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ENERGY HARVESTING FROM INDIAN COMMERCIAL POWER LINE: AN APPLICATION IN SMART GRID

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ABSTRACT

In this research paper, a new technology of energy method based on stray electric field of an electric power line of India at 230 V is presented. This energy can be used for low power wireless sensor and in future it can be used in charging smart phone etc. In our research we found that energy can be harvested and stored in the storage capacitor that is connected to a cylindrical aluminum foil wrapped around a commercial insulated 230 V power line. The average current flowing into 47 μ F storage capacitor is about 4.54 μ A with 60 cm long cylindrical aluminum foil. It is possible to operate wireless sensor node to transmit RF data in every 42 seconds. The harvested average power is about 47 μ W in this case. Since the energy can be harvested without removing insulating sheath, it is believed that the proposed harvesting technology can be applied to power the sensor nodes in wireless ubiquitous sensor network and smart grid system.

INTRODUCTION

A ubiquitous wireless sensor network (USN) has evolved recently, numerous sensor nodes are being installed in the commercial streets, houses, buildings, automobiles etc. to realize a "Smart Environment" (Cian O' Mathuna *et al.* 2008). This smart environment is based on wireless sensor network and various systems are employing tens or hundreds of wireless sensor nodes to collect and transmit information. However, in this sensor-rich world, powering the numerous wireless sensor nodes is a serious problem. Currently DC battery is used as a power source in most wireless sensor nodes, but, periodical replacement of batteries of numerous wireless sensor nodes is impractical. To solve this problem, research on self-sustainable wireless sensor node using environmental energy such as solar or vibration energy has been performed actively (Joseph A. Paradiso *et al.* 2005). However, a serious problem in using environmental energy is that the power extracted from environmental energy is not constant over time and its magnitude varies significantly (Kurt Roth *et al.* 2008). Energy can be harvested using magnetic field around power line, but, the problem in this case is that current must flow through the power line (Rohit Moghe *et al.* 2009).

To solve this problem, harvesting energy using electric field around commercial insulated 230V power line is introduced in this paper. According to Maxwell's equation, the displacement current (I_d) from a power line can be expressed as follow (John D Jackson, 1999):

$$I_d = \epsilon \int_s \frac{dE}{dt} \cdot ds \quad (1)$$

Where ϵ is dielectric constant, E is electric field intensity.

The first term on the right hand side is present in material media and in free space. It doesn't necessarily come from any actual movement of charge, but it does have an associated magnetic field, just as does a current due to charge motion. Some authors apply the name displacement current to the first term by itself (David J Griffiths, Jones & Bartlett 1999).

The electric displacement field is defined as:

$$D = \epsilon E + P \quad (2)$$

Where ϵ is the permittivity of free space, E is the electric field intensity; P is the polarization of the medium.

For Isotropic dielectric case $P = 0$.

$$D = \epsilon E \tag{3}$$

Current in capacitors

This displacement current can be used to charge the capacitor that is placed near the power line(Stuart B. Palmer *et al.*,1996, Raymond A. Serway *et al.*,2006).Consider the charging capacitor in the Figure 1.



Figure 1. Electrically charging capacitor with an imaginary cylindrical surface

The capacitor is in a circuit that causes equal and opposite charges to appear on the left plate and the right plate, charging the capacitor and increasing the electric field between its plates. No actual charge is transported through the vacuum between its plates. Nonetheless, a magnetic field exists between the plates as though a current were present there as well. One explanation is that a fictitious displacement current I_d "flows" in the vacuum, and this current produces the magnetic field in the region between the plates according to Ampère's law:

$$\oint_c B \cdot dl = \mu_0 \cdot I_d \tag{4}$$

Where \oint_c is the closed line integral around some closed curve C, B is the magnetic field measured in tesla, dl is an infinitesimal line element along the curve C, μ_0 is the permeability of free space, I_d is the net displacement current that passes through a small surface bounded by the curve C. The magnetic field between the plates is the same as that outside the plates, so the displacement current must be the same as the conduction current in the wires, that is,

$$I_d = I \tag{5}$$

Since the energy would be harvested from the stray electric field of the current carrying (voltage applied) conductor, this method can be termed as electric field energy harvesting. Unlike magnetic field energy harvesting, electric field energy harvesting can collect energy from a no-load AC power line in which conduction current does not flow. In our research, aluminum foil is wrapped cylindrically around an insulated AC power line to harvest electric field energy without removing the insulating sheath. The method is experimentally confirmed to successfully operate low power wireless sensor.

Method Of Stray Electric Field Energy Harvesting

In our research, the energy collected with cylindrical 20 cm aluminum foil wrapped around an insulated no-load AC power line connected to 230 V power. Diameter of the power line is 0.7 cm, thickness of the insulating sheath is about 0.2 cm, and diameter of the inner conducting wire is 0.15 cm, respectively. Equivalent circuit for the experimental setup is shown in Fig. 2(a) and 2(b). When aluminum foil is wrapped around the insulated 230 V power line in a cylinder-shape as shown in the Fig. 2(a), stray capacitance is generated between the inner conducting wire and the foil as shown in the Fig. 2(b). When 20 cm long foil is used, C_1 is measured as about 80 pF and the

parallel capacitance of C_2, C_3 is measured as about 92 pF. When voltage is applied to the AC power line, voltage is divided by the stray capacitors, and charge is stored in the storage capacitor. Since charges are transferred capacitively, electric energy can be harvested even though current is zero, i.e. in open-circuit case.

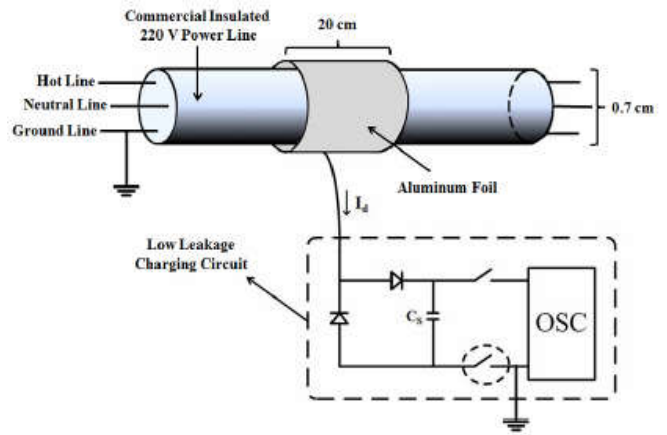
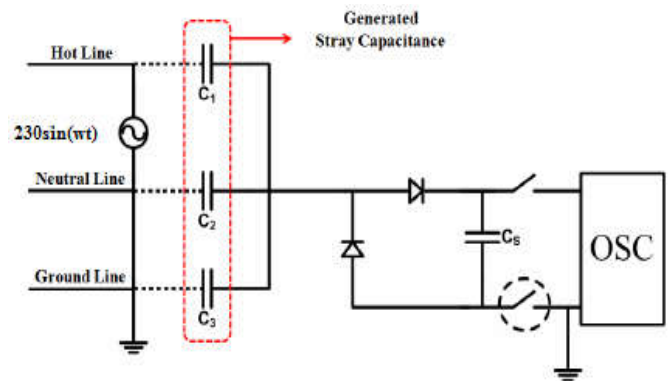


Figure 2(a). Stray electric field energy harvesting experiment



Figure(b). Equivalent circuit of stray electric field energy harvesting for experiment

EXPERIMENTAL RESULTS

Results for electric field energy harvesting

In our research, the experimental result when the length of the aluminum foil is 20 cm and the capacitance of the storage capacitor is varied show in figure 3. About 1600 nA of current flows into the storage capacitor regardless of storage capacitor capacitance when the power line and the harvesting circuit are directly grounded together during energy harvest (DG), and about 70~80 nA of current flows when the harvesting circuit is not grounded (No Ground, NG). The average current of NG harvesting circuit is very small since there is no loop for current flow. However, it is impractical to peel off the insulating sheath in order to connect with the ground. To solve this problem the following ground method is devised and tested.

It is well known that the ground line of the AC power line is grounded to the earth. Since concrete of buildings is connected to the earth by metal structures such as metal reinforcements, the earth and the concrete floor of the laboratory are assumed to be at the same zero electric potential. In this work, a 3x4 cm² conductor plate is contacted with concrete floor of building as shown in Fig. 4.

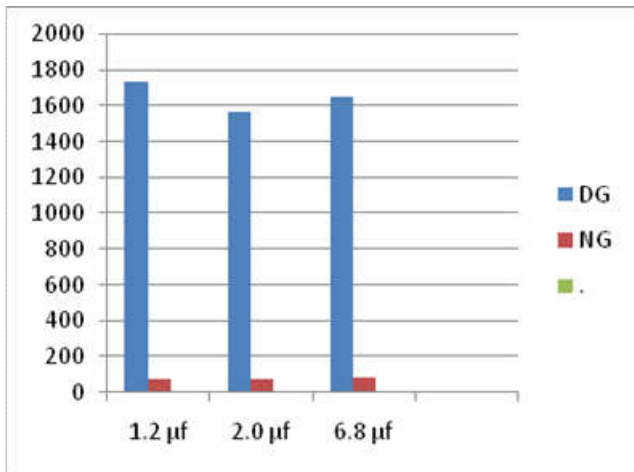


Figure 3. Average current with respect to storage capacitor capacitance

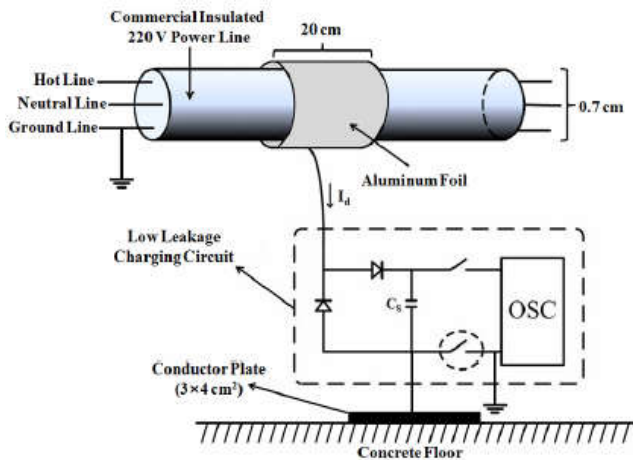


Figure 4. Conductor plate Ground harvesting circuit

In this case, oscilloscope probes are not connected to the storage capacitor during energy accumulation stage to prevent discharging to the ground. When 20 cm long aluminum foil and 2 μF storage capacitor are used, the average current flowing into storage capacitor for concrete plate ground circuit in which metal plate is used therefore contact resistance is reduced, is 1570 nA. This average current is close to the average current of DG circuit and this result confirms that the results implies that stray electric field energy can be collected using a harvesting circuit grounded to building floor or wall without removing the insulating sheath of the power line. Fig. 5 shows the average current flowing into 6.8 μF storage capacitor versus foil. It can be seen that average current is almost proportional to the foil length.

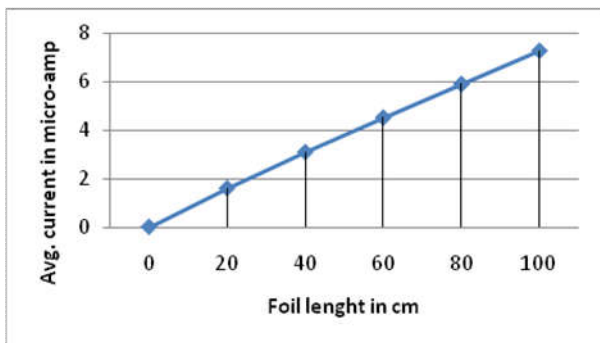


Figure 5. Average current with respect to foil length

Theoretical explanation is as follows. The stray capacitance increases proportional to the length of the foil wrapped around the power line. Because impedance is inversely proportional to the stray capacity in AC, average current flowing into the storage capacitor is proportional to the foil length. Accordingly, the amount of energy that can be collected in a given time increases proportionately to the square of the foil length. Fig. 6 shows the voltage of 6.8 μF storage capacitor for 1 minute when voltage of the power line is changed.

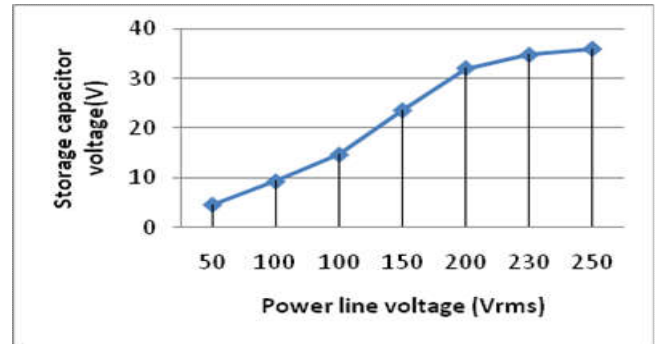


Figure 6. Voltage charged in the storage capacitor for 1 minute versus power line voltage

The foil length used is 60 cm. As shown in Fig. 7(a) and 7(b), the voltage of the storage capacitor for a given time increases almost proportionately to the power line voltage. The result implies that average current stored in the storage capacitor is increased and more energy can be collected. If this property is used to collect energy from high-voltage transmission line, the collected energy may be used to power smart grid sensor for monitoring of power line.

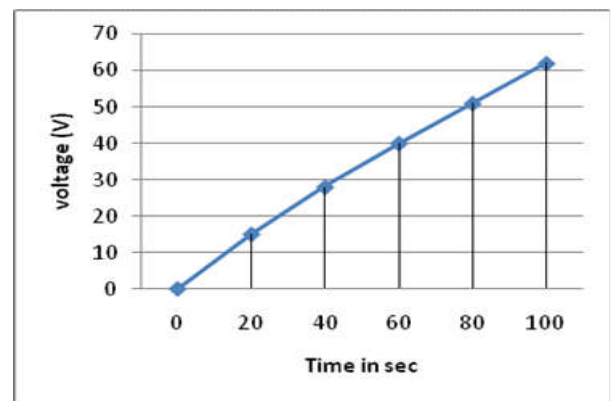


Figure 7(a). Voltage charged in storage capacitor over time

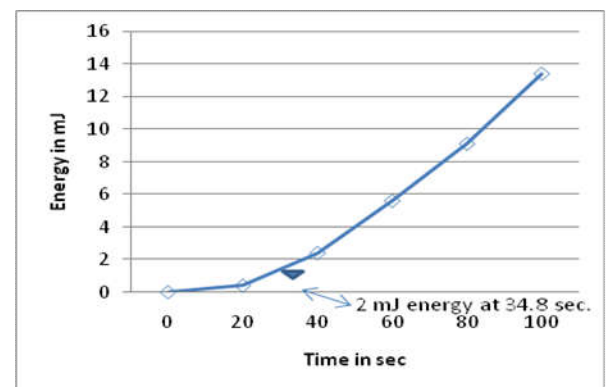


Figure 7(b). Energy charged in storage capacitor over time

Result for energy harvesting wireless sensor node

A 3300 μF capacitor charged to 10.5 V by a solar cell can be used to operate low-power wireless temperature sensor and transmit 100 sessions of radio frequency data to the receiver module in the complete dark (H.S. Kim *et al.*, 2009). This means that it is required about 2 mJ of energy to transmit a single wireless data. Fig. 7 shows the voltage and energy of 6.8 μF storage capacitor over time when 60 cm long aluminum foil is used. In our research found that about 2 mJ of energy is collected in 34.8 seconds.

C1 by the stray electric field energy harvester. When the charged voltage exceeds the breakdown voltage of Zener diode (D1), Q1 is turned on to make the current flow. As a result, voltage is applied to Q2 gate and Q2 is turned on. At this moment, previously disconnected ground path of the circuit is connected, which makes the storage capacitor to discharge and the following circuit to perform wireless data transmission. When voltage of the storage capacitor drops below 5.9 V due to the power consumption, low battery out(L_{Bout}) terminal of voltage regulator is grounded, then Q1 and Q2 are turned off automatically, and storage capacitor is again charged.

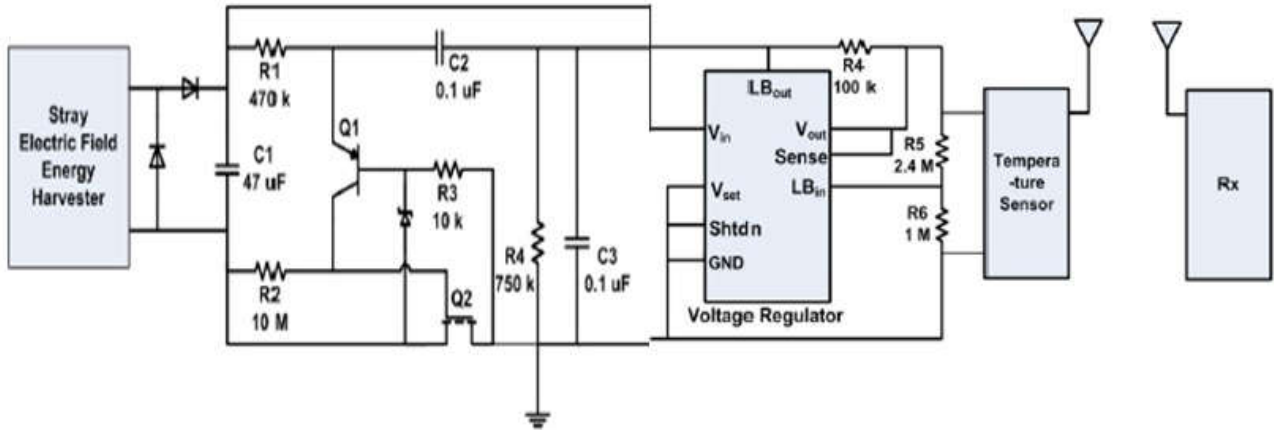


Figure 8. Circuit diagram for wireless node and receiver module

The result implies that temperature measurement, A/D conversion, digital signal processing and RF data transmission can be performed every 34.8 seconds, using the energy collected by wrapping 60 cm aluminum foil wrapping around the AC power line without removing the insulating sheath. Energy for wireless sensor operation must be collected until the stored energy is enough to drive the wireless sensor node and used at once. For this operation, an autonomous connection circuit (ACC) is required which can autonomously connect the sensor node when the harvested energy is high enough to operate the sensor node, and autonomously disconnect the sensor node for the next harvesting stage (Nathan S. Shenck *et al.*, 2001).

This prevents unnecessary discharge of the storage capacitor to 0 V. The Fig. 9(a) shows storage capacitor voltage waveform and received digital data waveform when 60 cm long aluminum foil and 47 μF storage capacitor are used. Completely discharged storage capacitor is charged in 130 seconds to reach 10.9 V, first wireless data transmission then occurs. Subsequently the capacitor starts charging again from 5.9 V and data is transmitted every 42 seconds. Fig. 9(b) shows the detailed digital data waveform of wireless data. It can be seen that voltage of the storage capacitor decreases during RF data transmission.

The experimental results confirm that temperature measurement, A/D conversion, digital signal processing and RF data transmission can be performed every 42 seconds, using the energy collected by wrapping 60 cm aluminum foil wrapping around the AC power line without peeling off the insulating sheath.

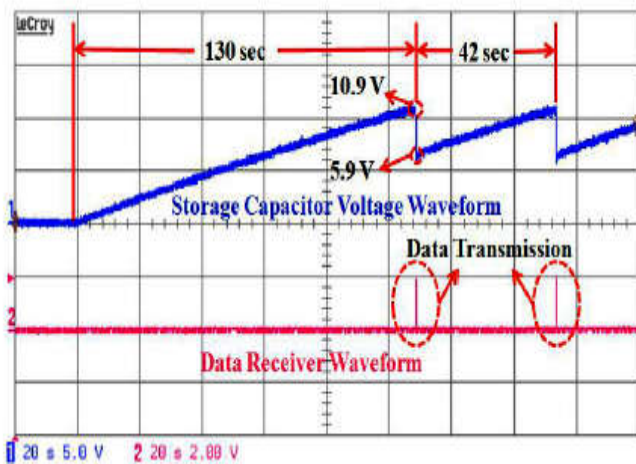


Figure 9(a). Storage capacitor voltage waveform & received digital data waveform

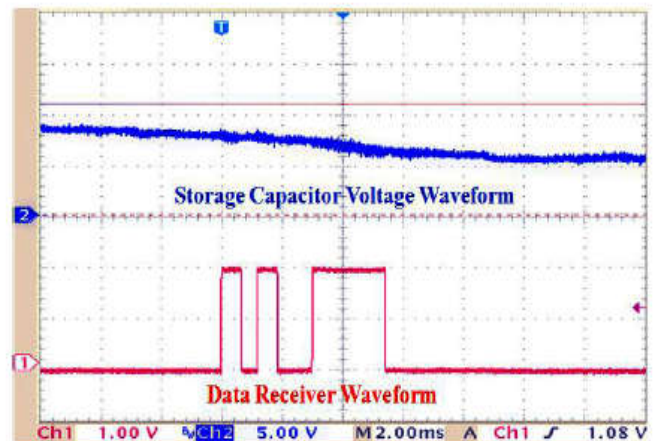
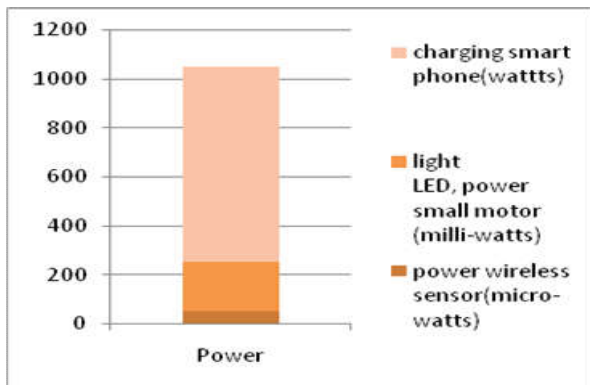


Figure 9(b). Detailed digital data waveform

The Fig. 8 shows the circuit diagram for wireless node and receiver module. Because Q2 is off at first, energy is stored in



What can we do with this energy? In future

Conclusion

In our research, a stray electric field energy harvesting technology of electric power line is presented as a novel concept for energy harvesting. This technology can be used to harvest energy from the power line using very simple energy harvesting circuit and metallic foil wrapped around the power line without peeling off the insulating sheath. It is experimentally confirmed that RF data transmission in every 42 seconds is possible when 60 cm-long aluminum foil is wrapped around a 230 V insulated power line. Because of easy installation, the proposed electric field energy harvesting technology can be employed widely in wireless ubiquitous sensor nodes. Furthermore, greater amount of energy can be harvested near the high voltage power transmission lines, it is believed that the proposed technology can be used to supply electric power to the wireless sensors in smart grid.

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