

# Electric Field Energy Harvesting Powered Wireless Sensors for Smart Grid

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**Abstract** – In this paper, a new energy harvesting technology using stray electric field of an electric power line is presented. It is 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 220 V power line. The average current flowing into 47  $\mu\text{F}$  storage capacitor is about 4.53  $\mu\text{A}$  with 60 cm long cylindrical aluminum foil, and it is possible to operate wireless sensor node to transmit RF data every 42 seconds. The harvested average power is about 47  $\mu\text{W}$  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.

**Keywords:** Stray electric field, Energy harvesting, Wireless sensor node, Smart grid, Self-sustaining sensor

## 1. Introduction

As ubiquitous wireless sensor network (USN) has evolved recently, numerous sensor nodes are being installed in the streets, houses, buildings, automobiles, etc. to realize a “Smart Environment” [1]. 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 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 [2].

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 [3].

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 [4]. To solve this problem, harvesting energy using electric field around commercial insulated 220 V 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:

$$I_d = \varepsilon \int_S \frac{d\mathbf{E}}{dt} \cdot d\mathbf{s} \quad (1)$$

where  $\varepsilon$  is dielectric constant,  $\mathbf{E}$  is electric field intensity. This displacement current can be used to charge the capacitor that is placed near the power line.

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 [4].

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. Rohit Moghe et al. in Georgia Institute of Technology harvested electric field energy by connecting a metal plate through a electric wire to an uninsulated bear wire [4]. This method cannot be applied to insulated power line as the insulating sheath must be removed. In this paper, 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 nodes.

## 2. Proposed Stray Electric Field Energy Harvesting

Fig. 1 shows an experimental setup measuring the energy collected with cylindrical 20 cm aluminum foil wrapped around an insulated no-load AC power line connected to 220 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,

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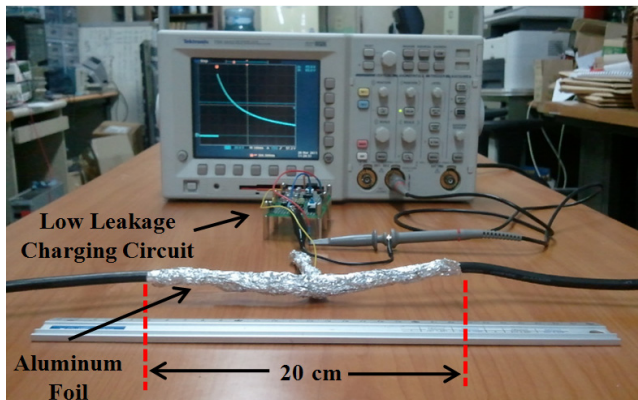


Fig. 1. Experimental setup for stray electric field energy harvesting

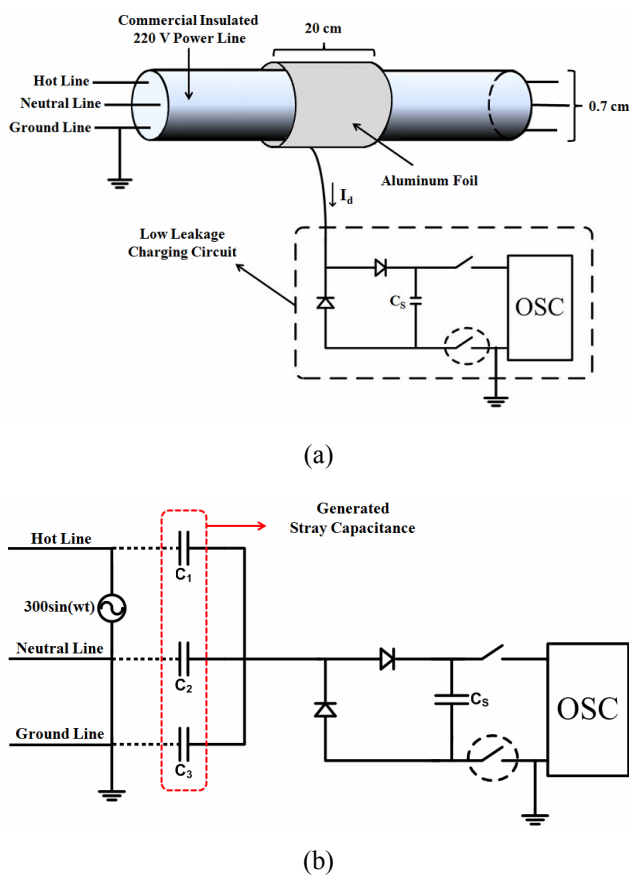


Fig. 2. (a) Diagram of stray electric field energy harvesting experiment; (b) Equivalent circuit

respectively. Equivalent circuit for the experimental setup is shown in Fig. 2.

When aluminum foil is wrapped around the insulated 220 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.

### 3. Experimental results

#### 3.1 Results for electric field energy harvesting

Fig. 3 shows the experimental result when the length of the aluminum foil is 20 cm and the capacitance of the storage capacitor is varied. 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.

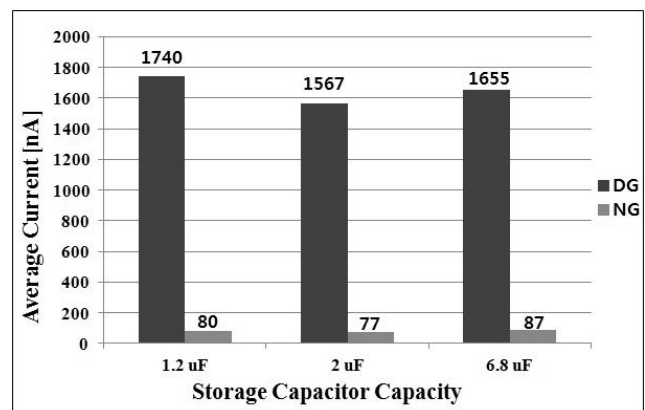


Fig. 3. Average current with respect to storage capacitor capacitance

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  $3 \times 4 \text{ cm}^2$  conductor plate is contacted with concrete floor of building as shown in Fig. 4. 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  $2 \mu\text{F}$  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

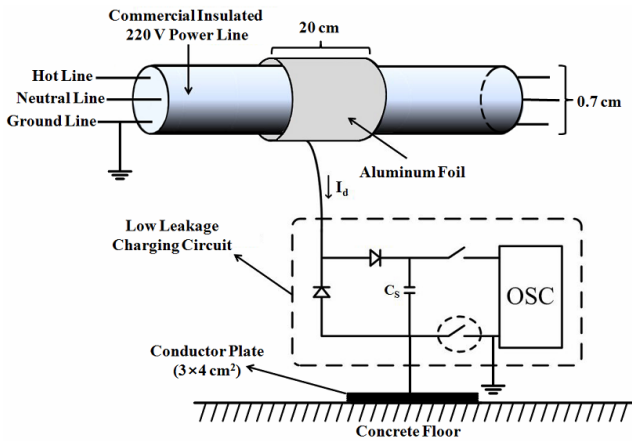


Fig. 4. Diagram of conductor plate Ground harvesting circuit

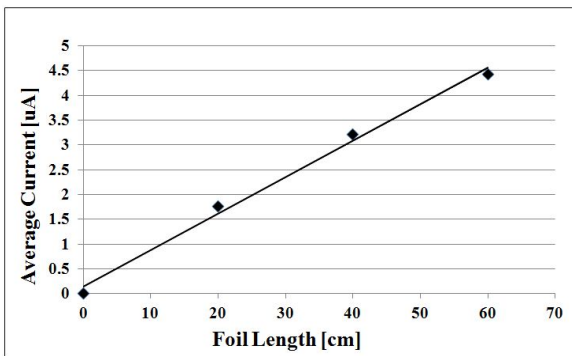


Fig. 5. Average current with respect to foil length

concrete floor of the building is at ground potential. 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  $\mu\text{F}$  storage capacitor versus foil. It can be seen that average current is almost proportional to the 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  $\mu\text{F}$  storage capacitor for 1 minute when voltage of the power line is changed. The foil length used is 60 cm. As shown in Fig. 7, 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.

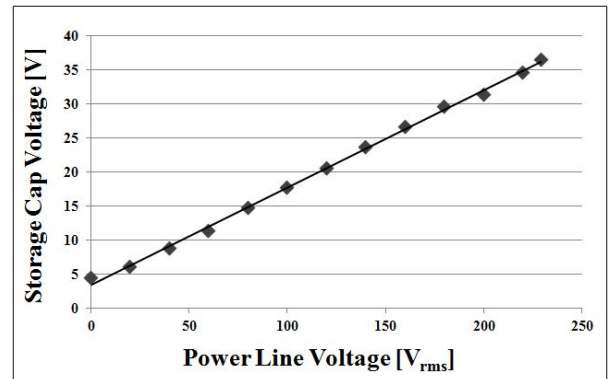


Fig. 6. Voltage charged in the storage capacitor for 1 minute versus power line voltage

### 3.2 Result for energy harvesting wireless sensor node

According to the previous research by the authors, 3300  $\mu\text{F}$  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 RF data to the receiver module in the complete dark [5]. 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  $\mu\text{F}$  storage capacitor over time when 60 cm long aluminum foil is used. It is found that about 2 mJ of energy is collected in 35 seconds. The result implies that temperature measurement, A/D conversion, digital signal processing and RF data transmission can be performed every 35 seconds, using the energy collected by wrapping 60 cm aluminum foil wrapping around the AC power line without peeling off the insulating sheath.

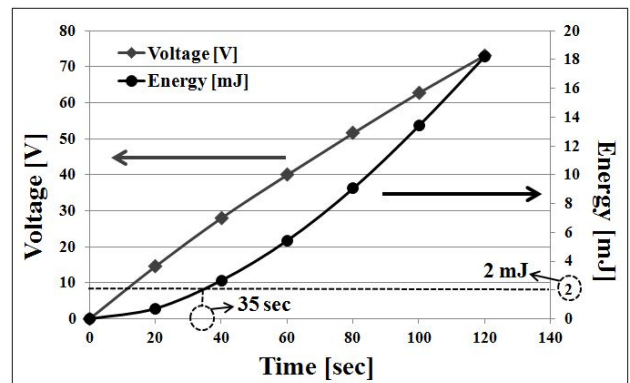


Fig. 7. Voltage and energy charged in storage capacitor over time

Fig. 8 shows the actual circuit used to operate wireless sensor using the collected stray electric field energy. The circuit is composed of energy harvester, power

management circuit, RF wireless sensor node, and RF data receiver circuit.

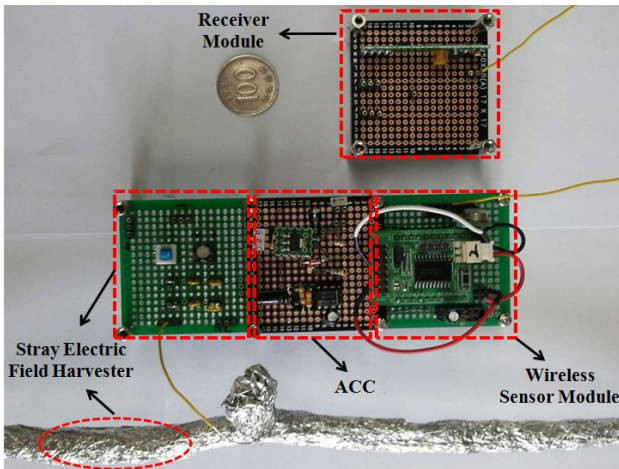


Fig. 8. Manufactured self-sustaining sensor module

Generally, the energy that can be collected by energy harvesting is very small. Therefore, 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 [6].

Fig. 9 shows the circuit diagram for wireless node and receiver module. Because  $Q_2$  is off at first, energy is stored in  $C_1$  by the stray electric field energy harvester. When the charged voltage exceeds the breakdown voltage of Zener diode ( $D_1$ ),  $Q_1$  is turned on to make the current flow. As a result, voltage is applied to  $Q_2$  gate and  $Q_2$  is turned on. At this moment, previously disconnected ground path of the

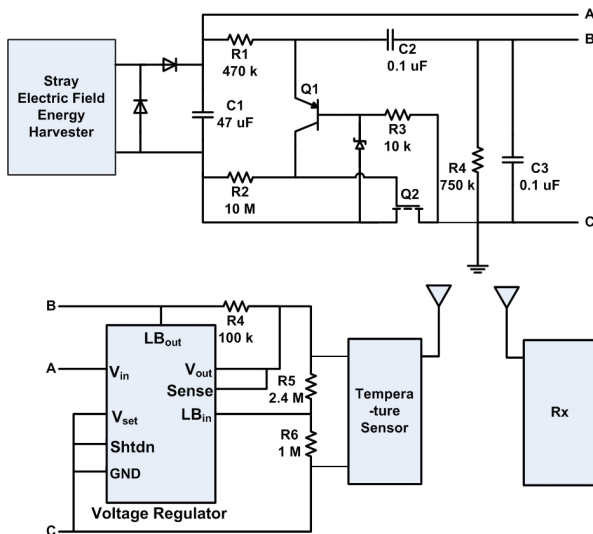
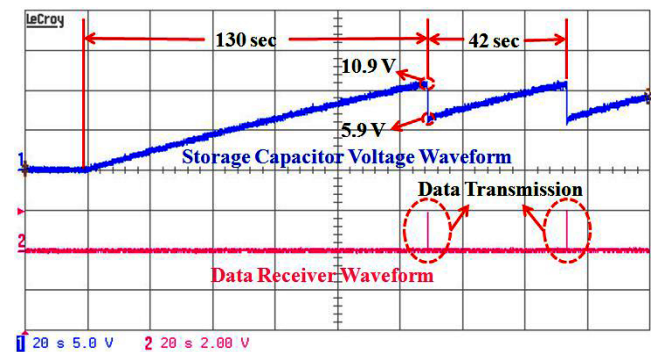


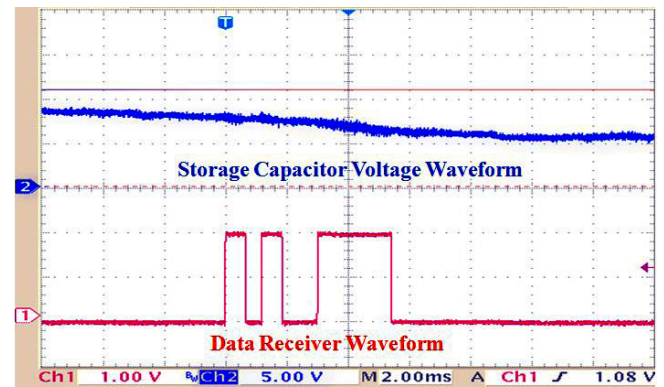
Fig. 9. Circuit diagram for wireless node and receiver module

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(LB<sub>out</sub>) terminal of voltage regulator is grounded, then  $Q_1$  and  $Q_2$  are turned off automatically, and storage capacitor is again charged. This prevents unnecessary discharge of the storage capacitor to 0 V.

Fig. 10(a) shows storage capacitor voltage waveform and received digital data waveform when 60 cm long aluminum foil and 47  $\mu$ F 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. 10(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.



(a)



(b)

Fig. 10. (a) Storage capacitor voltage waveform & received digital data waveform; (b) Detailed digital data waveform



#### 4. Conclusion

In this paper, 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 220 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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