A Low-Cost Electric-Field Energy Harvester for an MV/HV Asset-Monitoring Smart-Sensor

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***Abstract*-- This paper investigates the powering of smart-grid-sensors with electric fields (E-fields) present in abundance near most medium-to-high voltage (MV/HV) utility assets. A unique E-field energy harvester is proposed which is integrated into a sensor's enclosure, thereby ensuring low-cost and compact size. The proposed energy harvester can be used with multiple assets by virtue of its shape which also allows installation without interruption of the MV/HV asset. Design methodology of the harvester through Maxwell simulations along with a new and efficient circuit design for obtaining a regulated DC supply is presented. A medium voltage prototype of the proposed E-field energy harvester integrated with a wireless voltage sensor is built and tested on a 35 kV bus. The prototype provides 17 mW of continuous power at 35 kV with a high energy density. This power is enough to operate a low-duty cycle sensor node stuck-on to an MV/HV asset. The prototype shows promising results and demonstrates the efficacy of using E-fields for powering smart grid sensors for MV/HV assets.**

***Index Terms*—Electric fields, energy harvesting, smart sensors.**

I. Introduction

Grid reliability is of key importance for all utility companies. As demand for electrical energy increases, and as additional variability is introduced to the grid via solar and wind generation, legacy grid assets are being subjected to heightened levels of stress. To maintain and improve system reliability solutions for improving situational awareness, such as distributed grid-wide monitoring, are becoming necessary. Economical implementation of such solutions requires low-cost, self-powered, maintenance-free, wireless sensors [1].

The primary function of these sensors would be to provide periodic information on key health parameters specific a utility asset, such as current, voltage, and temperature. To be easily integrated into a utility system these sensors need to have a long life (>10 years), be self-powered and require no-maintenance.

Of the technological challenges encountered during sensor design, making the sensor self-powered while keeping the cost low is seen as a major issue. Solutions for low-cost self-powering have been proposed that use magnetic fields, mechanical vibrations, solar energy, and electric-fields (E-fields), though only limited research on E-field-powered sensors exists [2]-[7].

With the advent of ultra-low power sensor nodes in the market that can be powered with miniscule amounts of energy, enough to be harvested from the environment, a plethora of techniques become available to power these sensors and avoid the use of batteries [1]. Given that all medium-to-high voltage (MV/HV) utility equipment have abundance of E-fields present near them which can act as a source of energy for operating these autonomous sensors, it is possible to develop new innovative methods to power such sensor nodes using E-fields in addition to magnetic fields.

In this paper, a low-cost E-field energy harvesting technique, conceptualized by the authors in an earlier paper [2], has been detailed, and a prototype has been developed to demonstrate functionality on a high voltage bus.

The paper has been organized in the following manner: Section II presents the E-field energy harvesting basics and a review of earlier research in this area, followed by Section III where an effective design methodology of the E-field harvester is presented through simulations in Maxwell. In Section IV development of a scaled-down laboratory prototype has been detailed and the concept is validated. Section V presents circuit-level considerations of the harvester, and a unique circuit with a minimized component count has been proposed to obtain a regulated DC supply with minimum losses. Finally, Section VII presents the development of a medium voltage prototype of the E-field harvester, along with experimental results on a bus at up to 35 kV. Section VIII concludes the paper.

II. Electric Field Energy Harvesting- A Review

According to Maxwell's equation, a time-varying E-field produces a displacement current. This current can be used to charge a pair of conducting plates, storing the E-field energy in a capacitor, as shown in Fig. 1(a). In order to power a smart sensor with the size and current draw similar to the sensor of [1], an average of 470 μW needs to be continuously harvested from a particular E-field to allow for sustained sensor operation.

The theoretical concept of E-field energy harvesting was first proposed by the authors in a scoping study of electric and

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magnetic field energy harvesting [2]. However, it was shown that for low voltage applications E-field energy harvesting was not a feasible approach for powering wireless sensors due to possible size constraints. Therefore, this approach was not validated experimentally. However, for MV/HV assets, E-field energy harvesting was found to be worth pursuing.

Other authors have used a similar approach and have validated the concept of the E-field energy harvesting. For instance, in [3] authors experimentally show that a maximum energy of 148 μJ/m^3 can be harvested from a 400 kV substation having a maximum E-field strength of 5.8 kV/m, at 10 m above the ground plane.

In [4], authors show experimental testing of an approach similar to the concept introduced in [2]. The system harvests a discontinuous power of 15-20 μW from a 132 kV line. As the plate dimensions are not provided, an estimate on the power density in not available.

In [5], authors present a cylindrical energy harvester that wraps around an overhead conductor and uses a transformer to step down the developed voltage. The tubular harvester has a diameter of 30 cm and height of 55 cm. At 50 kV, close to 50 mW of power is harvested from the E-fields. The authors do not give details on the nature of this power, continuous or discontinuous.

In a similar investigation, authors present another cylindrical energy harvester [6][7]. The harvester has a smaller size than [5], but has a much larger power density; at 50 kV, it can harvest 13 mW of power. However, this power is discontinuous and is made available only after several minutes (15 – 20 min) of capacitive charging. Therefore, the average power density of the approach is quite low ~11 μW/cm^3.

In summary, the bulk of the research conducted in this area and the designs presented:

- are large in size, to allow for the harvesting of enough energy, and thus have low power densities
- are constrained in shape, e.g. most are cylindrical in shape, and need to clamp around a conductor, which limits them to harvesting energy near cables only, and precludes their use near assets with rectangular cross-sections
- are unwieldy to install, increasing the effective cost of the sensor
- have not been shown to integrate to a wireless sensor node

The E- field energy harvesting method presented in this paper attempts to avoid most of the above mentioned limitations and allows easy integration with a utility asset monitoring smart-sensor.

III. Designing An E-Field Harvester

The objective of achieving a small size or higher power density, and a low-cost requires optimal design of the energy harvester. Consider a system of two plates near an overhead conductor. The time varying E-field emanating from the energized conductor produces a displacement current which charges a capacitor formed by the two plates. It was shown through theoretical derivations in [2] that in such a system the harvested energy can be maximized by connecting one of the plates to the conductor rather than electrically floating the system. Such a system and its equivalent circuit are shown in Fig. 1.

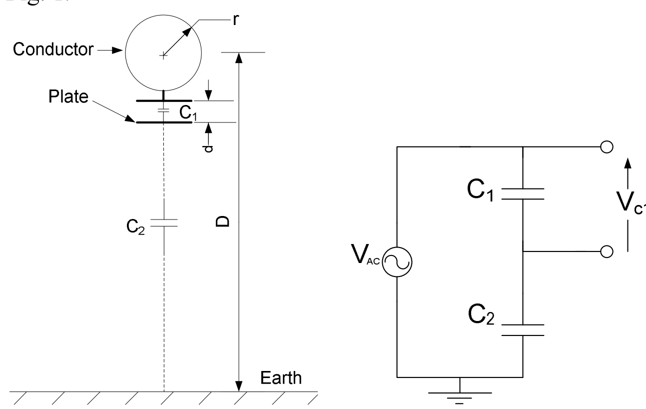


Fig. 1. (a) A two-plate system forming an E-field energy harvester with one plate bonded to the conductor above the earth for maximizing power, (b) equivalent circuit of system shown in (a)

Capacitance C_1 is given by in (1), where the capacitor's plates are assumed to be square and b^2 represents the plates' cross-sectional area.

$$C_1 = \frac{b^2 \varepsilon_o \varepsilon_r}{d} \tag{1}$$

The expression of C_1 is valid if the distance between the two plates is small as compared to the width (b) of the plates, and the distance of the plates from the earth is large. In a realistic scenario, due to the presence of fringing at the edges of the plates, the value of actual capacitance is slightly larger than the theoretical value.

The value of capacitance C_2 can be found by using the method of images and considering only the capacitance of the conductor over ground. The expression for C_2 is given by

$$C_2 = \frac{2\pi b \varepsilon_o}{\ln\left(\frac{2D}{r}\right)} \tag{2}$$

The voltage induced across the two plates, V_{C1} and peak power harvested are given by (3) and (4), where $V_{pk}\sin(\omega t)$ is the voltage of the conductor and V_{ac} is equal to $V_{pk}/\sqrt{2}$.

$$V_{C_1} = \frac{C_2}{C_1 + C_2} V_{ac} \sqrt{2} \sin(\omega t) \tag{3}$$

$$Q_{C_1} = \omega C_1 V_{C_{1RMS}}^2 = \frac{\omega C_1 C_2^2}{\left(C_1 + C_2\right)^2} V_{ac}^2 \tag{4}$$

Similar to the classical theorem of maximum power transfer, if we want to maximize Q_{C1}, a constraint can be found regarding the dimension of the plates, b, by setting C_1 equal to C_2, as given by (5). However, it should be noted that under typical system conditions, in order to keep the sensor reasonably small C_1 will always end up being much larger than C_2.

$$b = \frac{2\pi}{\varepsilon_r \ln\left(\frac{2D}{r}\right)} d \tag{5}$$

Using the above constraint on b, and with C_1 equal to C_2, the maximum possible reactive power of C_1 is given by

$$Q_{C_1}^{max} = \frac{\omega V_{ac}^2 \pi^2 \varepsilon_o d}{\varepsilon_r \left[\ln\left(\frac{2D}{r}\right)\right]^2} \tag{6}$$

With fringing effects taken into account, it is prudent to use finite element analysis (FEA) to compute accurate capacitances. Simulations showed a relatively large difference attributed to fringing (> 20%) between the theoretical results and simulated values. Therefore, Maxwell's FEA is used for further analysis in the paper. A sample Maxwell simulation shown in Fig. 2.

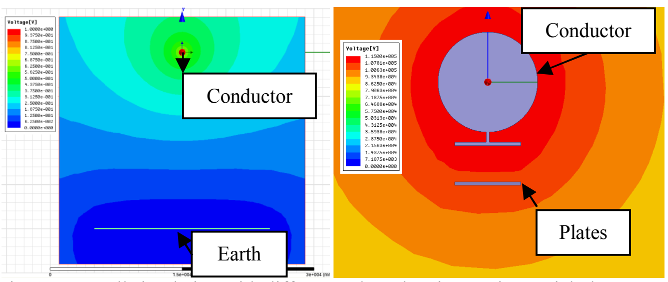
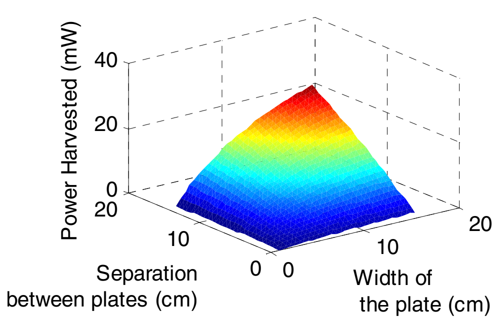


Fig. 2. Maxwell simulation with different colors showing equipotential planes

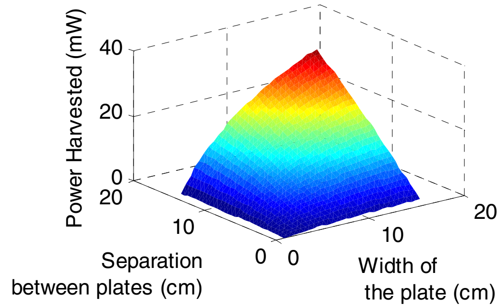
A range of simulations were performed to compute the power harvested and power density for a variety of cases. The range of values of d, b, D, ε_r and V_{ac} over which the peak harvested power was computed are given in Table I. The radius of the conductor was fixed at 15 mm. To test the feasibility of the concept, a total of 1800 distinct simulations were run and power for every parameter combination was computed. The results of the simulation are shown in Fig. 3.

TABLE I
SEARCH SPACE FOR THE OPTIMAL DESIGN

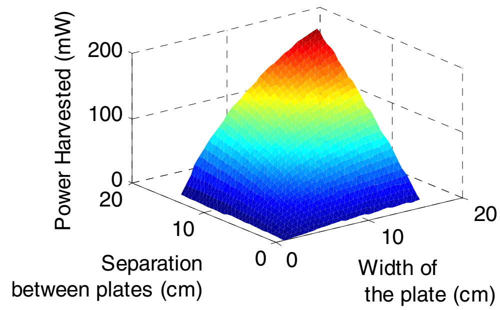
Parameter	Minimum value	Step size	Maximum value
b	1 cm	0.5 cm	15.5 cm
d	1 mm	0.5 cm	14.6 cm
ε_r	1	1	2
V_{ac}	25 kV	44 kV	69 kV
D	7.5 m	7.5 m	15 m



a) D = 15 m, V_{ac} = 25 kV, ε_r = 1



b) D = 7.5 m, V_{ac} = 25 kV, ε_r = 1



c) D = 15 m, V_{ac} = 69 kV, ε_r = 1

Fig. 3. Sensitivity analysis of power harvested from E- field with respect to change in dielectric constant, distance between plates, plate size and voltage

The following trends can be observed from Fig. 3.

1. The harvested power increases non-linearly with an increase in width of the plate b and distance between the plates d.
2. A decrease in the distance between the conductor and the earth D marginally increases the power harvested by the plates.
3. The harvested power increases dramatically with an increase in conductor voltage as it follows a squared relationship.

These plots can be used to design an effective E-field energy harvester. It can be observed that the power density reduces dramatically with an increase in line voltage. Consider, for instance, the width of the plates and the distance between the plates to be 15 cm each, then at 25 kV around 27 mW of peak power can be harvested. However, the power density is only 7.4 μW/cm^3. If the voltage is increased to 69 kV, the power density becomes 59 μW/cm^3. For a sensor similar to that of [1], and with a reasonable E-field energy harvestor size of 15 cm x 15 cm x 1 mm, the power density requirement for sustained operation is 21 μW/cm^3. Therefore, E-field energy harvesting becomes suitable for this sensor application at higher voltages.

IV. VALIDATION OF CONCEPT AT LOW VOLTAGE

To validate the concept of E-field harvesting a two plate system was built in the lab. The schematic of the setup is shown in Fig. 4(a). The actual setup is shown in Fig. 4(b). The setup comprises three plates; the top plate mimics a utility asset and is connected to a variable autotransformer, the middle plate is the energy harvesting plate which gets charged by the displacement current, the bottom plate is kept at the ground potential. The sizes of the plates and the distance between them are given in Table II.

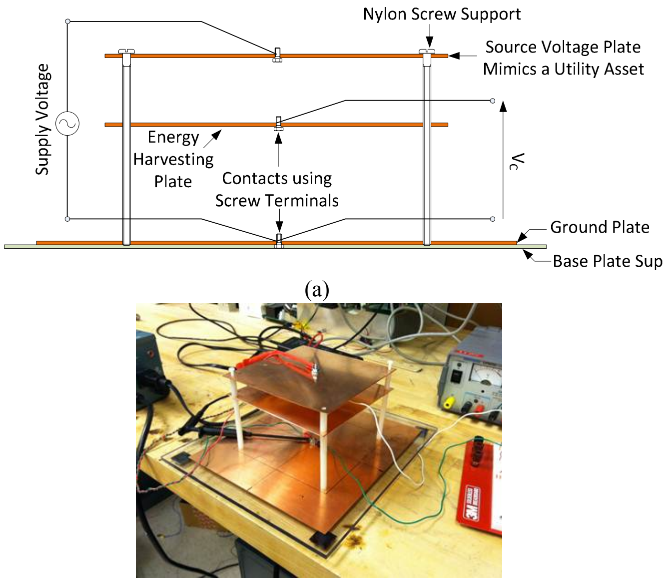


Fig. 4. a) Schematic of E-field energy harvesting test setup, (b) Actual lab test setup used to validate the concept of E-field energy harvesting

TABLE II
DIMENSIONS OF THE LOW-VOLTAGE E- FIELD ENERGY HARVESTER

Top Plate Dimensions (bxbxt) (mm)	Middle Plate Dimensions (bxbxt) (mm)	Bottom Plate Dimensions (lxwxt) (mm)	Top-to-Middle Plate Distance (mm)	Middle-to-Bottom Plate Distance (mm)
152 x 152 x 1	152 x 152 x 1	215 x 254 x 1	24	100

The energy was harvested by rectifying the AC voltage induced on the middle plate with respect to the ground plane to form a DC voltage across a DC capacitor. To compute the power harvested, the DC capacitor was discharged using different known load resistances (R_{Li}) and the voltage across the load resistor was measured. The power harvested was computed using V^2/R_{Li}. The circuit schematic of the E-field energy harvesting setup is shown in Fig. 5. The harvested power and power density under different conditions are shown in Fig. 6.

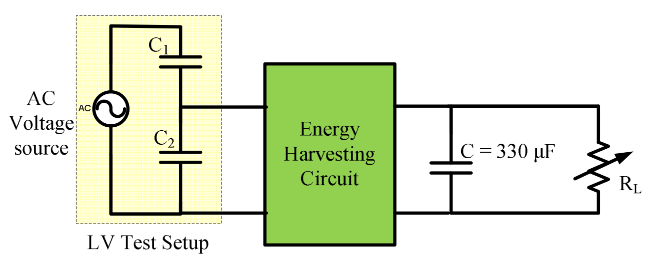


Fig. 5. Circuit schematic of the low-voltage prototype

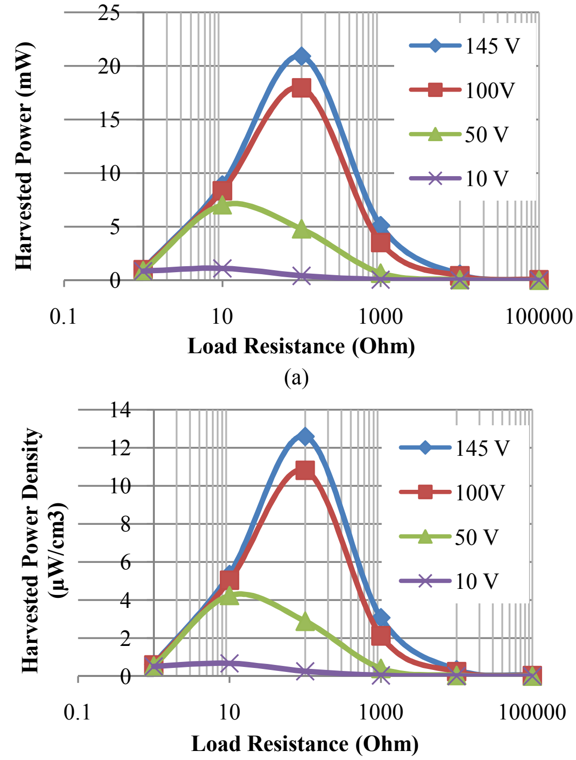


Fig. 6. Plots showing power and power density of the low-voltage E-field energy harvester at different loading levels and asset potential.

The experimental results validate the concept of E-field energy harvesting using a two-plate system. The maximum power that was harvested using the developed system was close to 20 mW, which may be sufficient for certain low duty cycle sensing applications. The experimental results show promise in the concept. Given that voltage sensing is of interest for many utility assets such as overhead conductors, disconnect switches etc., E-field energy harvesting can be a viable option for powering medium and high voltage sensors.

V. CIRCUIT CONSIDERATIONS

Apart from designing an optimal E-field energy harvesting system, it is essential to design an efficient and low-cost circuit for converting AC to regulated DC power. In this section, the circuit considerations of an E-field energy harvesting system are presented in detail. Consider Fig. 7 to be representative of the equivalent circuit of the considered E-Field energy harvesting system.

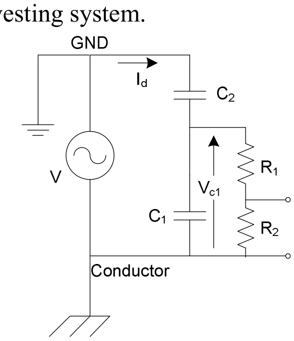


Fig. 7. Representative circuit used for circuit analysis

Note that the figure is flipped as compared to Fig. 1(b). Without any loss of generality, conductor is considered at the bottom and the ground potential is at the top. The reason being that the conductor acts as the reference potential for the energy harvester circuit. Capacitors C_1 and C_2 are system specific and depend on the height of the conductor above the earth and the construction of the energy harvester. In a realistic system, the values of C_1 and C_2 are in tens of picofarads and C_1 is much greater than C_2. R_1 and R_2 form a resistive divider to tap the voltage such that the fields can be converter to useful work, with R_1 chosen to be much greater than R_2. The system essentially acts like a current source. This can be proved as follows:

The displacement current through the circuit is given by

$$I_d = \frac{V\left(j\omega C_2 - \omega^2 C_1 C_2 \left(R_1 + R_2\right)\right)}{1 + j\omega\left(C_1 + C_2\right)\left(R_1 + R_2\right)} \tag{7}$$

Given a realistic system, and choosing R_1 and R_2 appropriately, the following inequality hold

$$1 >> \left|\omega\left(C_1 + C_2\right)\left(R_1 + R_2\right)\right| \tag{8}$$

If the above inequality is true, so is the following one

$$1 >> \left|\omega C_1 \left(R_1 + R_2\right)\right| \tag{9}$$

Multiplying ωC_2 on both sides of the expression,

$$\omega C_2 >> \left|\omega C_1 C_2 \left(R_1 + R_2\right)\right| \tag{10}$$

Using these inequalities, (7) can be reduced to

$$I_d = jV\omega C_2 \tag{11}$$

As C_2, ω, and V are system dependent, if it is assumed that these quantities do not change significantly over time, I_d becomes a time-invariant quantity. Therefore, the system acts like a current source within the bounds of the assumptions that were considered above.

Further, rearranging (9)

$$\left|\frac{1}{\omega C_1}\right| >> \left|\left(R_1 + R_2\right)\right| \tag{12}$$

Equation (12) shows that most of the current I_d flows through R_1 and R_2, while C_1 is bypassed.

Using this information, an optimal circuit can be designed for harvesting E-fields. As the sensor circuits require DC voltage from 2.5-5 V for operation, the voltage tapped by the resistor needs to be rectified and conditioned. Some approaches for achieving these objectives are given in Fig. 8. The simple half-wave and full-wave rectification techniques are a robust method of obtaining an unregulated DC voltage at the output. However, these methods require additional components to regulate the voltage without significant loss of efficiency. Fig. 8(c) shows a buck converter after the AC/DC stage that produces a regulated DC output. However, this approach uses filter components such as inductors which can make the circuit large in size. Furthermore, the efficiency of this approach is reduced due to the presence of a multiple power conversion stages, namely AC/DC and DC/DC.

A direct AC/DC regulated conversion approach has been suggested in Fig. 8(d) (circuit A). This circuit uses the fact that the input is essentially a current source and therefore does not need any filter inductors. Moreover, it uses fewer components than the two stage conversion technique. The modes of operation of Circuit A are given in Table III. This circuit was simulated using MATLAB and the results are shown in Fig. 9.

Another approach is also proposed in Fig. 10 (circuit B), which uses fewer components than circuit A. The modes of operation of circuit B are given in Table IV. This circuit was also simulated using MATLAB and the results are shown in Fig. 11. Although, circuit A is superior to the two-stage power conversion technique in terms of efficiency, circuit B is even more attractive than circuit A. A qualitative comparison between the two proposed circuits is given in Table V.

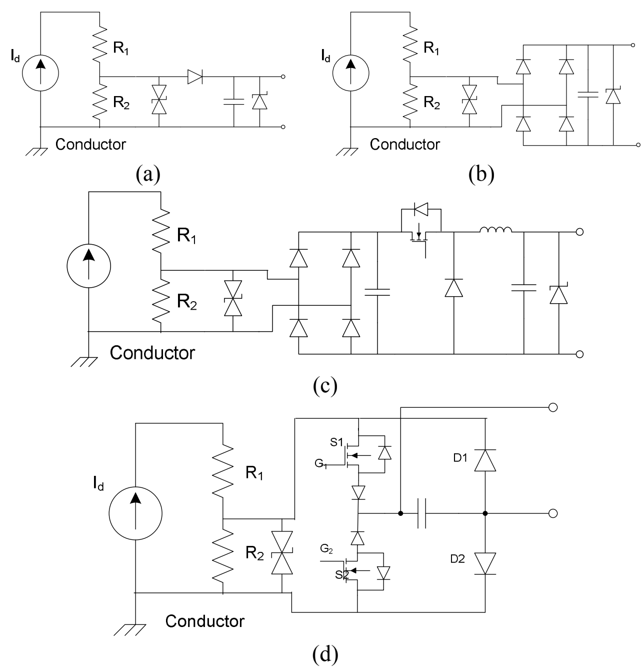


Fig. 8. (a) Half-wave, (b) Full-wave unregulated supply, (c) Two-stage AC/DC regulated supply, (d) Proposed single-stage AC/DC supply (circuit A)

TABLE III
MODES OF OPERATION

Mode	I_d	Switch State	Operation
1	Positive (Negative)	S1 ON (S2 ON)	I_d flows through S1 (S2), D2 (D1) and charges the output capacitor
2	Positive (Negative)	S1 OFF & S2 OFF	I_d flows through R1 and R2, output capacitor is bypassed
3	Positive (Negative)	S2 ON (S1 ON)	I_d flows through S2 (S1), D1 (D2) and charges the output capacitor

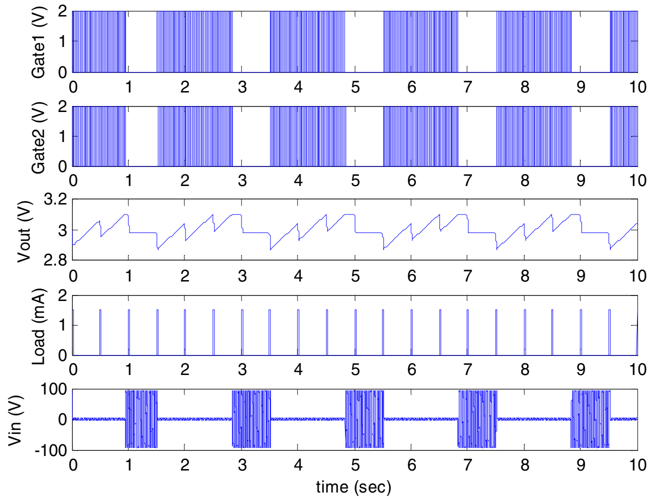


Fig. 9. MATLAB simulation of circuit A shows DC voltage regulation at 3 V under a pulsed load current of 1.5 mA every 0.5 sec, C_1= 100 pF, C_2=10 pF, R_1=2 MΩ, R_2=500 kΩ, C_{dc}=330μF

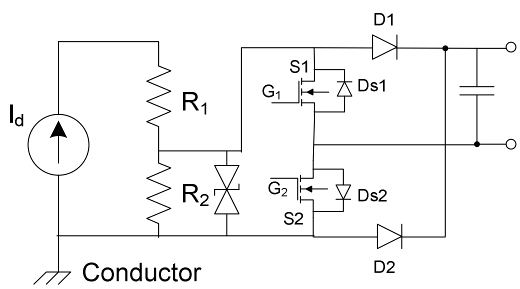


Fig. 10. Proposed superior single-stage AC/DC supply (circuit B)

TABLE IV
MODES OF OPERATION

Mode	I_d	Switch State	Operation
1	Positive (Negative)	S1 ON & S2 ON	I_d free-wheels through S1 and Ds2 (S2 and Ds1)
2	Positive	S1 OFF & S2 OFF	I_d flows through Ds1, capacitor, Ds2 and energy is transferred to output
3	Negative	S1 OFF & S2 OFF	I_d flows through D2, capacitor, Ds1 and energy is transferred to output

TABLE V
QUALITATIVE COMPARISON OF THE TWO PROPOSED SINGLE-STAGE REGULATED AC/DC SUPPLIES

Circuit A	Circuit B
Requires complex gate drive circuitry as the gate pulses need to be higher than the positive DC supply to turn on the MOSFETs	As the gate is referenced to the ground, gate pulses are easy to synthesize
Requires independent control of the two switches	Both switches are turned on and off simultaneously
Requires input voltage polarity information	Does not require input voltage polarity information
Higher voltage stresses on switches S1 and S2, which leads to increased cost	Lower voltage stresses on switches S1 and S2, which leads to reduced cost
Higher losses than circuit B, as one switch and two diode drops are seen	Lower losses than circuit A, as only two diode drops are seen

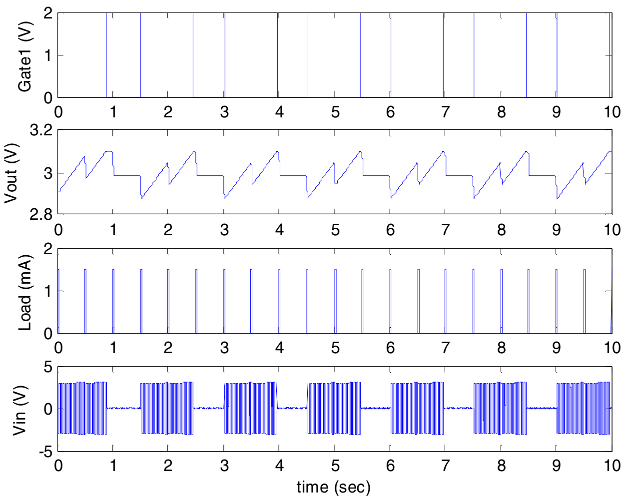


Fig. 11. MATLAB simulation of circuit B shows DC voltage regulation at 3 V under the same simulation setup as Fig. 9.

VI. MEDIUM VOLTAGE PROTOTYPE

A prototype of the energy harvester was built to test the efficacy of the approach introduced in this paper. The schematic of the developed self-contained energy harvester prototype is shown in Fig. 12. The energy harvester prototype uses the metallic enclosure as one plate of the E-field energy harvesting capacitor. The metallic enclosure comes in contact with the high voltage asset and is naturally shorted to it at the time of installation. A modification to the enclosure is made in that another metallic plate is provided at one end of the enclosure separated by a small distance (~1 mm). The thin capacitor formed by the metallic plate and the enclosure act as the energy harvester. The enclosure houses the energy harvester circuitry, signal conditioning, and protection circuitry, with room for any other electronic components desired to be added to the enclosure for additional applications such as voltage sensing. This E-field energy harvester can be integrated into the metal enclosure at the time of manufacturing, allowing a simpler assembly of the final product. The concept of using a metal plate integrated into the enclosure as the energy harvester is a novel concept introduced in this paper which helps in increasing the overall performance of the energy harvester by increasing its power density. The energy harvesting metal enclosure acts as a Faraday cage for the electronics and protects them from corona discharge and high E-field gradients.

In this research, a standard-sized aluminum enclosure was used for building the energy harvester unit. Note that the size of the energy harvester can be further reduced but for the sake of adding functionality, such as voltage sensing, and to maintain workability for this proof-of-concept prototype, the energy harvester was made intentionally larger than required. The actual prototype of the energy harvester is shown in Fig. 13.

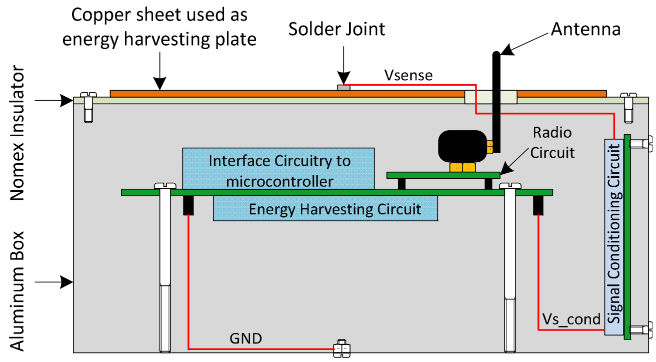


Fig. 12. Final energy harvester prototype schematic to show E-field plates (The size of the harvester is relatively large for the proof-of-concept prototype)

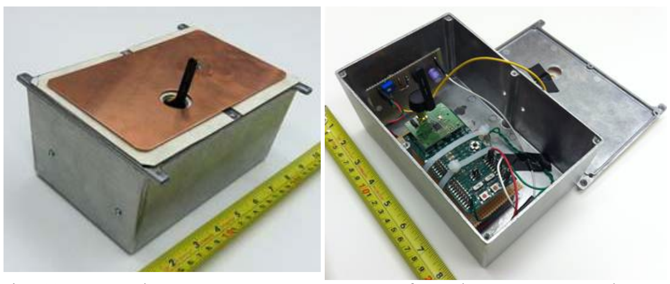


Fig. 13. Energy harvester prototype as a part of a voltage sensor tested at NEETRAC (plate dimension 12.7 cm x 7.6 cm x 1 mm)

A block schematic of the experimental setup is shown in Fig. 14. The fabricated prototype was also used to integrate a new voltage sensing technique, which is explained in a companion paper [8]. The circuit rectifies the AC voltage, the rectified signal is buffered using a voltage follower circuit and subsequently low-pass filtered. The signal is then fed into one of the ADC channels of the microcontroller of a TI-CC2530 module. Thereafter, the signal is processed and passed to an algorithm which computes the voltage of the asset. The voltage data is then used to compute an indicator of harvested energy, which is transmitted to a remote coordinator via ZigBee®.

The actual test system used to demonstrate the energy harvested by the prototype is shown in Fig. 15. The setup uses a step-up transformer that can produce voltages up to 100 kV. To mimic a practical scenario of an overhead line, a voltage bus was connected to the transformer and the voltage sensor prototype was attached to this high voltage (HV) bus. The HV bus was 1 m above the earth.

During the experiment the input voltage was varied over 5-35 kV. The output load resistance was varied from 25 Ω to 5 kΩ. The results of the experiment are shown in Fig. 16.

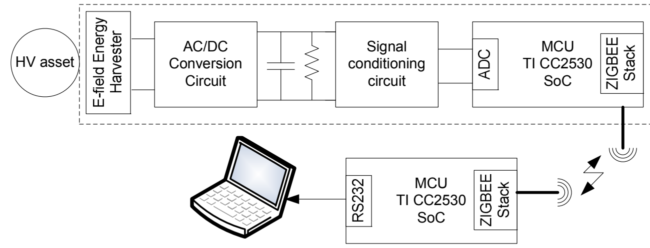


Fig. 14. Block schematic of the energy harvesting experiment

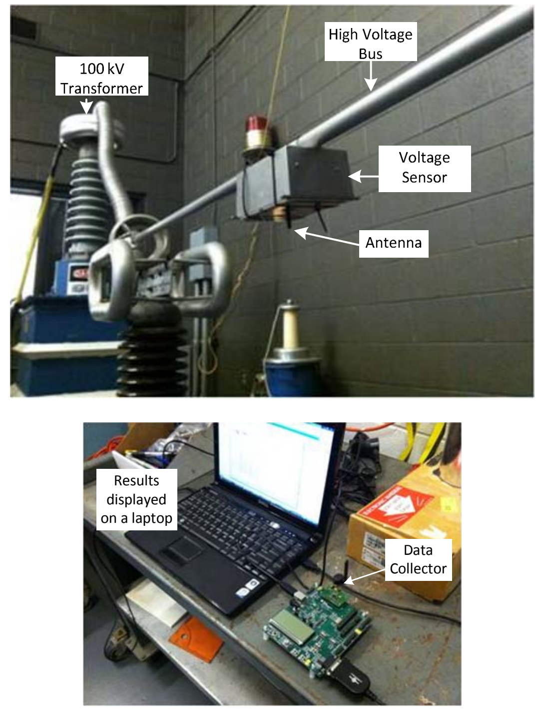


Fig. 15. Actual test setup at NEETRAC

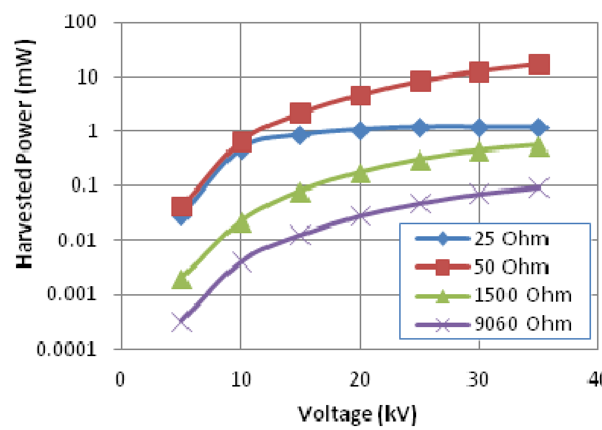


Fig. 16. Power harvested from developed prototype at different output load levels and asset voltages

It can be seen that at 35 kV, nearly 17 mW of continuous power was derived, giving the system a power density of 1870 $\mu W/cm^3$. This is about twenty times larger than the simulations of the previous section; the smaller *D* (2 m vs 15

m) and larger r (6 cm vs 1 cm) of the experimental setup are the main contributors to this discrepancy. Also, it should be noted that the 17 mW of harvested power is continuous. The effective power can be larger for the burst-type operation that is typical for lower duty cycle sensor operation. Moreover, with further increase in voltage levels, the power harvested will increase. This particular prototype was used for the dual purpose of voltage sensing and energy harvesting with the same package.

VII. Conclusions

This paper presented a new approach for low-cost E-field energy harvesting. This method was shown to be easily integrated into a smart grid sensor (a voltage sensor in this paper). Unlike previous work in this area, the energy harvester was not cylindrical and has the potential of being used for different types of MV/HV utility assets. A design methodology for the harvester was presented along with a new circuit for converting AC power directly into regulated DC sensor power supply. The proposed circuit has a lower component count and fewer losses as compared to other two-staged approaches. A medium voltage prototype was built and integrated with a voltage sensor. Experimental results showed a continuous power of 17 mW at 35 kV bus voltage. This power is enough to operate a low-duty cycle sensor node attached to a MV/HV asset. The prototype shows promising results and demonstrates the efficacy of using E-fields for powering MV/HV smart grid sensors.

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