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An Electric Field Energy Harvesting System Prototype for Smart High-Voltage Transmission Grids

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Abstract. The increasing deployment of smart power lines and smart grid infrastructures requires a large number of distributed Internet of Things (IoT) devices for wireless monitoring, which has motivated the development of autonomous, maintenance-free power supplies. Electric-field energy harvesting (EFEH) exploits the displacement current induced by the time-varying electric field surrounding alternating-current power conductors. This enables non-contact energy extraction, the available power of which scales primarily with line voltage, capacitive coupling and operating frequency, while remaining independent of line current. This paper presents the design and laboratory validation of a complete EFEH system for high-voltage power lines comprising a harvesting interface, a rectification stage and power management circuitry. The system was evaluated in a controlled high-voltage cage. The experimental results demonstrate the functionality of the proposed system in sustaining intermittent wireless operation at an applied voltage of 10 kV. This capacity is evidenced by the successful transmission of Bluetooth Low Energy sensor data at 130-second intervals. These results provide experimental evidence to support the displacement-current scaling laws theoretically predicted for EFEH and clarify its practical operating limits as a power source for battery-less smart-grid IoT devices.

Key words. Energy harvesting, electric field, high voltage, ultra-low-power electronics.

1. Introduction

Electric-field energy harvesting (EFEH) is a non-contact capacitive technique used to extract energy from the electric field surrounding alternating-current (AC) power conductors. The time-varying electric field thus induces a displacement current between the energised conductor and the nearby electrode, which can be rectified and stored to supply ultra-low-power electronic devices. In light of Maxwell's electromagnetic theory, EFEH has been identified as a potentially viable power supply solution for distributed smart grid monitoring. This is due to its ability to function reliably in all weather conditions, its compatibility with existing transmission infrastructure, and its lack of galvanic contact. EFEH is especially well-suited to conductors with voltage present but little or no current, such as lightly loaded or standby transmission lines, when compared with harvesters based on magnetic fields or vibrations [1-3].

Early experimental validation was demonstrated on low-voltage insulated conductors. In [3], wrapping an aluminium foil sleeve around an insulated AC power line produced an average charging current of 4.53 µA and an average harvested power of 47 µW when using a sleeve measuring 60 cm and a capacitor with a value of 47 µF. This enabled wireless sensor transmissions at 42-second intervals. For low-voltage domestic lines, switching-based charge management strategies were introduced to overcome limitations caused by parasitic capacitance. In reference [4], an actively controlled system operating on a 230 V, 50 Hz line achieved a DC output power of 367.5 µW using a 90 cm copper sheet. This represented a 95.6% improvement on conventional rectification, with an output voltage of approximately 105 V across a 30 MΩ load.

Recent research in the field of electric field harvesting has shifted towards medium- and high-voltage (MV/HV) distribution and transmission lines, where stronger electric fields enable greater power harvesting. Kang et al. [5] demonstrated the first instance of autonomous operation of a wireless sensor node powered by electric-field energy harvesting under actual three-phase 765 kV transmission lines. The placement of a conductor tube covered with aluminium foil between the lines and ground forms a capacitive voltage divider that harvests displacement current, independent of the line load. The harvested energy is rectified, stored, and managed by a hysteretic power-management circuit, enabling intermittent operation of a Zigbee-based temperature sensor. Field measurements demonstrated harvested powers of approximately 0.17 mW at a 4 m height, enabling wireless data transmission at intervals of approximately 25 s. The transmission period exhibited an inverse proportionality to the square of the installation height. Zeng et al. [6] presented a study on an

EFEH power source for a 110 kV transmission line. They reported displacement currents ranging from tens to hundreds of microamperes, with an energy harvesting capacity of 620 µW/µA. They also demonstrated conversion efficiencies of up to 61% and milliwatt-level DC output power using a four-stage ladder conversion circuit. Srilaket et al. [7] presented a high-energy EFEH architecture on a 67 kV bus bar, surpassing milliwatt-class systems. They achieved approximately 5 W with a single harvesting line and up to 6.88 W with dual lines. This system delivered 11.78 V and 274.4 mA, sufficient to power a 5 W LED directly, with a maximum harvesting capability of approximately 0.5 W per unit length.

Concurrent with these power-scaling endeavours, research has emphasised the fundamental limitations and system-level trade-offs inherent to EFEH. Riba et al. [8] systematically quantified the physical constraints imposed by capacitive coupling, parasitic capacitances, and voltage level. The findings of the study demonstrated that, while harvested power scales favourably with voltage, practical performance is strongly influenced by geometry, grounding conditions, and power-management efficiency.

Further efficiency improvements have been achieved through active charge-transfer management. In [9], a low-potential EFEH prototype operating at an equivalent voltage of 110 kV was found to achieve open-circuit voltages of 3.88 kV, short-circuit currents of 50.5 µA, and transferred charges of 165 nC. Meanwhile, average output power increased from 0.043 mW to 48.3 mW thanks to dedicated power management. Building on these findings, doctoral research in [10] presented a system-level framework for MV EFEH. This system demonstrated an output power of 17.1 mW from a 12.7 kV line via a self-triggered pulsed flyback converter with displacement currents of 150–170 µA. Together, these studies demonstrate that active charge-transfer control and power electronics design are critical factors in maximising harvested power in MV EFEH systems. This makes system-level optimisation more important than electrode scaling for deployable smart grid monitoring applications.

Micallef et al. [11] proposed a non-intrusive electric-field energy harvesting (EFEH) system for powering batteryless wireless sensor networks under 525 kV power lines. Utilising an analytically validated capacitive coupling model, a two-plate aluminium harvester integrated with rectification, energy storage, and an ultra-low-power hysteretic comparator facilitates intermittent operation of a commercial Zigbee-based sensor without the necessity of galvanic contact or external grounding. As demonstrated by field experiments, approximately 3.3 mJ is recovered in less than 40 seconds, corresponding to an average harvested power of 66–83 µW. This is sufficient for periodic wireless sensing.

This work validates the proposed EFEH system within a high-voltage laboratory cage, thereby demonstrating the feasibility of battery-less wireless sensing. With an applied voltage of 10 kV, the system transmits sensor data via Bluetooth Low Energy at an average interval of 130 seconds, confirming the feasibility of using the system for self-powered smart grid IoT devices.

2. Harvester and Electronics Design

There are three key parameters for designing an efficient electric field energy harvester. These are the insulation material of the inner layer, the inner layer's thickness, and the harvester's length. It is estimated that the microcontroller inside the IoT device must run for at least 400 ms to acquire, process and send data via BLE, which corresponds to approximately 19 mJ. To obtain this energy, a 470 µF capacitor must be charged between 3 V and 9.5 V, as demonstrated in (1). To charge the capacitor within a reasonable timeframe (130 seconds), several harvesters of different lengths were tested in the laboratory. Experimentally, it was found that a cylindrical harvester with two layers and a length of 36 cm was needed to achieve the specifications. The inner layer is a 3 mm thick grey elastomer film (MP-42/11 by CATU) and the outer layer is a 16 µm thick standard aluminium film, as shown in Fig. 1. All materials used to assemble the harvester were available in the laboratory. Special care has been taken to prevent air from getting trapped between the layers of the harvester. Once assembled, the harvester is mounted over an aluminium pipe with a 50 mm diameter that acts as the power line conductor. The harvester has two copper wire output connections. One is connected to the external aluminium layer, and the other is connected to the power line, i.e., the aluminium pipe.

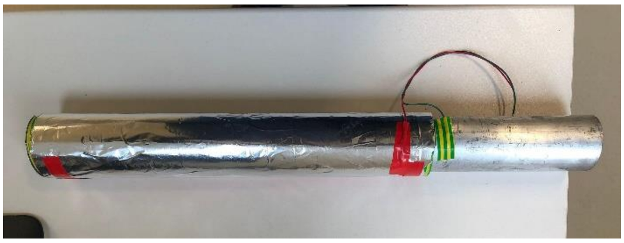

Fig. 1. Photograph of the harvester prototype for this work.

The proposed electric field energy harvesting (EFEH) system includes a full-wave rectifier, a storage capacitor, and a control circuit with protection features. These components work together to collect energy from the harvester and power a DC/DC converter, which then supplies energy to an Internet of Things (IoT) device, as shown in Fig. 2. Switching a power MOSFET controls the charge and discharge of the storage capacitor between two predetermined voltage thresholds (V_{TH} and V_{TL}). Note that all electronic components are powered by a single storage capacitor and, consequently, they must withstand a wide range of supply voltages.

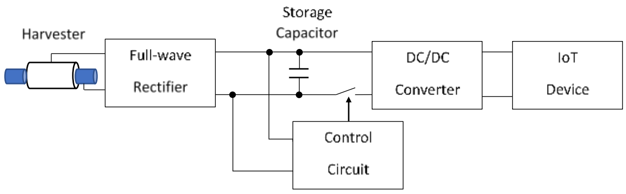

Fig. 2. Block diagram of the designed EFEH system.

Ultra-low-power electronics have been designed to improve the system's efficiency, as shown in the schematics of Fig. 3. The rectifier is based on four small-signal Schottky diodes (model BAT41) from STMicroelectronics. Energy is stored in a 470 μF molded tantalum capacitor (model TPME477K010R0023) from KYOCERA AVX. Since the capacitor's voltage rating is 10 V, a Zener diode (model 1N5347BG from ON Semiconductor) is installed in parallel with the capacitor to prevent damage in the event of a fault in the control circuit. A discrete Schmitt trigger, based on two nano-power comparators with built-in reference (model LTC1540 from Analog Devices), a CMOS D-type flip-flop (model CD4013B from Texas Instruments) working as an asynchronous S-R latch, and an N-channel power MOSFET (model IRL540NPBF from Infineon), has been designed to efficiently control the charge and discharge of the storage capacitor. Two voltage dividers enable the adjustment of voltage thresholds for switching the power MOSFET on and off during storage capacitor discharge and charge, respectively.

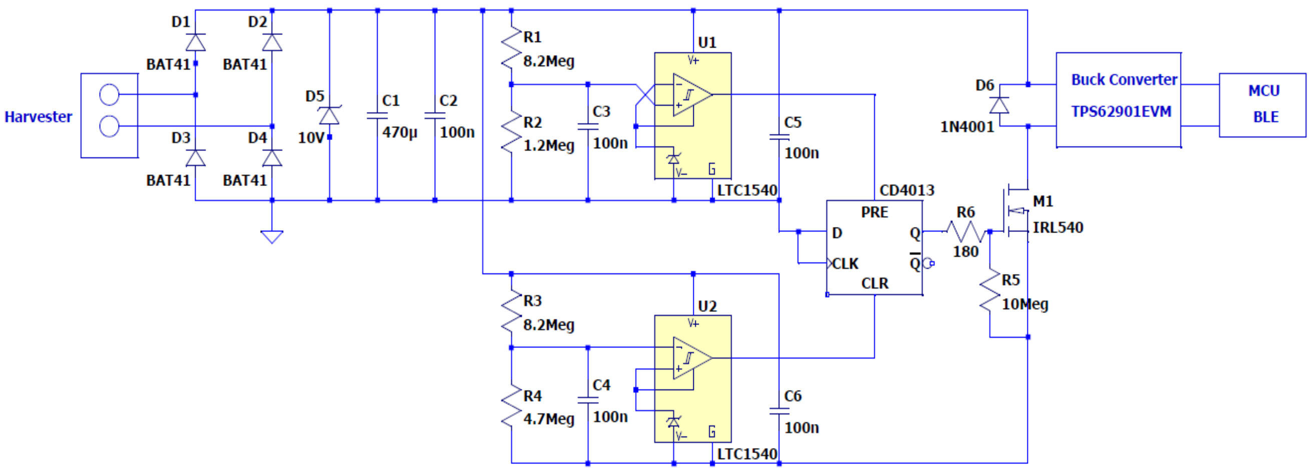

Fig. 3. Schematic of the electronics of the designed EFEH system.

The current prototype has the following thresholds: V_{TH} = 9.5 V to switch on the MOSFET (discharge phase) and V_{TL} = 3 V to switch off the MOSFET (charge phase). All components have been chosen for their wide power supply range, as they are all powered from the same storage capacitor. Finally, the EFEH system's load consists of a commercial step-down Buck converter evaluation module (model TPS62901EVM-069 from Texas Instruments) connected to an IoT device. When the voltage of the storage capacitor reaches 9.5 V, the power MOSFET switches on, turning on the DC/DC power converter and feeding the IoT device while discharging the capacitor. The discharge stops once the capacitor voltage drops to 3 V, since the power MOSFET switches off.

Fig. 4. Photograph of the control electronics of the EFEH system together with the DC/DC power converter.

The IoT device consists of a microcontroller board with Bluetooth Low Energy (BLE) capabilities (the XIAO nRF52840 model from Seeed Studio) and two sensors: a thermistor (the PTFC102T1G0 model from Measurement Specialties) and a Hall-effect current sensor (the DRV5053EAQLPG model from Texas Instruments).

The microcontroller's firmware is responsible for acquiring data (temperature and current), processing signals (temperature filtering and computation of the root mean square and average values of the power line current), encrypting data, and transmitting messages via Bluetooth Low Energy each time the board is powered on. Because the available energy is minimal, encrypted data is sent using BLE advertising messages to reduce energy consumption.

The available energy to be discharged in each cycle can be calculated as:

$$E = \frac{1}{2}CV_{TH}^2 - \frac{1}{2}CV_{TL}^2 \quad (1)$$

where E is the energy available to feed the power converter, C is the capacitance of the storage capacitor, and V_{TH} and V_{TL} are the upper and lower thresholds of the Schmitt trigger, respectively. In the current prototype, since C = 470 μF, V_{TH} = 9.5 V and V_{TH} = 3 V, the available energy is 19.1 mJ.

3. Experimental Results of the Electronics

Some experiments have been carried out to demonstrate that the electronics are truly ultra-low-power. In fact, the quiescent current of the control circuit has been measured versus the applied voltage in the laboratory. As shown in Fig. 5, the maximum current drawn is 3.1 μA at 1.2 V, which is reasonable since the integrated circuits used operate from 2 V. The current consumption increases almost linearly with the voltage after this point, reaching a maximum of 2.6 μA at 9.5 V. Therefore, the harvester must supply a minimum of 3.1 μA to properly charge the storage capacitor.

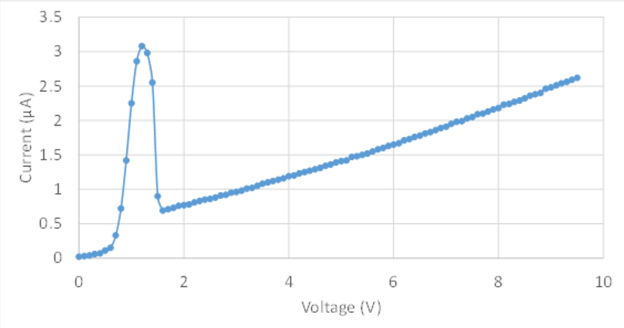

Fig. 5. Quiescent current of the control circuit of the EFEH system versus the voltage of the storage capacitor.

Some experiments have been conducted to show that the energy stored in the capacitor is sufficient to power the IoT device and send BLE messages containing sensor information during each discharge of the storage capacitor. In fact, the voltage applied to the power converter, as well as the current drawn by the IoT device, were captured using a digital oscilloscope in the laboratory. As shown in Fig. 6, discharging the storage capacitor takes nearly 450 ms while the microcontroller acquires, processes, and sends data via BLE. The voltage of the storage capacitor (yellow) drops from 9.5 V to 3 V, while current peaks (blue) of over 100 mA occur. At least two repetitions of the same message are sent by BLE, which is enough for real-time monitoring.

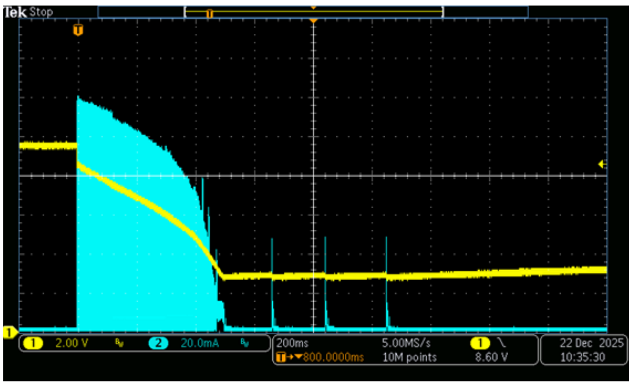

Fig. 6. Voltage applied to the DC/DC power converter (yellow) and current drawn by the IoT device (blue) during a discharge from 9.5 V to 3 V.

4. Experimental Setup for High Voltage Test

The experimental setup used to evaluate the performance of the designed EFEH system in a high-voltage environment consists of a commercial adjustable high-voltage power supply (Tecnolab RD-6, 10 kV RMS, 50 mA RMS, 50 Hz, 600 VA maximum output), a high-voltage cage connected to ground, and two digital BLE multimeters (Promax PD-184, RMS 4 1/2 digits Bluetooth), as shown in Fig. 7. The harvester, along with the control electronics and the multimeters, is suspended in the middle of the high voltage cage.


Fig. 7. Experimental setup to test the EFEH system prototype in a high-voltage environment.

5. Experimental Results in High Voltage

Some experimental results were carried out inside the laboratory's high-voltage cage (Fig. 7) to demonstrate the validity of the designed EFEH system (harvester and electronics). As shown in Figure 8, when subjected to 10 kV, the system can periodically charge and discharge the storage capacitor from 3 V to 9.5 V, sending BLE messages every 130 seconds on average. The mean value of the charging current is 35 μA.

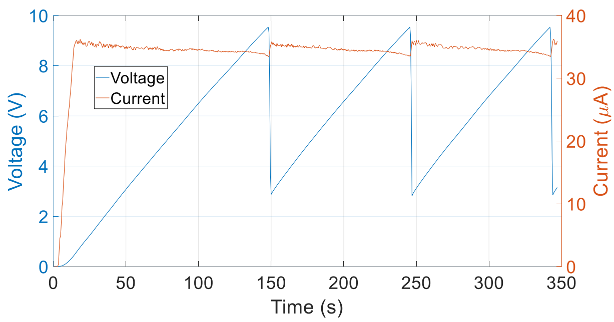

Fig. 8. Voltage and average charging current of the storage capacitor at 10 kV in the high voltage cage.

The proposed EFEH has been tested experimentally within the limits of the high voltage power supply, ranging from 1 kV to 10 kV. As illustrated in Figure 9, the available current of 1 kV is inadequate to achieve the desired high threshold of 9.5 V for charging the storage capacitor.

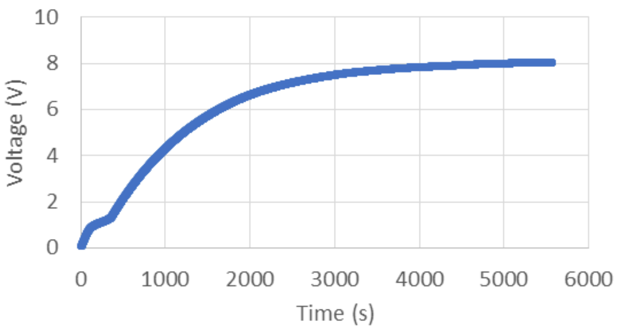

Fig. 9. Voltage of the storage capacitor at 1 kV in the high voltage cage.

Fig. 10 shows the behaviour of the developed EFEH system prototype under different line voltages. It is clear that the higher the line voltage, the shorter the charging time of the storage capacitor, since the higher the line voltage, the higher the charging current of the storage capacitor.

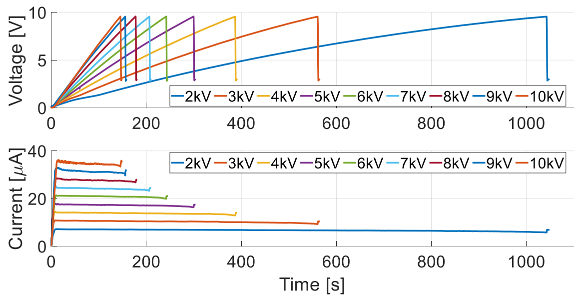

Fig. 10. Voltage (on the top) and average charging current of the storage capacitor (on the bottom) at different line voltage in the high voltage cage of the laboratory.

The harvester, together with the rectifier, behaves as an approximately constant DC current source, whose value depends linearly on the line voltage, as shown in Fig. 11.

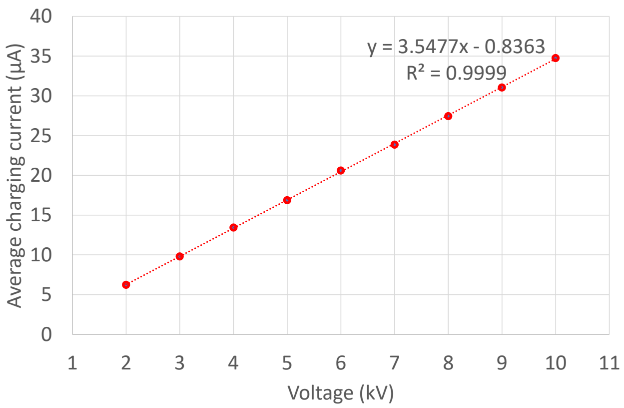

Fig. 11. Average charging current of the storage capacitor versus line voltage.

As confirmed in the experimental setup, the connection of external instruments, such as multimeters, to the EFEH system's electronics has a significant impact on the energy harvesting behaviour. As shown in Figure 12, the transmission rate of the message decreases when the multimeters (voltmeter and ammeter) are not connected.

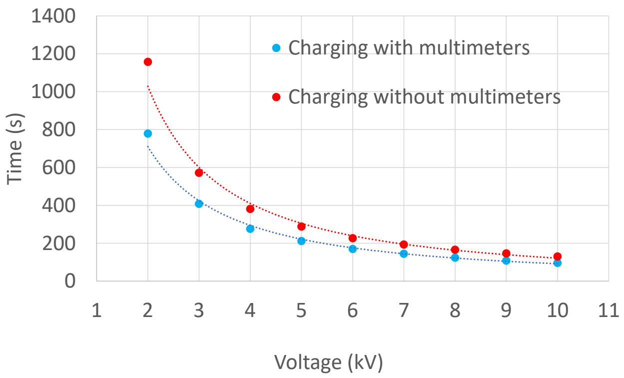

Fig. 12. Message transmission rate versus line voltage with and without multimeters.

The rate of BLE message transmission without multimeters can be represented by the following equation:

$$t = 1710.7\, V^{-1.269} \qquad (2)$$

where t is the time interval, in seconds, between two transmissions, and V is the high-voltage electrode voltage, in kilovolts.

Experimental results indicate that the IoT device can repeat the same BLE message at least twice in each transmission during the discharge of the storage capacitor. The maximum number of repetitions for each BLE message is six.

6. Conclusion

This work demonstrates the feasibility of Electric-Field Energy Harvesting (EFEH) as a robust, non-contact power source for autonomous IoT nodes in high-voltage environments. The proposed system is able to achieve self-sustained operation independent of line current by exploiting displacement currents. This addresses a critical limitation in traditional current-transformer-based harvesters.
Experimental validation confirms that the developed energy management architecture, which is optimised for ultra-low-power consumption, efficiently converts environmental electric fields into regulated energy. Specifically, the system successfully managed energy cycles of 19.1 mJ, thereby enabling consistent sensor data acquisition and BLE transmission at a rate of 130 seconds and at a 10 kV potential. The results obtained from this study provide empirical validation of the theoretical scaling laws of EFEH and establish a clear operational envelope for battery-less smart grid monitoring. The findings of this research provide a scalable framework for maintenance-free wireless sensor networks in power infrastructures.
Future work will centre on the evaluation of the system's performance in uncontrolled outdoor environments, with consideration given to the influence of variable conductor heights and atmospheric conditions on harvesting efficiency.

Acknowledgement

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