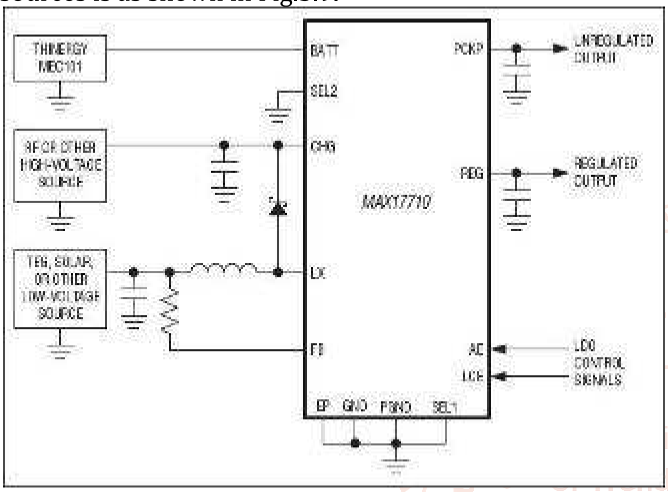

Fig.3.9: Maxim Integrated MAX17710 multiple source circuit. [11]

4. CONCLUSIONS

Harvesting energy from nonconventional sources in the environment has received increased interest over the past few years as designers/researchers look for alternative energy sources for low-power applications such as powering wireless sensors, autonomous systems and internet-of-things (IoTs).

Even though energy harvested is small and in the order of mill watts, it can provide enough power for wireless sensors, embedded systems, and other low-power applications.

4.1. THE WAY FORWARD FOR OIL AND GAS COMPANIES (IOCS) OPERATING IN NIGERIA NIGER DELTA REGION

This is the best way to go out of the three options specified in section 1.2 of this paper. This is because the other two options involve optimization or management of energy in the WSN's battery whereas this option replenishes the battery's depleted energy by scavenging or tapping from its immediate environment which is in abundant.

The authors recommend that the International Oil Companies (IOCs) operating in Nigeria Niger Delta region should turn to these energy harvesting alternatives in order to power their critical WSN-based oil and gas pipelines monitoring systems scattered all over the swamps of the Niger Delta region.

This reason is simple; this will save a lot of maintenance costs and guarantee longer life span of the monitoring systems and network. In this way, the vast oil and gas pipelines, including oil wells and installations, will be safe from vandalisation.

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