# A Scoping Study of Electric and Magnetic Field Energy Harvesting for Wireless Sensor Networks in Power System Applications


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*Abstract* -- **This paper explores the existing energy harvesting technologies, their stage of maturity and their feasibility for powering sensor nodes. It contains a study of the energy requirements of the sensor nodes that are a part of the commercial domain. Further, it investigates methods and concepts for harvesting the energy from electric and magnetic fields present near utility assets through laboratory experimentation. The flux concentrator based approach that scavenges the magnetic field was considered to be the most promising solution providing nearly 250mW of power sufficient to power a sensor node.**



*Index Terms*—**Monitoring, power grid, sensor networks, energy harvesting, electric fields, magnetic fields.**


## I. Introduction

The goal of transforming the present grid into a more intelligent one- a *Smart Grid* has become the major focus for utility companies to stay ahead in the market. This requires efficient grid wide monitoring of the power lines and utility assets to ensure efficient asset utilization and hence increased return on investment. The various parameters that are of interest and require monitoring outside the substation are voltage, current, overhead conductor sag measurement, temperature profile of conductors, ac power, current/voltage transients and harmonics, power quality disturbances, system frequency, fault detection, etc. While the parameters that are of interest and that lie inside the substation domain are power transformer winding temperature, insulating oil levels, operating temperatures of switches and other devices, etc. to name a few [1].

Monitoring the assets and power lines outside of the substation environment is rather challenging because of the vast distances that need to be covered, harsh weather conditions and power requirements. A promising monitoring solution for such conditions is a network of small wireless communication units that are equipped with sensors and a processing chip. Such a network is termed as the *sensor network*.

These sensor networks comprise of a network of numerous sensors that use a multi-hop communication scheme and require very low power for operation. Wireless sensor networks have certain conspicuous advantages; first of all each node can be made very cheap. Secondly, they are self organizing in nature and further the networks have a self healing characteristic. Above all, the research and development encompassing sensor networks has been channeled in a manner where they can be applied to a huge system, similar to a power grid [2]-[9]. A brief market survey of such sensor nodes is presented in Table I.

The present day sensor nodes use batteries for operation, where the battery voltage requirement ranges from 3 to 5V. A typical sensor node load requirement during a transmit or receive operation is 25-50 mA, while during the sleep mode the requirement reduces to only around 10s of µA. This implies that the power requirement of most of the sensor is on the order of a few milliwatts during the transmit/receive operation and a few microwatts during the sleep mode. The power requirement of the sensor nodes vary depending on the distance of communication and the noise present in the environment. The battery requirement of a typical sensor node is a 9 V Li battery having a capacity of 1200 mAh.

Assume a realistic scenario where a particular sensor node would be required to transmit or receive data once every 15 minutes or upon occurrence of an *event*. Also, the total operation time for a sensor node is assumed to be around three seconds. Further, assume that the transmit/receive load requirement of the sensor node is 35 mA for a typical distance of 200 m and the sleep mode requirement is 75 µA. Thus,

Active mode energy requirement per day

$$= 96 times \left[ 35mA \times \frac{3}{60 \times 60} hrs \right] = 2.8mAh$$

Sleep mode energy requirement per day

$$\approx \left( 24hrs \times 75\mu W \right) = 1.8mAh$$

Total energy requirement per day= $4.6mAh$

Number of days that the battery would last

$$\approx \frac{1200mAh}{4.6mAh} = 260days < 1 \text{ year}$$

The above calculations suggest that in a realistic sensor node scenario, its' battery would be depleted in less than a year. Also, as the distance of transmission / reception increases, the life of the battery further decreases. Considering the large number of sensors present in the network, it would become impossible to change the battery in all of the sensor nodes after every few months. This would also give rise to additional maintenance expense that will discourage the utilities from implementing such a technology. Therefore, a method that enables these sensor nodes to be powered autonomously from the environment may be a promising solution to the above problem.

One of the techniques that can enable autonomous powering of the sensor node is energy harvesting. It is a technique that allows scavenging of stray energy present in the environment. There are various methods and sources that can be used to harvest power; namely Vibration, Thermal, Solar, Magnetic Field, etc. [10]-[15].

In this paper, section II presents a survey of all the energy harvesting techniques available in the literature and also briefly highlights the energy harvesting products available in the market. In Section III, the concept of electric field energy harvesting which is not available in the literature or the commercial domain is analyzed. Section IV presents discussion and experimental results of a piezoelectric based magnetic field energy harvesting approach. Finally, section V discusses harvesting of energy from the magnetic field through electromagnetic induction. This section also presents experiments performed to find a suitable core size for harvesting energy from the magnetic field around a utility asset, such as a conductor, busbar, disconnect switch etc.

TABLE I
WIRELESS COMMUNICATION NODE MARKET SURVEY

| Product (Company) | Specifications | | Picture |
|---|---|---|---|
| G-Link 2.4 GHz Wireless Accelerometer Node (Micro Strain) [16] | Power Consumption | TX-25mA RX-25mA Sleep-0.5mA |  |
| | Battery | 3.7V Li ion | |
| | Range of RF link | 70 m line of sight | |
| IMOTE2 (Crossbow) [17] | Power Consumption | Active - 33mA Sleep - 390 μA |  |
| | Battery Voltage | 3.2V-4.5V | |
| XBEE Zigbee/802.15.4 Modules (DigiInternational) [18] | Power Consumption | Active- 50mA Sleep - 10 μA |  |
| | Supple Voltage | 2.8V-3.4V | |
| | Range | 600m | |

## II. ENERGY HARVESTING TECHNOLOGY REVIEW

It is evident that the sensor network technology can be made feasible for monitoring the power grid only if it derives power autonomously from the environment. There are plenty of sources available and present near the utility assets through which energy suitable for powering such nodes can be scavenged. This section presents a review of the state-of-the-art energy harvesting technology and a market survey of a few products that use different energy harvesting techniques for deriving power.

### A. *Vibration Based Energy Harvesting*

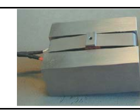
Mechanical vibrations can be converted to electrical energy using a number of techniques. In the literature, these have been broadly divided into three groups:

- Piezoelectric Technique - using the property of a piezoelectric material to generate electric potential under mechanical stress.
- Inductive spring mass system - using Faraday's law of electromagnetic induction by placing a magnet attached to a spring inside a coil. Vibration of the magnet causes an induced voltage in the coil.
- Electrostatic method - it relies on changing the capacitance of a vibration dependent variable capacitor.

Designing a generalized energy harvesting system that functions for any vibrating source becomes challenging, as the efficiency with which the energy is harvested depends on the resonant frequency of vibration, which may not be the same for the different sources. Some of these issues have been addressed in the literature [19]-[27].

A survey of the energy harvesting products based on mechanical vibrations was performed and summarized in Table II.

TABLE II
MARKET SURVEY OF VIBRATION BASED ENERGY HARVESTING PRODUCTS

| Product (Organization) | Specifications and Features | | Picture |
|---|---|---|---|
| Piezoelectric Based Energy Harvesting Products | | | |
| Volture Piezo Energy Harvester-PEH20W (Mide) [28] | Harvested Power (Strong Vibrations) | 20 mW |  |
| | Frequency Range | 50-150 Hz | |
| VEH-APA400M-MD (Cedrat) [29] | Maximum Harvested Power | 95 mW |  |
| | Frequency | 110 Hz | |
| Inductive based Energy Harvesting Products | | | |
| PMG27 Microgenerator (Perpetuum) [30] | Maximum Harvested Power | 4mW |  |
| | Vibration Frequency | 17.2 Hz | |
| VEH360 (Ferro Solutions) [31] | Harvested Power | 10.8mW |  |
| | Vibration Frequency | 60Hz | |
| Electrostatic Based | | | |
| Energy Harvesting Shoe (Scientific Research Institute) [10] | 800 mW of power per shoe at a pace of 2 steps per sec | |  |

### B. *Thermal Energy Harvesting*

Systems, environments, or objects at different temperatures offer the opportunity for harvesting energy through heat transfer. The devices used to scavenge the energy due to temperature difference are called thermogenerators and this concept is called thermal energy harvesting. A thermo generator is based on the Seebeck effect, which states that two dissimilar metals joined at two junctions maintained at different temperatures produce an electrical voltage across the junction. The resultant voltage is proportional to the difference in temperature between the hot and the cold junction.

Although harvesting of energy using temperature difference between systems may sound promising, however, there is a fundamental limit to the maximum efficiency at which energy can be harvested from a temperature gradient. This limit is governed by the Carnot cycle. Carnot efficiencies are limited for small $\Delta T$. For example, going from body temperature ($37^0$C) to a cool room ($20^0$C) yields only 5.5% efficiency.

In order to increase the effective power output from a thermogenerator, good design practice has to be undertaken. Some of the design aspects are discussed in the literature [32]-[39].

A survey of the thermal energy harvesting products was performed and results are shown in Table III.

TABLE III
MARKET SURVEY OF THERMAL BASED ENERGY HARVESTING PRODUCTS

| Product (Company) | Specifications and Features | | Picture |
|---|---|---|---|
| Thermo Life (Thermo Life Energy Corporation) [40] | Temperature Difference | 10 °C |  |
| | Open Circuit Voltage | 11 V | |
| | Power | 135µW | |
| TMG127 (Kyrotherm) [41] | Temperature Difference | 100 °C to 20 °C |  |
| | Voltage Output | 2.6 V | |
| | Power Output | 458 mW | |
| Seiko Thermic Wristwatch (Seiko) [42] | The watch absorbs body heat from the back case and dissipates it from the front of the watch to generate power with its thermal converter. | |  |

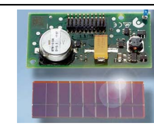
## C. Solar Energy Harvesting Concept

Solar energy harvesting has been prevalent for a long time and has become a mature technology now. Solar energy can be harnessed with the help of a photovoltaic (PV) system that converts sunlight into electricity. Solar panels are characterized by two parameters, the open circuit voltage ($V_{oc}$) and the short circuit current ($I_{sc}$). A battery acts as a voltage source, whereas a solar panel behaves as a voltage limited current source. As the amount of incident solar radiation decreases (increases), the value of $I_{sc}$ also decreases (increases), however, $V_{oc}$ remains almost constant. Due to its current source-like behavior, it is difficult to power the load system directly from the solar panel. Hence, an energy storage element, such as a rechargeable battery or an ultracapacitor, is used to store the energy harvested by the panel and provide a stable voltage to the system.

A perennial supply of sunlight is necessary for harvesting solar energy which may not be feasible all the time. Moreover, solar cells suffer from the major disadvantage of very low efficiency of energy conversion. Single crystal solar cells have efficiencies of about 15% for commercially available cells and over 20% for high-end research cells. Thin-film polycrystalline cells exhibit efficiencies of 10 – 13%. Thin-film amorphous silicon solar cells have a lower efficiency ranging from 8 – 10%, but are well suited for indoor applications, as their spectral response closely matches that of fluorescent white light. Efficiency of cadmium telluride (CdTe) cells ranges from 8 – 13%, however, thin-film CdTe solar cells are widely used due to their good performance under a wide range of light conditions [43]-[46].

PV modules are quite popular and a plethora of products are available in the market. A brief description of popular products with specifications is listed in Table IV.

TABLE IV
MARKET SURVEY OF SOLAR BASED ENERGY HARVESTING PRODUCTS

| Product (Company) | Specifications and Features | | Picture |
|---|---|---|---|
| Sensor Transmitter Module STM110 (Enocean) [47] | Solar cell Power RF transmitter module. Operates at 2V Operation in darkness > 60 hrs | |  |
| Solio Hybrid 1000 (Solio) [48] | Rated Output Voltage at 1000W/m$^2$ | 6 V |  |
| | Rated Current at 1000W/m$^2$ | 165 mA | |

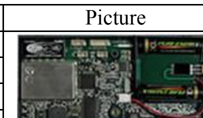
## D. EM Wave Energy Harvesting Concept

Analysis of electromagnetic waves show that the power density produced by an antenna is approximately equal to $E^2/Z_0$, where $Z_0$ is the radiation resistance of free space (377 Ω) and $E$ is the local electric field strength in volts/meter. Thus, an electric field of 1 V/m yields 0.26 µW/cm$^2$. But electric fields of this order are rare except when close to a powerful transmitter [10].

A solution to this problem can be the deliberate transmission of RF energy solely for the purpose of powering devices. This practice is commonplace in Radio Frequency Identification System (RFID) which derives energy inductively, capacitively or radiatively from the tag reader.

There are two different principles on which RFID tags are powered [49] - Active and Passive. Active RFID tags are powered by batteries. Passive RFIDs derive power autonomously using the RF signals from the base station. The passive concept is used in the WPT and WPR series Power Harvester module manufactured by Power Cast [50]. The specifications are shown in Table V.

TABLE V
SPECIFICATIONS OF POWER HARVESTER MODULE BY POWER CAST

| Product Type | WPR9006 | WPR2407 | Picture |
|---|---|---|---|
| Efficiency | 70% | |  |
| Voltage Range | 1.2 - 6 V | | |
| Current Output | 160 µA | 23 µA | |
| Frequency | 900 MHz | 2400 MHz | |

### E. *Magnetic Field Energy Harvesting Concept*

The magnetic field near transmission/distribution lines produced by the ac current flowing through these lines can be used to power sensors installed in the vicinity. AC powerline sensors which sense the electrical conditions, such as power, voltage, current, line sags, temperature, etc. are useful to electric utilities companies and help them better anticipate a likelihood of an unexpected outage occurring due to faulty or overloaded line.

Most of the products present in the commercial domain are based on transformer action for energy harvesting. In order to utilize this concept they need to clamp around the conductor. This limits their application, as in some cases it may not be practical to clamp around the conductor. However, if it is possible to clamp around the conductor, then it proves to be an efficient means of scavenging power.

The products available in the market that use this technique of energy harvesting are presented in Table VI.

TABLE VI
MARKET SURVEY OF MAGNETIC-FIELD BASED ENERGY HARVESTING PRODUCTS

| Product (Company) | Specifications and Features | Picture |
|---|---|---|
| Power Line Sensor (Protura) [51] | - Sends the information using GPRS.<br>- Powered by a special designed two-piece transformer, which scavenges power from the magnetic field around the transmission line.<br>- The harvesting circuit powers the sensor when the current in the line is more than 55Amp, while below this value of current the auxiliary supply powers the device |  |
| Power Donut (USi) [52] | - It transmits data on demand using GSM wireless cell phone technology.<br>- Operates on the harvested energy for current above 50A in the line. |  |

## III. ELECTRIC FIELD ENERGY HARVESTING ANALYSIS

According to the fundamentals of electrostatics, every energized conductor has a radial electric field. For ac lines, the electric field varies with time according to Maxwell's law given by $I_d=\varepsilon d\varphi_E/dt$. Where, $I_d$ is the displacement current, $\varepsilon$ is the electric permittivity, and $\varphi_E$ is the electric flux density.

In theory $I_d$ can be used to charge a pair of capacitor plates and hence store the electric field energy in the capacitor. This energy is given by $E=0.5CV^2$. Where, E is the energy stored in the capacitor, C is the capacitance and V is the voltage across the plates. Since this energy would be scavenged from the stray electric field of the current carrying conductor, this method can be termed as Electric field Energy harvesting (E-Field energy harvesting).

Now, consider the same two plate system such that one of the plates is shorted to the conductor. The plates are at a distance h from the earth and the separation between the two plates is d. This configuration is shown in Fig. 1, and its equivalent circuit is depicted in Fig. 2.

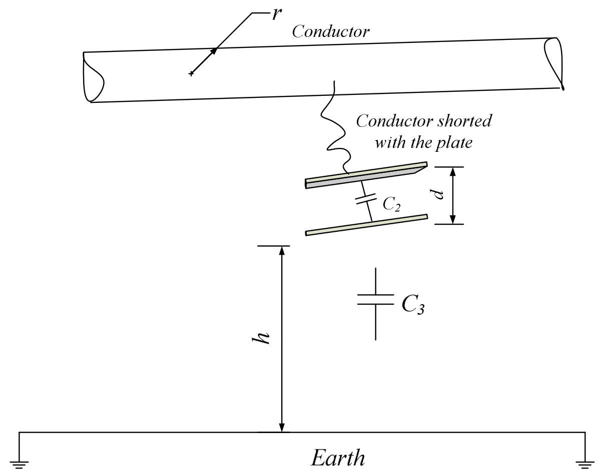



Fig. 1. Parallel plate system for E-field harvesting

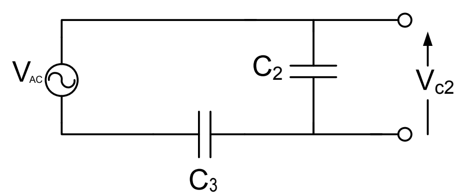



Fig. 2. Equivalent circuit of the E-field energy harvesting system

The geometry of the plates gives the value of C2, while C3 can be calculated using the standard method of images. The expressions for the various electrical parameters are given in (1) and (2).

$$C_2=\frac{l^2\varepsilon_0 K}{d}\,Farad,\qquad C_3=\frac{2\pi l\varepsilon_0}{\log\left(\frac{2\pi h}{l}\right)}\,Farad \tag{1}$$

$$E=\frac{1}{2}C_2{V_{c2}}^2\ Joules,\qquad V_{c2}=\left(\frac{C_3}{C_3+C_2}\right)V_{ac}\ Volts \tag{2}$$

where $V_{ac}$ is the line voltage, $V_{c2}$ is the voltage across capacitance $C_2$, K is the dielectric constant, $C_2$ is the capacitance of the plates, $C_3$ is the capacitance between the lower plate and the earth, d is the separation between the plates, l is the length of the plate and h is the height of the plate from the earth.

Using (1) and (2), theoretical calculations for different configurations of the plates were performed to test the feasibility of the proposed concept. Table VII shows the power harvested for different plate separations. The system parameters chosen for the feasibility study were- $V_{ac}$ =115 kV, r=1 inch, D = 15 m, h=D-d, l=15cm and K=1.

TABLE VII
THEORETICAL RESULTS OF E-FIELD ENERGY HARVESTING

| Plate Separation | Displacement Current | Voltage across the | Capacitance C2 (picoF) | Harvested Power |
|---|---|---|---|---|

| d (cm) | (μA) | plates (kV) | | (mW) |
|---|---|---|---|---|
| 1 | 52.7 | 7.02 | 19.92 | 29.5 |
| 3 | 47 | 18.77 | 6.64 | 70.2 |
| 5 | 42.4 | 28.22 | 3.98 | 95.2 |

95mW of power is obtained at 5cm plate separation. However, 5cm separation is not a practical solution. Moreover, the size of the plates was chosen as 15cm, which again may not be a feasible option.

Thus, another set of results were obtained where the distance between the plates was fixed at 1 cm and the plate size was varied. The results in Table VIII show that the energy reduces considerably on reducing the size of the plates.

TABLE VIII
THEORETICAL RESULTS OF E-FIELD ENERGY HARVESTING WHEN THE PLATE SIZE IF VARIED

| Plate Size $l$ (cm) | Displacement Current (μA) | Voltage across the plates (kV) | Capacitance C2 (picoF) | Harvested Power (mW) |
|---|---|---|---|---|
| 3 | 7.1 | 23.7 | 0.797 | 13.5 |
| 5 | 13.7 | 16.4 | 2.213 | 17.9 |
| 7 | 20.8 | 12.7 | 4.338 | 21.1 |

Finally, different dielectric materials would result in different levels of harvested power. This can be seen from Fig. 3, which shows a variation of harvested power on varying the dielectric strength of the material as the plate separation is varied.

## IV. EXPERIMENTAL TESTING OF PIEZOELECTRIC BASED ENERGY HARVESTING

A bimorph design consists of a passive metal substrate glued to a piezoceramic strip. When the ceramic is deflected, a voltage proportional to the deflection is produced and this process is reversible. A magnet is attached to the edge of a piezoelectric bimorph bender and kept in the varying magnetic field of an ac current. As the magnet oscillates, a time varying deflection is produced in the piezoelectric ceramic which consequently produces an ac voltage. This is shown in Fig. 4.

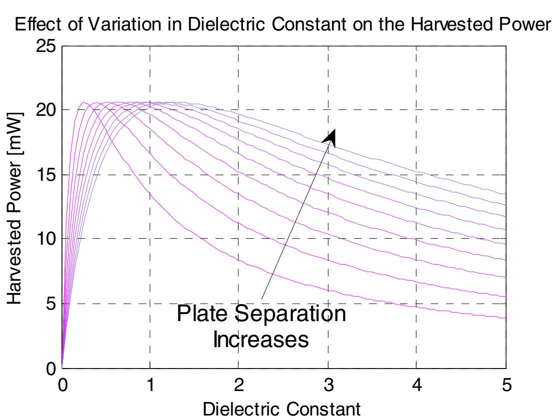



Fig. 3. Graph shows variation of harvested energy with change in dielectric constant

The frequency of oscillation of the magnet and hence the voltage would be 60Hz, the same as the frequency of the current in the conductor. In essence, the magnetic field energy is converted to electrical energy through the vibrational kinetic energy of the piezoelectric bender.

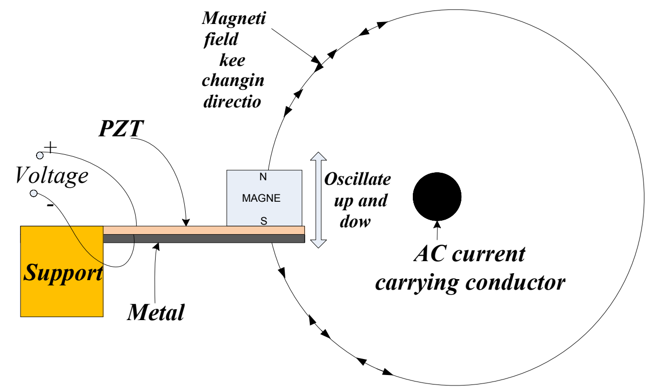



Fig. 4. Concept of piezoelectric based magnetic field energy harvesting

Reference [27] shows that maximum energy that can be harvested from the piezoelectric bimorph bender if it is kept at an angle of 45 degrees to the magnetic field lines of the conductor and very close to it. Furthermore, the support on which the piezoelectric bender is mounted should be rigid. Piezoelectric bimorphs are sharply tuned at the resonant frequency. This was verified through an experiment which showed a rate of reduction of voltage as high as 35% per Hz.

In order to test the feasibility of the concept shown in Fig. 4, an experiment was performed with a piezoelectric bimorph benders procured from Piezo Systems Inc and NdFeB (Neodymium Iron Boron) magnets procured from K&J Magnetics. The equivalent circuit diagram of the experiment is shown in Fig. 5.

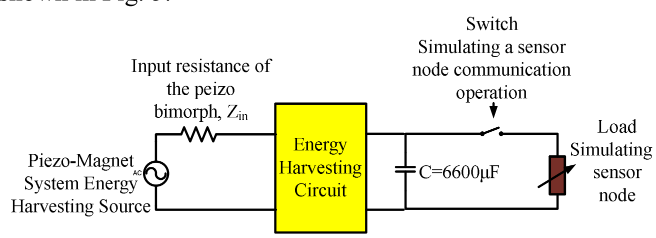



Fig. 5. Equivalent circuit of the experiment to simulate a sensor node operation powered with the energy scavenged from the magnetic field using a piezoelectric bimorph.

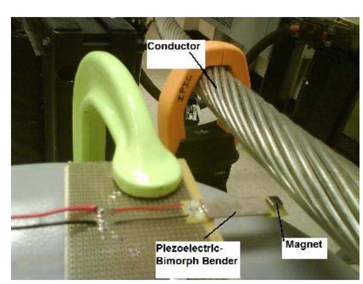


Fig. 6. Actual setup for the equivalent circuit shown in Fig. 5.

| | | | | | |
|---|---|---|---|---|---|
| 1000 | 560 | 2 | 8.12 | 0.41 | 108.24 |

The experiment was aimed at simulating a typical wireless sensor node operation, requiring power on the order of 10s of mWs in the active mode lasting for 2-3 sec. For most of the time the sensor node is in the idle mode where it only needs around 100s of μWs lasting for 10-15 min depending on the load duty cycle. It was observed that the piezoelectric bender had high source impedance and hence a low load driving capability. However, it still had the capability to provide power in the form of small pulses to the sensor node. This was be done by pumping energy into a capacitor. During the idle period, energy was pumped into the capacitor which increased its voltage while during the active mode the stored energy was used to support the load requirement of the sensor node, resulting in a voltage reduction. The experiment used an energy harvesting circuit with a 6600μF capacitor. The circuit was designed in such a way that when the capacitor voltage reached $\approx$5V, a voltage appeared across the output terminals of the circuit and the circuit became capable of driving a load, while if the capacitor voltage got below $\approx$3V the output voltage went to zero and did not appear until the capacitor voltage again rose to 5V. The reason for choosing these voltage levels is that most of the electronics of the sensor nodes operate at these voltage levels. A typical operation cycle of the sensor node can be seen in Fig. 7.

This experiment was repeated for different load levels and current in the primary conductor. The results are shown in Table IX. The capacitor is discharged from 5V to 3V every time it is loaded (when the sensor is transmitting/receiving data), this corresponds to $E=0.5C(V_1^2-V_2^2)=$ 52.8mJ. Also, the time taken for this discharge is 2 sec (see Table IX). Thus, average power delivered is 26.4mW.

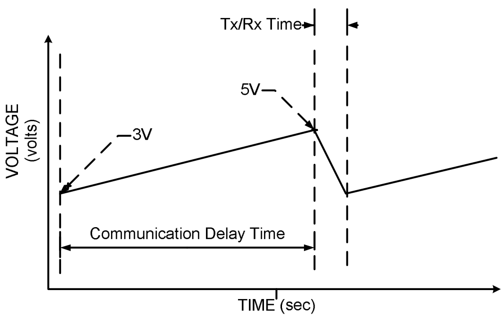



Fig. 7. Graph showing the typical operation cycle of a sensor node powered with a piezoelectric energy scavenging source.

TABLE IX
PIEZOELECTRIC BASED MAGNETIC FIELD ENERGY HARVESTING TEST RESULTS

| Primary Current (Amps) | Load (ohm) | Tx/Rx Time (sec) | Communication Delay Time (min) | Duty Cycle (%) | Power (μW) |
|---|---|---|---|---|---|
| 600 | 560 | 2 | 13.42 | 0.248 | 65.4 |
| | 1000 | 4 | | 0.494 | 65.2 |
| | 1500 | 6 | | 0.741 | 60.7 |
| 800 | 560 | 2 | 10.36 | 0.32 | 84.4 |

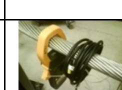
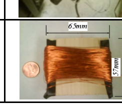
This experiment demonstrates that even though a piezoelectric bimorph bender has the disadvantage of very high source impedance resulting in a low power output, it might prove to be feasible for an application that requires a very low duty cycle, such as the wireless sensor node.

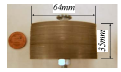
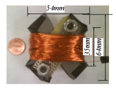
## V. EXPERIMENTAL TESTING OF MAGNETIC FIELD ENERGY HARVESTING CONCEPT

The magnetic field present around utility assets can be harnessed using a device that sticks on to the asset and converts the magnetic field energy into useful electrical energy. In accordance with this concept, different core structures were tested. The energy harvesting device has to be sufficiently small in size to ensure a compact sensor. This constraint rules out the Rogowski coil which is bulky as compared to the other designs (see Table X). Also, rectification of the harvested power from ac to dc requires the use of switches which have a voltage threshold on the order of a few hundred mVs that needs to be surpassed. The results shown in Table X clearly show that an air cored coil would be incapable of crossing this threshold and hence face a major design challenge for use in energy harvesting. It should also be noted that as the number of turns increase so does the copper losses. It is clear from the results that the silicon steel core coils even with more turns give much higher power than air core coils.

The experimental results show that the flux concentrator, an x-shaped core, has the ability to concentrate the nearby flux in the most efficient manner. The flux concentrator also has the advantage of small size and, above all, it can stick to the conductor. It does not have to be clamped around the conductor, which is a requirement for most of the units available in the market. The alignment and distance of the core with respect to the conductor holds prime importance during implementation. Although a known fact, it was verified experimentally that a complete misalignment of the core with respect to the conductor leads to reduction in the energy harvested by a factor of almost 200. Also, the energy harvested is almost inversely proportional to the distance of the core from the conductor.

TABLE X
MAGNETIC FIELD ENERGY HARVESTING USING DIFFERENT CORE CONFIGURATIONS

| Type of Coil | No. of turns | O.C. Voltage at 200A primary current (V) | OC Voltage at 1000A Primary Current (V) | Max. Harv-stable Power (mW) | Picture/Test Set up |
|---|---|---|---|---|---|
| Rogowski Coil | 18 | 0.03 | 0.16 | 8 |  |
| 28AWG wire wound on a | 200 | 0.24 | 1.21 | 29.8 |  |

| | | | | | |
|---|---|---|---|---|---|
| Wooden Core | | | | | |
| 28AWG wire wound on a hollow semi cylindrical Silicon Steel Core | 250 | 0.37 | 1.77 | 210.2 |  |
| 28AWG wire wound on a Flux Concentrator | 300 | 0.50 | 2.64 | 257 |  |
| Flux Concentrator Connected to a Transformer | 300 | 12.5 | 70.6 | 225 |  |

## VI. CONCLUSIONS

A discussion on various energy harvesting techniques available in the literature was presented. The research effort was focused on harvesting energy from electric and magnetic fields available near most utility assets. A technique that exploits the electric field available near a current carrying conductor was developed. This technique shows that theoretically sufficient amount of energy can be harvested from the electric field to power a sensor node. However, the size of such a device may be quite large. In the example considered, it was 15cm long and therefore may not be a suitable technique for energy harvesting in most of the applications.

Further, different techniques of energy harvesting using the magnetic field around a current carrying utility asset were investigated. The method where a piezoelectric bimorph was used to scavenge energy provided an average power of 26.4 mW. Its inability to provide power continuously was one of the major drawbacks of this technique.

Finally, different core configurations were used for harvesting the magnetic field of a conductor. A maximum power of 257 mW was obtained using a flux concentrator and this proved to be the most promising technique.

The investigation performed in this paper was an attempt to make sensor networks truly ‘pervasive’ with an ultimate aim of achieving a wireless sensor network based grid wide monitoring system- an essential ingredient for the “*Smart Grid*” of the future.

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