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Electric Field Energy Harvesting from Variable Frequency Voltage Sources for Battery-less Internet of Things

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Summary

Internet of Things (IoT) aims to bring connectivity and integration of power system assets, focusing on active management. To ensure the reliability standards of smart cities, IoT requires a wide range of distributed network of wireless sensor nodes. However, energizing these vast networks is highly complex. This work presents a low-power system for electric field energy harvesting, focusing on smart-city applications (Urban IoTs). In particular, we examined design aspects that maximize energy harvesting efficiency according to mains frequency. Experimental findings disclose that a harvester that works at 5 MHz can deliver up to 11 mJ, in approximately 5 minutes. Since the leakage current of diodes is higher than harvester's current, we introduce a new management circuit, called serial switch-only rectifier (SSOR). The proposed approach is simulated and experimentally evaluated. Empirical results show that a harvester based on SSOR circuit out-performs a harvester based on a full-bridge rectifier and voltage doubler by collecting more charge, approximately 40%.

KEYWORDS:
Energy harvesting, electromagnetic induction, electromagnetic coupling, capacitance transducers, home area network.

1 | INTRODUCTION

Global warming, demographic growth, and economic expansion of countries have provoked an increase in demand for electrical energy worldwide, requiring the development of more complex power systems based on non-conventional renewable energies [1]. The integration of these technologies in traditional transmission and distribution systems is not often straightforward, demanding sophistical mechanisms to guarantee the proper operation [2]. Nowadays, the monitoring of complex dynamical behavior of power systems consists of a hybrid system that merges two leading technologies: robotics [3] and wireless sensor nodes (WSNs) [4]. Although robots develop preventive and corrective maintenance works on power systems, survey inspections are costly. To this end, WSNs emerge as a cost-effective technology to implement self-sustainable monitoring in all power system stages, such as extensive area networks (WANs), near area networks (NANs), and home/building area networks (NAN/BAN) [5].

Urban IoT paradigm demands a large number of wireless sensor nodes (WSNs) to connect different assets distributed on home and building area networks (HAN/BAN) [5]. To ensure optimal communication and high-accuracy data collection, WSNs must operate on an ongoing and timely basis [6]. Nowadays, battery-less sensors based on energy harvesting architectures emerge as a promising technology to seamlessly monitor, control, and manage smart-city assets [7]. For HAN/BAN scenarios, different methods, namely, piezoelectric, solar, thermal, radio-frequency waves, electric-field, and magnetic-field, have been proposed

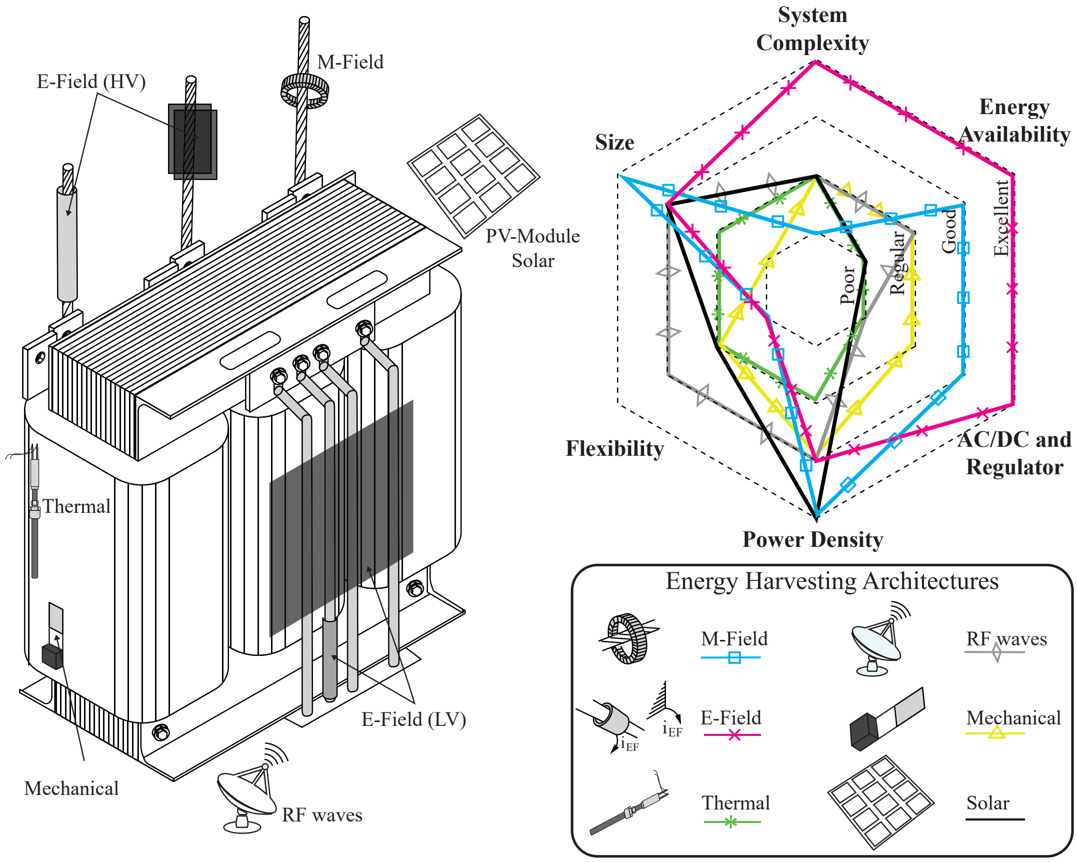

FIGURE 1 Smart-grid sensor node architectures deployed on the energized wires (both high/medium voltage and low voltage applications).

to harvest available energy in the environment[8,7,9,10,11]. Figure 1 summarizes several leading technologies according to main characteristics and the trade of preference.

Because of low complexity, ambient autonomy, sufficient power density, and excellent flexibility, electromagnetic energy harvesters are regarded as protruding scavenging technology. These harvesters are classified into two architectures: magnetic field energy harvesting (MFEH)[12] and electric field energy harvesting[13]. Although the power density of EFEH (up to 26 μW) is smaller than MFEH (up to 150 μW), EF energy harvesters are independent of the power-line current and can operate even open circuit condition. Preliminary works focused on high and medium voltage (HV/MV) overhead transmission lines monitoring, and electrical assets management operations in power systems[14,15]. These harvesters were presented as part of a sensing system capable of determining transmission line parameters such as conductor temperature, distance to the ground, and degree of icing in power-lines to reduce the failure occurrence related to sags and increased vibrations of conductors.

According to the power line coupling, electric field energy harvesters (EFEHs) can be classified into two groups: cylindrical or multi-plate topologiese[14,16,17,18,15,10,4]. In general, the incorporation of metallic electrodes on the nearby electric-field to energized wires creates an electrical network that could be seen as a capacitive voltage divider, as shown in Fig. 1. The network complexity depends on the electrodes' number and disposition[4]. If the harvester is in contact with the line, the network is reduced to two capacitors (C_1 and C_2) serially connected[13]. These capacitors represent the coupling among the electrode and power line and ground reference, respectively. The power is harvested from the capacitive coupling between the power conductors and electrodes. Loads can be integrated into C_1 (in direct contact with the power line)[14,17,15,10] or C_2 (floating capacitor)[19,20]. On the other hand, non-contact harvesters avoid over-voltage and discharging issues[20]. However, the power available is very low.[4].

This work presents a low-power system for electric field energy harvesting, focusing on domestic smart-city applications (Urban IoTs). We introduce a comprehensive analysis of the mains frequency effects in EFEHs performance. On the other hand, an important constraint is related to the diode leakage current, because it limits the harvester's current. In this regard, a management circuit, called serial switch only rectifier (SSOR), is proposed. The proposed approach is simulated and experimentally

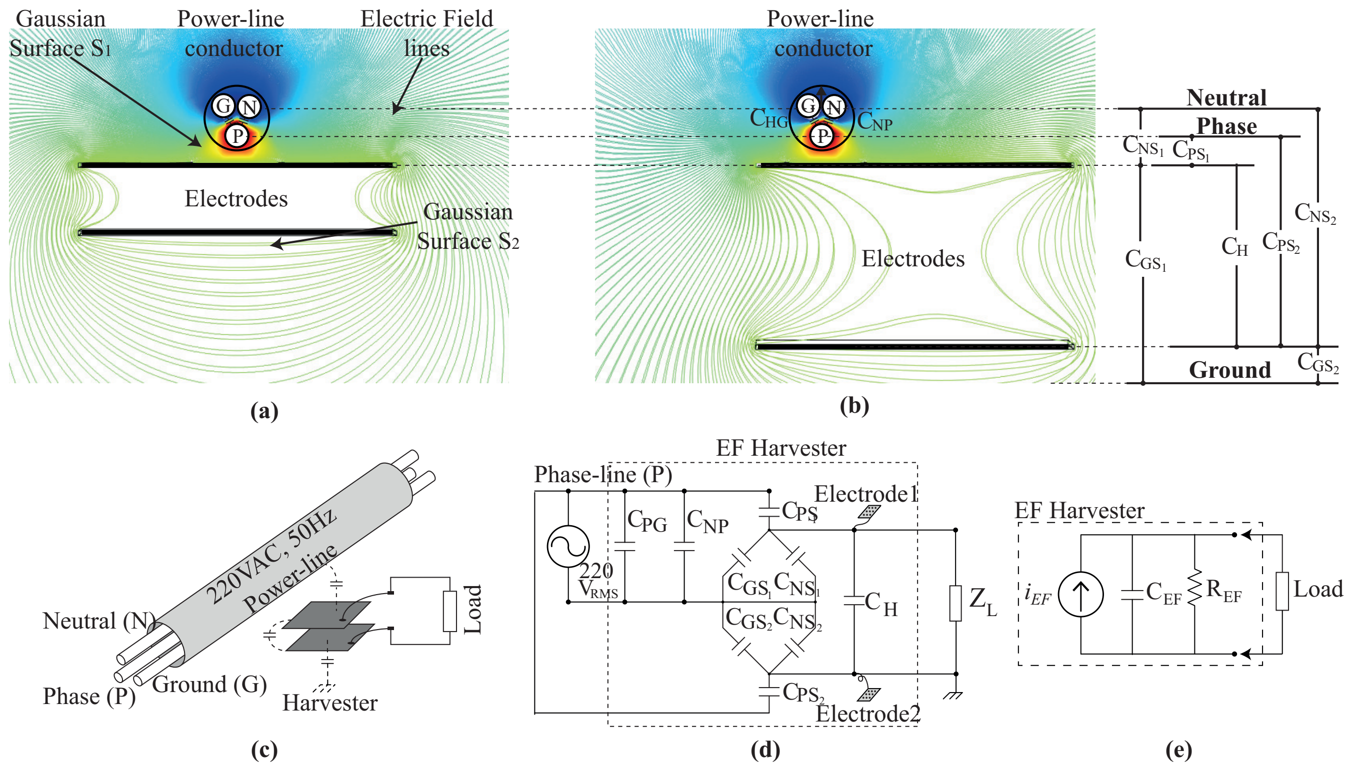

FIGURE 2 Cross-section of 220 V three-wire power line and equipotential lines. **(a)** The electrodes separation is 2 cm and the harvester is centered with the energized wire; **(b)** The electrodes separation is 4 cm and the harvest is positioned at the right of energized wire. **(c)** Schematic of two-plate concept and the capacitive voltage divider dispersion; **(d)** Equivalent circuit of the EFEH, showing parasitic capacitances; **(e)** Simplified model of the EFEH.

evaluated, and its performance is compared with classic circuits (full-bridge rectifier and voltage doubler). The remainder of this work is organized as follows. Section 2 reviews the characteristics of EFEHs. Section 3 discloses the performance of serial switch only rectifier management circuit. Section 4 shows fundamental design principles that are used to maximize the output power by the EFEH, according to mains frequency. Section 5 shows the conclusion of this work.

2 | ELECTRIC FIELD ENERGY HARVESTING

According to Maxwell's equations, a time-varying electric field produces a displacement current given by 1, which can be devolved capacitively to a storage capacitor.

$$I_d = \frac{\varepsilon_0 d\Phi_E}{dt}, \tag{1}$$

where ε_0 is the permittivity of the dielectric material between energized wire and electrode and Φ_E is the electric flux. The maximum energy stored per half-cycle in this capacitor is computed as,

$$E = \frac{1}{2} C_S {V_{DC}}^2, \tag{2}$$

where C_S is the value of the storage capacitor, and V_{DC} is the voltage accumulated. Since this method takes advantage of electric-field around an energized conductor, it is called electric field energy harvesting [14,16,17,18,15,10,4].

In conventional EFEHs, the electrodes located at different distances to the energized conductor create a capacitive network that can be seen as a voltage divider. Figures 2a and 2b shows the electric field distribution of an energized wire (3-wires, Phase-Ground-Neutral), and the effects of putting a two-plate harvester on this field. The values of parasitic capacitances C_{PS_i}, C_{NS_i}

and C_{GS_i} depends on both electric field magnitude around energized wires and the geometry of the complete coupled systems, and they are given by,

$$C = \frac{\varepsilon \oiint_S \mathbf{E} \cdot d\mathbf{S}}{\int_a^b \mathbf{E} \cdot d\mathbf{l}}, \tag{3}$$

where C is the values of parasitic capacitances, $\mathbf{E}$ is the electric field intensity, $\mathbf{S}$ is the electric-flux-coupling Gaussian surface, $\mathbf{l}$ is length differential between the electrode and the power line and ε is the permittivity of the dielectric material between power-line and electrode.

Electric field energy harvesters consist of four basic stages to deliver sustainable energy. Briefly, each harvester stage can be defined as follows:

- *Power-line Coupling:* It is the representation of the capacitive network, that can be formed by one or several electrodes and one or several power-lines. The energy is harvested by connecting different circuits to terminals of any parasitic capacitor.
- *Energy Conversion:* The power output by the electric field harvester cannot be directly used by the load circuits as micro-controllers, wireless nodes, etc. The alternating current and voltage across the harvester capacitor need to be conditioned and converted to appropriately current and voltage levels, that can be used by the load's circuits.
- *Power Output:* Electronic schemes in charge of efficiently matching the low power harvested to the consumption of the load, within some limited operation schedule.

The model, as shown in Fig. 2d, aims to collect the available energy in the capacitive network by deviating the displacement current from the conductor to a load. The capacitive system can be reduced to a sinusoidal current source in parallel with a capacitor, using Norton's equivalent. As Fig. 2e illustrates, the harvester can be modeled as a sinusoidal current source in parallel with a capacitance C_{EF} and resistance R_{EF}. For the sake of this analysis, assume that R_{EF} is despicable. Therefore, the input equivalent impedance (which is a simple capacitor) is given by,

$$C_{EF} = \frac{\left(C_{GS1} + C_{NS1} + C_{PS1}\right)\left(C_{GS2} + C_{NS2} + C_{PS2}\right)}{C_{PS_1} + C_{GS_1} + C_{NS_1} + C_{PS_2} + C_{GS_2} + C_{NS_2}} + C_H. \tag{4}$$

Capacitors C_{GSi}, C_{NSi} and C_{PSi} depend only on the geometry of the harvester. With respect to C_H, although its minimum value depends on the geometry of the harvester, any element connected across its terminals affects the capacitance, thus it cannot be considered constant.

The Thevenin equivalent voltage source is given by

$$V_{EF} = \frac{V_{line}}{C_{eq} + C_H}\left[\frac{C_{PS_1}\left(C_{GS_2} + C_{NS_2}\right) - C_{PS_2}\left(C_{GS_1} + C_{NS_1}\right)}{C_{PS_1} + C_{GS_1} + C_{NS_1} + C_{PS_2} + C_{GS_2} + C_{NS_2}}\right] \tag{5}$$

where,

$$C_{eq} = \frac{\left(C_{GS1} + C_{GN1} + C_{PS1}\right)\left(C_{GS2} + C_{GN2} + C_{PS2}\right)}{C_{GS1} + C_{GN1} + C_{PS1} + C_{GS2} + C_{GN2} + C_{PS2}}. \tag{6}$$

The Norton equivalent current source is given by

$$i_{EF} = \omega_{EF} C_{EF} V_{EF} \sin\left(\omega_{EF} t\right), \tag{7}$$

where ω_{EF} is the angular frequency.

The maximum power can be extracted from harvester if the power converter and the load present a conjugate impedance match to the harvester ($Z_L = R_{EF} + j/\omega_{EF} C_{EF}$). The theoretical generalized maximum power is given by

$$P_{RECT(max)} = \frac{{I_{EF}}^2 R_{EF}}{8} = \frac{{\omega_{EF}}^2 {C_{EF}}^2 {V_{EF}}^2 R_{EF}}{8}. \tag{8}$$

Unlike conventional power supplies and commercial batteries, which have relatively low internal impedance, the EFEH generators internal impedance is very high. This high internal impedance restricts the amount of output current that can be driven by the EFEH source to the micro-amperes range. Likewise, the inductance needed to present a conjugate match is impractical since the harvester capacitance is tiny (tens of pF), which implies a high inductance (tens of Henries). Also, the power output by the electric field harvester cannot be directly used by electronic devices; it needs to be conditioned and converted to a form usable by the load circuits. In this context, a large number of practical load circuits (e.g., voltage doubler, full-bridge rectifier, switch-only rectifier, DC-DC converters) could replace the resistive loads.

3 | SERIAL SWITCH-ONLY RECTIFIER

Electric-field energy harvesters aim to provide a regulated voltage to connected loads (both analog and digital). Due to the nature of these harvesters, the output power needs to be previously conditioned and converted to a form usable by the load circuits. Also, traditional management circuits (Voltage doubler, full-bridge rectifier, etc.) are affected by the leakage current of diodes that constraints the electrode size (i.e., It is necessary larger electrodes). Since the gathered energy is mostly limited, efforts should focus on the use of low loss embedded systems and power-saving polities to extend the sensor lifetime. Even though there are already several preliminary works to insert EFEHs in low-voltage systems, the main applications are related to large cylindrical harvesters (up to 60 cm), which are directly mounted on energized wires. This section introduces a new management circuit called Serial switch-only rectifier (SSOR), as shown in Fig. 3a. The circuit consists of a bidirectional switch serially connected to a full-bridge rectifier. Three premises are assumed: (1) R_{EF} is negligible; (2) the value of smoothing capacitor C_S is more significant compared to the amount of C_{EF}; (3) the voltage at the output of the rectifier V_{DC} is essentially constant.

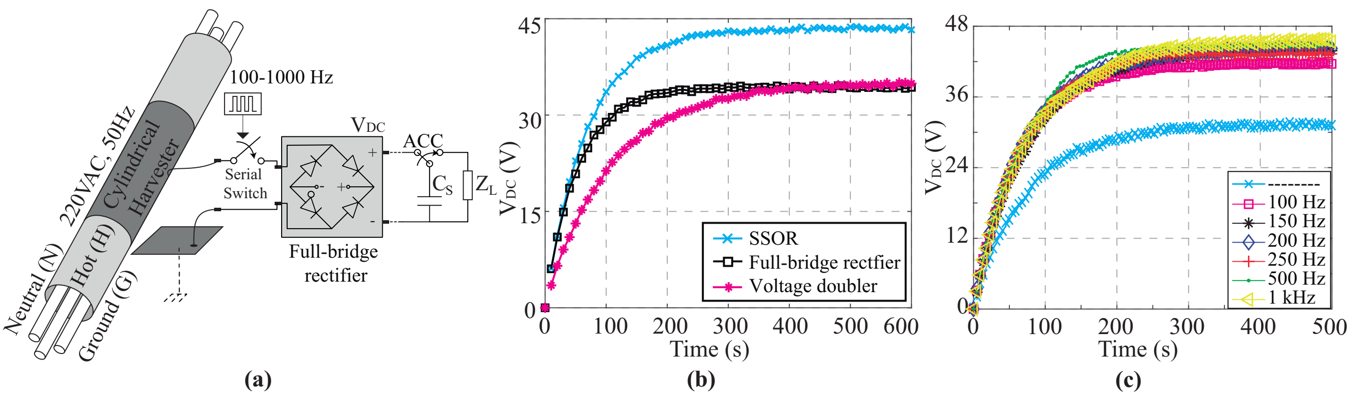

FIGURE 3 Serial switch-only rectifier; **(a)** Representative depiction of the EFEH concept; **(b)** Charging pattern of C_S, changing management circuit (Length: 5 cm), under the open-circuit conditions; **(c)** Charging pattern of C_S according to the switching frequency (Length: 5 cm), under the open-circuit conditions.

A cylindrical harvester was used to perform all the measurements reported in this section. The cylindrical capacitor had a length of 5 cm and is in contact with the insulator of an energized wire. A diode 1n4007 is selected, whose value of voltage drop V_D is 0.7 V, and the typical junction capacitance is 8 pF, according to the manufacturer. Also, the leakage current is 700 nA. As shown in Fig. 3a, the electric field is stored in a capacitor after rectified. However, the power to be extracted by harvesting is not continuous, requiring an autonomous connection circuit (ACC) that commutes between charging mode and load connection mode. As Fig. 3b suggests, empirical findings show that a harvester based on the SSOR out-performs a harvester based on a full-bridge rectifier and voltage doubler by collecting more charge, approximately 40%. Therefore, experimental results show that harvesting considerably more energy with negligible dimensions (i.e. smaller electrodes) is practically accessible. According to these results, EFEHs based on SSOR is a promising solution to power the new generation of ultra-low-power systems. Although the energy increases with the switching frequency, high frequencies do not have a significant contribution to the harvesting process. The measurement results in Fig. 3c shows that using a switching frequency of 1 kHz increases by 6% compared to a switching frequency of 100 Hz. In other words, it is possible to reduce commutation losses without to reduce available energy.

4 | FREQUENCY ANALYSIS

Following Eq. 8, the available power depends on three parameters V_{EF}, electrode length C_{EF} and electric-field frequency ω_{EF}. This section presents a comprehensive analysis of the frequency effect on the power density of EFEHs.

Briefly, the device consists of a base station (boost converter and pulsed flyback inverter) that converts direct voltage 5 V to alternating variable frequency voltage 20 V, and a cylindrical harvester that stores the base station electric-field, variable frequency from 50 Hz to 5 MHz. The electrodes are constructed of aluminum due to their favorable weight conditions compared

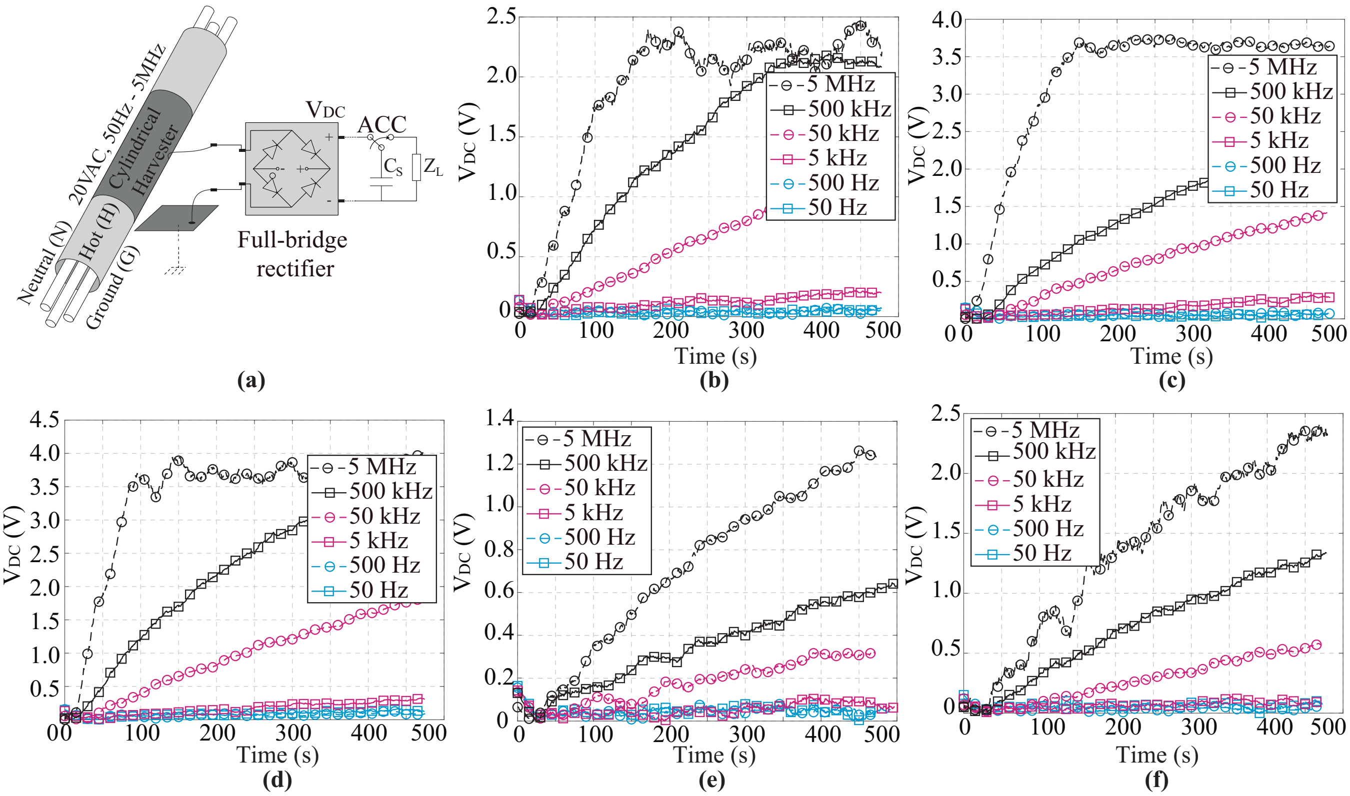

FIGURE 4 Frequency analysis; **(a)** Representative depiction of the EFEH concept; **(b)** Charging pattern of C_S under the open-circuit conditions with sheath length of 10 cm and square voltage source; **(c)** Charging pattern of C_S under the open-circuit conditions with sheath length of 30 cm and sinusoidal voltage source; **(d)** Charging pattern of C_S under the open-circuit conditions with sheath length of 30 cm and square voltage source; **(e)** Charging pattern of C_S under the open-circuit conditions with sheath length of 5 cm and sinusoidal voltage source; **(f)** Charging pattern of C_S under the open-circuit conditions with sheath length of 5 cm and square voltage source.

to other materials (e.g., copper, gold). The sheath surface has a variable length between 5 cm and 30 cm. A full-bridge (based on Schottky diodes) rectifies the voltage induced on the electrodes, the energy is stored in a 4700 μF electrolytic capacitor, for practical purposes. The storage capacitor works as a voltage regulated current source that supplies power to a fixed load, at controlled intervals. By analyzing the variations in the power extracted by the combine, the sensor can determine different parameters and conditions of the lines, such as vibrations of the cables, distance from the conductor to the ground, and essential environmental variations. Additionally, when operating directly with the electric field, the sensor can warn of possible sabotage in the transmission line due to cable theft.

As Fig. 4a illustrates, the circuit consists of a cylindrical harvester (variable length) that is connected to a variable frequency voltage source (fixed voltage of 20 V). A power management circuit with a 4700 μF storage capacitor was implemented, adopting a full-bridge rectifier. As seen in Fig. 4b, when the frequency is altered from 50 Hz to 5 MHz while keeping the length constant, the gathered voltage significantly increases for the same time. The measurement results in Figs. 4c and 4d show that harvester length should be increased to collect more charges. Also, the available energy depends on the effective value of the voltage (RMS value). In other words, more frequent data transmission can be enabled because the storage capacitor charging time is reduced. As Fig. 4e and 4f suggest, it is worth noting that a cylindrical harvester (square voltage source) can store up to 11 mJ while another one stores (sine voltage source) 5 mJ, in approximately 5 minutes while keeping the frequency and length constant.

As shown in Fig. 5, if an insulation layer (dielectric material) is installed between electrode and wire, the available energy increase, because the scavenging performance is directly associated with the permittivity of the material that forms the harvester. Empirical findings in Fig. 5 show that polyimide film (Kapton, relative permittivity 3.34) outperforms paper (relative permittivity 1.4) by storing more charges, approximately 50 percent more, in the same charging period.

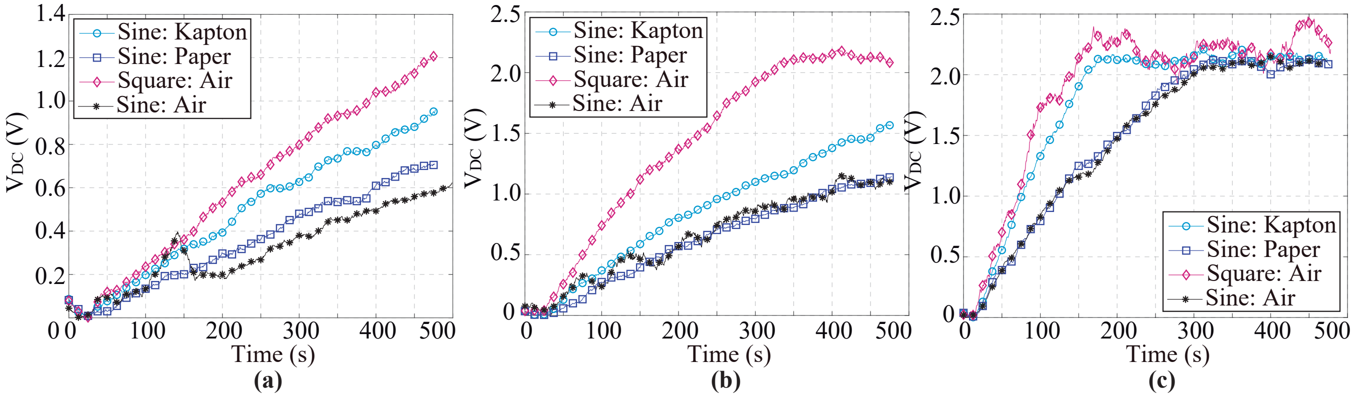

FIGURE 5 Comparison of EFEHs based on different dielectric materials, under the no load condition; **(a)** Sheath length: 5 cm; **(a)** Sheath length: 10 cm; **(a)** Sheath length: 30 cm.

5 | CONCLUSION

Electric field energy harvesting is the only technology that has the capacity of functioning both in open-circuit and energized power lines. The amount of power available for an electric harvester is related to its size. Experimental findings showed that a cylindrical harvester (5 cm length) could store 120 μJ in approximately 5 minutes. The development of management energy circuits that are capable of working with small electrodes is an open challenge. The current empirical advances related to this topic have shown that the use of a bidirectional switch connected in serial connection with the harvester increases the output power available by 40% concerning conventional management circuits. In other words, the stored energy increases to 180 μJ. Even though the output power increments significantly, the power density is not enough. In this context, this paper presented an exhaustive analysis of behavior EFEH according to electric-field frequency. The measurement results show that a harvester that works at 5 MHz can deliver up to 11 mJ, in approximately 5 minutes. In light of this result, variable frequency systems can be considered as a viable solution for more powerful harvesters, and wireless charging systems based on electric-field.

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CONFLICT OF INTEREST

Authors have no conflict of interest relevant to this article.

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