Serial Switch Only Rectifier as a Power Conditioning Circuit for Electric Field Energy Harvesting

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Abstract: Because traditional electronics cannot directly use the alternating output voltage and current provided by electric field energy harvesters, harvesting systems require additional regulating and conditioning circuits. In this field, this work presents a conditioning circuit, called serial switch-only rectifier (SSOR) for low-voltage electric field energy harvesting (EFEH) applications. The proposed approach consists of a tubular topology harvester mounted on the outer jacket of a 230 V three-wires electrical cable (neutral, ground, and phase), in which terminals are connected to SSOR. We compare SSOR performance with classic electronic approaches, such as a full-bridge rectifier and voltage doubler. Experimental findings showed that the gathered energy by a 1 m cylindrical harvester increased in approximately 73.3% using the SSOR as a power management circuit. Experimental findings showed that the gathered energy by a 1 m cylindrical harvester increase in approximately 73.3% using the SSOR as a power management circuit. This increase is principally due to the fact that a serial bidirectional switch disconnects the harvester from the rest of the management circuit, enhancing the charge collection process. Although simulated results disclosed that SSOR increased collected energy for smaller-scale harvesters (experimental tests obtained using a 10 cm cylindrical harvester), additional losses in bidirectional switch reduced its performance. In addition, we introduce a comprehensive analysis of EFEH systems based on SSOR according to the mains frequency for future power systems.

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 sophisticated mechanisms to guarantee the proper operation [2]. In this context, wireless sensor networks (WSNs) are aimed at bringing connectivity and integration between different power system stages. These networks consist of thousands of sensors to ensure reliable data transmission and effective communication [3]. Therefore, there exists a need to energize this large number of sensors to guarantee operational demands. In this context, rechargeable battery systems have enabled portable electronic applications-however, several constraints related to lifespan, dimensions, and availability. Energy harvesting devices appear as emerging technologies to replace traditional battery systems. A vast set of different variables in power system environments may be exploited as power sources. Energy harvesting architectures are classified into four groups as mechanic stimuli, electromagnetic...
radiation (electric field (EF), magnetic field, radio-frequency waves), heat, and light [4–9]. Figure 1 summarizes several leading technologies according to main characteristics and the trade preference.

Because of the abundant surrounding electromagnetic field in a power system, electromagnetic harvesters are regarded as an outstanding scavenging technology. There are two alternatives: magnetic field energy harvesting (MFEH) [10] and electric field energy harvesting (EFEH) [11]. Magnetic field energy harvesting exploits magnetic induction in a nearby coil in the proximity of the energized electrical conductor in which a current flows. Although the power density is high (up to 150 µW) and the system configuration is compact, the harvester efficiency drastically reduces with the conductor’s current and the distance to power-line [9]. Likewise, the system requires isolation because it is in direct contact with the energized wire [6].

On the other hand, a time-varying electric field generates a displacement current that can be capacitively transferred to an electrical load. Unlike magnetic field harvesters, EF energy harvesters are independent of the power line current (i.e., they run even open circuit condition). Albeit the power density is less than the MFEH technology (up to 25 µW), it is sufficient to power the new generation of ultra-low-power chipsets. Preliminary works focused on high and medium voltage (HV/MV) overhead transmission lines monitoring, and electrical assets management operations in power systems [12,13]. 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 are broadly classified as cylindrical or multi-plate topologies [8,12–17]. In general, the incorporation of metallic electrodes on the transmission line electric field creates an electrical network that could be seen as a capacitive voltage divider, in which complexity depends on the electrodes’ number and disposition [17]. If the harvester is in contact with the line, the network is reduced to two capacitors \(C_1\) and \(C_2\) serially connected [11]. 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) [8,12,13,15] or \(C_2\) (floating capacitor) [18,19]. On the other hand, non-contact harvesters avoid direct contact with the transmission line [19]. However, the power available is sharply reduced [17].

Despite the success of HV/MV harvesting approaches, the development of low voltage applications has several constraints due to source scarcity and design constraints [11]. To ensure high-accuracy data collection and continuous communication, low-voltage EFEH systems need the execution of low-power design methodologies based on the energy-efficient design of management circuits, optimized electrode topologies, and enhanced communications architectures [17]. Preliminary findings showed that a 60 cm long aluminum harvester could gather 4.7 mJ in 1 min [20], while a 20 cm long cooper harvester is able to collect 20 mJ in 15 min [16]. In 2017, Koc University presented a comprehensive study of low-voltage tubular harvesters [11], where the authors introduce the effect of electrical characteristics of the material that form the electrode in the scavenging process. Additionally, a new multi-layer model was proposed, which collects 12.5 mJ in 15 min. Another work on low voltage is presented by Reference [17], where a non-contact two-plate harvester destined to run in mobile applications is proposed. In addition, a mechatronized maximum power point tracking system allows increasing the scavenged energy by the harvester.

This work presents a low-power management circuit for electric field energy harvesting from three-core electrical wires. Because the electromagnetic radiation in low-power systems is limited, the management circuits need to be highly efficient. In this context, we analyze the performance of serial switch-only rectifier for low-voltage applications, focusing on the reduction of harvester length. The proposed approach is simulated and experimentally evaluated, and its behavior is compared with classic management circuits (full-bridge rectifier and voltage doubler). In addition, we present a frequency study to determine the performance of the EFEH technologies under frequency variation,
inspiring in future power systems (e.g., aerospace applications, computing devices, telecommunication systems, electrical vehicles, and microgrids) [21–25]. The remainder of this work is organized as follows. Section 2 reviews the characteristics of EF harvesters and explores the harvester’s power according to the connected load type. Section 3 describes the SSOR behavior. Section 4 discloses the performance of serial switch-only rectifier management circuit and shows fundamental design principles that are used to maximize the output power by the EF energy harvesters, according to mains frequency. Section 5 presents the SSOR performance and compares the proposed approach with traditional power management circuits. Finally, Section 6 shows the conclusions of this work.

| Energy source | Methods | Power | Pros | Cons | Ref |
|---------------|---------|-------|------|------|-----|
| Electromagnetic Radiation | MF | 103 μW cm⁻³ | No moving parts, high flexibility, compact configuration, extended lifetime. | Need active power line, core clamped in the line, need insulation. | [9,10] |
| | EF | 0.1-100 μW cm⁻³ | Long lifetime, compact configuration, only need active voltage source, low-cost. | AC output power, high capacitive impedance, affected by external parasitic capacitors | [11,13] |
| | RF | 0.01-10 μW cm⁻³ | Abundant in urban environments, simple materials, extended state of the art. | Low efficiency, noise issues, rectenna design, not continuous output. | [7] |
| Heat | Pyroelectric | ~10-100 mW cm⁻² | Long lifetime, compact design, high flexibility. | Highly dependent on temperature gradients, low efficiency, limited to wearable devices. | [4] |
| | Thermocouple | ~50 mW cm⁻² | Can be used as a sensor, acceptable power density, no moving parts, high flexibility. | Low efficiency, need high temperature gradients. | [6] |
| Solar | Photovoltaic | ~20 mW cm⁻² | High power density, the inexhaustible energy source, no moving parts. | Daily technology, cannot directly connected to load (voltage-limited current source.) | [6] |
| Mechanical Stimuli | Piezoelectric | ~1-50 mW cm⁻² | High power density, abundant in the ambient, high adaptability, robust technology. | AC output power, high capacitive impedance, high cost of dielectric material. | [4,5] |
| | Triboelectric | ~1-50 mW cm⁻² | High output voltage, high efficiency at low frequencies, high flexibility, high power density. | AC output power, high capacitive impedance, complex configuration. | [4] |

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

### 2. Material and Methods

Conventional EFEH topologies introduce one or more electrodes near the proximities of power-lines, thus creating capacitive networks to manage available displacement current. To this
end, we propose a cylindrical EFEH system composed of a single-electrode, as shown in Figure 2a. As Figure 2b illustrates, the system composed of three-core electric wire and length-varying electrode creates a capacitive network, which can be seen as a capacitive voltage divider. This network is reduced to a simplified model using Norton’s and Thevenin’s theorems, as shown in Figure 2c,d.

According to Thevenin’s theorem, the voltage of harvester (open circuit condition) is given as

\[ V_{EF} = \frac{C_{HP}}{C_{GP} + C_{NP} + C_{HP}} V_{li} \sin(\omega_{EF}t), \]  

where \( C_{GP} \), \( C_{NP} \), and \( C_{HP} \) are parasitic capacitors that represent the coupling between each wire and the metallic shield, \( V_{li} \) is the line voltage (230 V at 50 Hz [26]), \( \omega_{EF} \) is the angular frequency, and \( t \) is the time. In addition, the input harvester impedance can be stated as

\[ C_{EF} = C_{GP} + C_{NP} + C_{HP}. \]  

Parasitic capacitors \( C_{GP} \), \( C_{NP} \), and \( C_{HP} \) are described by the following equations:

\[ C_{GP} = C_{NP} = C_{HP} = \frac{2\pi \varepsilon_0 \ell}{r_1 \ln \left( \frac{r_2}{r_1} \right) + \ln \left( \frac{r_3}{r_2} \right) + \frac{1}{\varepsilon_1} \ln \left( \frac{r_4}{r_3} \right)}, \]  

where \( r_1, r_2, r_3 \), and \( r_4 \) are determined according to Figure 2e, \( \varepsilon_1 \) is the relative permittivity (polyvinyl chloride \( \varepsilon_r = 4 \)), and \( \ell \) is the shielding wrap length (harvester’s length).

On the other hand, the harvester’s current (short-circuit condition) is determined using Norton’s theorem and it can be computed as

\[ i_{EF} = \omega_{EF} C_{EF} \sin \left( \omega_{EF} t - \frac{\pi}{2} \right), \]  

where \( V_{EF} = \frac{C_{HP}}{C_{GP} + C_{NP} + C_{HP}} V_{li} \).

2.1. Management Circuits

Electric-field harvesters aim to provide a regulated voltage to analog and/or digital load circuits. However, the output power cannot be directly used by electronic devices, it needs to be conditioned and converted to a form usable by the load circuits. In this regard, power converters can be considered as a promising alternative for low-power management circuits since they can extract the maximum power available out of the EF energy harvester [17,27–29]. This section is aimed at providing a power analysis of the main management circuits for EFEH sensors based on performance and efficiency. A cylindrical harvester was used to perform all the measurements reported in this section. The cylindrical capacitor...
had a length of 10 m and is in contact with the insulator of an energized wire. A diode 1n4007 is selected, in which value of voltage drop \( V_D \) is 0.7 V and the typical junction capacitance is between 2.5 pF and 30 pF, according to the manufacturer.

2.1.1. Voltage Doubler

As illustrated in Figure 3a, the voltage doubler (VD) is an array of two diodes and two capacitors. In this topology, a storage capacitor (bus DC capacitor) \( C_b \) is connected to the converter’s output. The output voltage \( V_{DC} \) is two times the maximum input voltage \( V_{EF} \). Every positive half-cycle of the input current can be divided into two regions, as shown in Figure 3b. In the interval between \( t = t_{on} \) to \( t = t_{off} \) the current flows into \( C_{EF} \) to charge it. \( C_b \) is not charged due to both diodes are reverse-biased. This condition occurs while \( V_{EF} \) is less than \( V_{DC} + V_D \). Otherwise, in the interval between \( t = t_{on} \) to \( t = t_\pi \), the diode \( D_1 \) turns on and the harvester’s current flows into \( C_b \) to charge it. This condition continues until the harvester’s current changes the direction. During the negative half-cycle, diode \( D_1 \) is forward biased, and the harvester’s voltage is \(-V_D\). In addition, the storage capacitor current is zero. The power delivered to the output by the voltage-doubler circuit is

\[
P_{RECT,VD} = C_{EF} V_{DC} f_{EF} (2V_{EF} - V_{DC} - 2V_D). \tag{5}
\]

It is possible to note that at low values of \( V_{DC} \), most of the charge available flows from the harvester into the output but the voltage is low. On the other hand, if the \( V_{DC} \) is high, very little charge flows into the output. When \( \partial P_{RECT,VD} / \partial V_{DC} = 0 \), the optimal voltage rectified is \( V_{DC, \text{opt}} = V_{EF} - V_D \), and the maximum power delivered can be given by

\[
P_{RECT,VD, \text{max}} = \frac{\omega_{EF} C_{EF} (V_{EF} - V_D)^2}{2\pi}. \tag{6}
\]

Figure 3c shows the comparison between theoretical, simulated, and experimental results. Experimental findings show that the maximum power is achieved when \( V_{DC} \) is equal to the maximum value of the open-circuit voltage. However, the circuit is inefficient in every negative half-cycle. In other words, the current does not flow into the output.

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**Figure 3.** Main management circuits. (a) Voltage-doubler circuit; (b) current and voltage waveforms for a voltage-doubler circuit; (c) theoretical, simulated, and experimental output power considering a voltage doubler; (d) full bridge rectifier circuit; (e) current and voltage waveforms for a full bridge rectifier circuit; (f) theoretical, simulated, and experimental output power considering a full bridge rectifier.
2.1.2. Full Bridge Rectifier

A full-bridge rectifier (FB), as shown in Figure 3d, is one of the most commonly used rectified systems to convert the electric-field energy harvester AC output into a DC voltage. Full-bridge rectifier analysis is carried out under similar conditions to the voltage doubler study. The voltage and current waveforms associated with this circuit are shown in Figure 3e. Unlike the voltage doubler topology, this topology ensures that the power always flows from the EF harvester to the storage capacitor. In other words, the harvester’s current flowing to the storage capacitor occurs every half-cycle. Initially, the current charges the harvester’s capacitor $C_{EF}$ in the interval between $t = t_{on}$ to $t = t_{off}$. The current does not flow to $C_b$ due to the fact that the diodes are reverse-biased. When the harvester’s voltage $V_{EF}$ is equal to the storage capacitor voltage $V_{DC} + 2V_D$, the diodes $D_1$ and $D_4$ are forward-biased. This condition occurs continuously until the current changes the direction. In the negative half-cycle, the harvester has a similar behavior. All diodes are initially reverse-biased as long as the $V_{EF}$ is less than the $V_{DC}$. If $V_{EF}$ is equal to $V_{DC} + 2V_D$, the pair of diodes $D_2$ and $D_3$ are forward-biased, and the current flows to the load. The power delivered to the output using the full-bridge rectifier circuit is

$$P_{RECT,VD} = 4C_{EF}V_{DC}f_{EF}(V_{EF} - V_{DC} - 2V_D).$$ (7)

When $\partial P_{RECT,FB}/\partial V_{DC} = 0$, the optimal voltage rectified is $V_{DC,opt} = V_{EF}/2 - V_D$. The maximum power that can be obtained using the full-bridge rectifier, considering ideal diodes is given by

$$P_{RECT,FB(max)} = \frac{\omega_{EF}C_{EF}(V_{EF} - 2V_D)^2}{2\pi}.$$ (8)

Figure 3f shows a comparison between theoretical, simulated, and experimental results. Unlike the voltage doubler circuit, full-bridge rectifier needs two additional diodes. However, the maximum power that can be extracted is the same as that obtained using a voltage-rectifier circuit. Experimental results show that full-bridge rectifier reduces the maximum voltage to half. Since the full-bridge rectifier operates two times every cycle, the amount of charge lost is reduced.

3. Serial Switch-Only Rectifier

Even though there are already several preliminary works to insert the EFEH paradigm in urban and low-voltage systems, the current approaches basically consist of cylindrical harvesters mounted on three-core electrical wires, which are directly connected to classic converters (see Section 2.1). It is possible to ensure the energy transfer from the harvester to load by taking into account two premises: (i) the harvester’s current needs to be much higher than the leakage current, and (ii) parasitic capacitors of the diode package should be insignificant compared with $C_{EF}$. The conventional solution is either to increase the harvester length or harvester number. However, efforts should focus on using low loss embedded systems and power-saving polities to extend the sensor lifetime. This section introduces the management circuit called serial switch-only rectifier (SSOR). As Figure 4a illustrates, the circuit consists of a bidirectional switch serially connected to traditional management circuits (Figure 4b,d). When the $S_1$ bidirectional switch is turned off, $C_{EF}$ is rapidly charged. During this time, $C_{EF}$ works in an open-circuit mode. When $S_1$ is turned on, the circuit runs as a classic circuit. During this state, $C_{EF}$ transfers the energy gathered in open circuit mode, which increases the transfer energy to load. The voltage and current waveforms associated with this circuit are shown in Figure 4c,e.
4. Results

A set of experiments was conducted in simulation and field environments. The proposed approach was simulated using the PSIM software and linking this with MATLAB 2020a. In addition, field tests were carried in a 230 V system at 50 Hz. The technical specifications of the proposed system are summarized in Table 1, and the prototyped circuit board and the proposed harvester are shown in Figure 5.

Briefly,

- The device deployed in real applications consists of an aluminum tube (different length) mounted on three-core electrical wire. Electrical wire is a flexible mains cable with three 0.5 mm$^2$ solid copper conductors. The mains supply is between 220 and 240 V (50 Hz).
- Both harvester’s terminals are connected to SSOR circuit. We select a diode 1n4007 as a switch. $V_D$ is 0.7 V, and the typical junction capacitance is in order of pico-farads (2.5 pF at 100 V and 30 pF at 0.7 V). The gathered energy is stored in a 100 $\mu$F capacitor.
- Bidirectional switch topology is a diode embedded MOSFET consisting of a full-bridge rectifier (1n4007 diodes) connected in parallel with a IRF840-MOSFET. This circuit requires only one active element that reduces the number of external sources to energize drivers. In addition, the switching control is easy because it is only needed to generate a simple PWM signal.
- An Arduino Nano generates the PWM signal (duty cycle fixed 50%). Switching frequency is defined between 100 Hz to 5 kHz. For the sake of this work, the controller is powered using external sources. The controller works in ultra-low power mode to reduce power consumption.
- Despite the fact that this work uses external sources, the device can be replaced with nanoelectromechanical systems (NEMS), in which consumption is less than 1 nJ per cycle [30]. On the other hand, the controller can be replaced with ultra-low power microcontroller, type STM32L4 [31], in which consumption is less than 1.5 mJ.
- As shown in Figure 4a, an autonomous connection circuit (ACC) is used to commute between charging and load connection modes. To this end, an IRF-840 MOSFET is selected. Similar to Arduino energizing, the transistor is externally powered. Arduino Nano controls the opening and closing of ACC.
- The proposed approach was simulated using the PSIM software and linking this with MATLAB 2020a.
We replace $C_b$ with a DC voltage source to determine the harvester’s power according to the DC bus voltage. In addition, switching frequency is set at 5 kHz. It is worth noting that, for large harvesters, SSOR topologies (i.e., SSOR connected to FB and SSOR connected to VD) outperform traditional management circuits, by supplying more power, as shown Figure 6a. Although harvesting considerably more energy with reduced dimensions (i.e., smaller electrodes) is practically accessible (see Figure 6b), if the harvester length is significantly reduced full-bridge rectifier is the optimal option (see Figure 6c). The most common reason for this phenomenon is power losses in the bidirectional switch for SSOR topologies.

The discontinuous working model proposed in Reference [11] establishes that the load is connected to the harvester during a brief time. The remaining time is devoted to collect energy in $C_b$. As shown in Figure 6, the maximum voltage that guarantees positive power, increases for SSOR architectures (see Table 2). As Figure 7a,b suggest, a harvester based on the SSOR outperforms a harvester based on a full-bridge rectifier and voltage doubler by collecting more charge, approximately 73.3%. 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 Figure 7c shows that using a switching frequency of 5 kHz increases by 4.5% compared to a switching frequency of 100 Hz. In other words, it is possible to reduce commutation losses without to reduce available energy. It is also worth noting that if the switching frequency is increased, the duty
cycle should be reduced to increase gathered energy. However, the increase is not significant (up to 9%). For low switching frequencies, the duty cycle should be 50% because small duty cycles broadly reduce efficiency.

Figure 6. Output power by electric field energy harvesters equipped with different management circuits; (a) harvester length: 10 m; (b) harvester length: 1 m; (c) harvester length: 10 cm.

Figure 7. SSOR; (a) gathered energy in $C_b$; (b) charging pattern of $C_b$, changing management circuit (Length: 1 m), under the open-circuit conditions; (c) charging pattern of $C_b$ according to the switching frequency (Length: 1 m), under the open-circuit conditions.

Table 2. Comparison between proposed management circuits: Maximum power available and maximum output voltage.

| Management Circuit | Harvester’s Length | FB     | VD     | SSOR + FB | SSOR + VD |
|--------------------|--------------------|--------|--------|-----------|-----------|
| Maximum power      | 10 m               | 332.5 µW | 229.0 µW | 675.5 µW | 512 µW    |
| Maximum voltage    | 10 m               | 60 V   | 80 V   | 75 V      | 110 V     |
| Positive power     | 1 m                | 9.91 µW | 5.47 µW | 21.42 µW  | 12.9 µW   |
| Maximum power      | 1 m                | 30 V   | 30 V   | 40 V      | 50 V      |
| Positive power     | 1 m                | 8.66 µW | 4.34 µW | 3.95 µW   | 5.89 µW   |
| Maximum power      | 10 cm              | 8 µW   | 3 V    | 2 V       | 2.5 V     |
| Positive power     | 10 cm              | 1.5 V  | 1.5 V  | 1 V       | 2 V       |
4.2. Frequency Analysis

Following Equation (4), the available power depends on three parameters voltage for harvester $V_{EF}$, electrode length $C_{EF}$ and electric-field frequency $\omega_{EF}$. 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 to other materials (e.g., copper, gold). The sheath surface has a variable length between 5 cm and 30 cm. A SSOR-FB rectifies the voltage induced on the electrodes (see Figure 8a), the energy is stored in a 4700 $\mu$F 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. In addition, when operating directly with the electric field, the sensor can warn of possible sabotage in the transmission line due to cable theft.

As seen in Figure 8b, 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 Figure 8c,d show that harvester length should be increased to collect more charges. In addition, the available energy depends on the effective value of the voltage. In other words, more frequent data transmission can be enabled because the storage capacitor charging time is reduced. As Figure 8e,f 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 min, while keeping the frequency and length constant.

![Figure 8. Frequency analysis; (a) representative depiction of the EFEH concept; (b) charging pattern of $C_b$ under the open-circuit conditions with sheath length of 10 cm and square voltage source; (c) charging pattern of $C_b$ under the open-circuit conditions with sheath length of 30 cm and sinusoidal voltage source; (d) charging pattern of $C_b$ under the open-circuit conditions with sheath length of 30 cm and square voltage source; (e) charging pattern of $C_b$ under the open-circuit conditions with sheath length of 5 cm and sinusoidal voltage source; (f) charging pattern of $C_b$ under the open-circuit conditions with sheath length of 5 cm and square voltage source.](image-url)
As shown in Figure 9, if an insulation layer (dielectric material) is installed between electrode and wire, the available energy increase because of the scavenging performance is directly associated with the permittivity of the material that forms the harvester. Empirical findings in Figure 9 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 9](image)

Figure 9. 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. Discussion

According to Maxwell equations, a time-varying electric field (vacuum or medium) produces a displacement current density given by

$$J_D = \epsilon_0 \frac{\partial E}{\partial t} + \frac{\partial P}{\partial t}.$$  \hspace{1cm} (9)

where: $\epsilon_0$ is the permittivity of free space, E is the electric field intensity, and P is the polarization of the medium.

The displacement current can be deviated to an electrical load by taking advantage of the generated capacitive coupling between energized wires and conducting materials. However, the alternating current provided by the harvester cannot be directly used by electrical loads, thus requiring conditioning and regulating circuits for proper operation. All this, plus a restriction of energy consumption due to the scarcity of electromagnetic fields in domestic environments limits the use of management circuits. This work demonstrated that SSOR can increase the available power by the harvester even for low-voltage applications. A comparison of the characteristics of this work, compared to the ones of the other representative methods in the literature, is presented in Table 3.
Table 3. Comparison of the existing power management circuits.

| Management Circuit | Ref | Power/Energy | Voltage | Size | Characteristics |
|--------------------|-----|--------------|---------|------|-----------------|
| Voltage Doubler     |     | 12 mJ        | 220 V   | 10–60 cm | Double-layered cylindrical; capacitive load; Home automation. |
|                     | [11] |              |         |      |                 |
| - Advantages:       |     | Low energy losses related to switching states; Energy transfer: two-times per cycle |         |      |                 |
| - Disadvantages:    |     | Low efficiency for more massive harvesters; Leakage current diodes; Need regulating circuit |         |      |                 |
| Smaller harvesters  |     | 1.75 J       | 220 V   | 50×50 cm | Plate topology; capacitive load; lighting elements for IoT systems. |
|                     | [32] |              |         |      |                 |
| Full-bridge Rectifier |    | 0.6 µW      | 220 V   | 7×7×2 cm | Floating capacitor; plate topology; resistive load WSN for Smart-Grid |
|                     | [17] |              |         |      |                 |
| - Advantages:       |     | Only need two diodes; compact configuration; low energy losses related to switching states. |         |      |                 |
| - Disadvantages:    |     | Low efficiency for more massive harvester; Leakage current diodes; Need a regulating circuit |         |      |                 |
| Smaller harvesters  |     | 360 mJ       | 100 V   | 10–40 cm | Cylindrical harvester; Temperature and Illuminance Sensor |
|                     | [34] |              |         |      |                 |
| Our work            |     | –            | 220 V   | 10 cm | Cylindrical harvester; capacitive load; SSOR circuit; IoT devices |
| Larger Harvester    |     | 120 mJ       | 220 V   | 1 m   |                 |
|                     |     |              |         | 10 m  |                 |

In domestic environments, electric field energy harvesters are used to low-duty-cycle sensing applications because of the low power output by harvesters (see Reference [11,35]). Since the energy transfer rate to load is much higher than power flow from the AC side, it is needed to develop a pulsed energy transfer protocol. An autonomous connection system (ACC) regulates the on/off of the load. Mainly, this system consists of a FET and a voltage detector system. Typically, an ACC consumes between 27 uJ to 128 uJ (AP4410BEC) [36]. On the other hand, the heart of the system is the ultra-low-power microcontroller (MCU). We studied the behavior of CC1310 [37]. The chip operates at 1.8 V and consumes 13.4 mA (Active mode) and 700 nA (Sleep mode). A time of 500 ms has been established for the sensing and forwarding information. The chip consumes 12 mJ and 1.2 mJ of energy in Active and Sleep modes, respectively. As seen in Figure 7, 1 m aluminum shell stores 25 mJ of energy in 100 µF capacitor in 15 min (maximum time limit to domestic monitoring [38]). The total energy per operation is 13.32 mJ, which is less than the harvested energy 25 mJ. The energy excess can be used to power dedicated sensors (e.g., temperature, humidity, voltage).

6. Conclusions

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 (1 m length) could store 165 mJ in approximately 60 min. 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 73.3% concerning conventional management circuits. In other words, the stored energy increases to 114 mJ. 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 10 min. 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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References
1. Gungor, V.C.; Sahin, D.; Kocak, T.; Ergut, S.; Buccella, C.; Cecati, C.; Hancke, G.P. A Survey on Smart Grid Potential Applications and Communication Requirements. *IEEE Trans. Ind. Inform.* 2013, 9, 28–42. [CrossRef]
2. Lu, N.; Cheng, N.; Zhang, N.; Shen, X.; Mark, J.W. Connected Vehicles: Solutions and Challenges. *IEEE Internet Things J.* 2014, 1, 289–299. [CrossRef]
3. Sudevalayam, S.; Kulkarni, P. Energy Harvesting Sensor Nodes: Survey and Implications. *IEEE Commun. Surv. Tutor.* 2011, 13, 443–461. [CrossRef]
4. Wang, Z.L. On Maxwell’s displacement current for energy and sensors: The origin of nanogenerators. *Mater. Today* 2017, 20, 74–82. [CrossRef]
5. Abasian, A.; Tabesh, A.; Rezaei-Hosseinabadi, N.; Nezhad, A.Z.; Bongiorno, M.; Khajehoddin, S.A. Vacuum-Packaged Piezoelectric Energy Harvester for Powering Smart Grid Monitoring Devices. *IEEE Trans. Ind. Electron.* 2019, 66, 4447–4456.
6. Akan, O.B.; Cetinkaya, O.; Koca, C.; Ozger, M. Internet of Hybrid Energy Harvesting Things. *IEEE Internet Things J.* 2018, 5, 736–746.
7. Lu, X.; Wang, P.; Niyato, D.; Kim, D.I.; Han, Z. Wireless Networks with RF Energy Harvesting: A Contemporary Survey. *IEEE Commun. Surv. Tutor.* 2015, 17, 757–789. [CrossRef]
8. Moghe, R.; Iyer, A.R.; Lambert, F.C.; Divan, D.M. A Low-Cost Wireless Voltage Sensor for Monitoring MV/HV Utility Assets. *IEEE Trans. Smart Grid* 2014, 5, 2002–2009. [CrossRef]
9. Hosseinimehr, T.; Tabesh, A. Magnetic Field Energy Harvesting from AC Lines for Powering Wireless Sensor Nodes in Smart Grids. *IEEE Trans. Ind. Electron.* 2016, 63, 4947–4954. [CrossRef]
10. Yuan, S.; Huang, Y.; Zhou, J.; Xu, Q.; Song, C.; Thompson, P. Magnetic Field Energy Harvesting under Overhead Power Lines. *IEEE Trans. Power Electron.* 2015, 30, 6191–6202. [CrossRef]
11. Cetinkaya, O.; Akan, O.B. Electric-Field Energy Harvesting in Wireless Networks. *IEEE Wirel. Commun.* 2017, 24, 34–41. [CrossRef]
12. Zangl, H.; Bretterklieber, T.; Brasseur, G. A Feasibility Study on Autonomous Online Condition Monitoring of High-Voltage Overhead Power Lines. *IEEE Trans. Instrum. Meas.* 2009, 58, 1789–1796. [CrossRef]
13. Moghe, R.; Yang, Y.; Lambert, F.; Divan, D. A scoping study of electric and magnetic field energy harvesting for wireless sensor networks in power system applications. In Proceedings of the 2009 IEEE Energy Conversion Congress and Exposition, San Jose, CA, USA, 20–24 September 2009; pp. 3550–3557. [CrossRef]
14. Guo, F.; Hayat, H.; Wang, J. Energy harvesting devices for high voltage transmission line monitoring. In Proceedings of the 2011 IEEE Power and Energy Society General Meeting, Detroit, MI, USA, 24–29 July 2011; pp. 1–8. [CrossRef]
15. Moser, M.J.; Bretterklieber, T.; Zangl, H.; Brasseur, G. Strong and Weak Electric Field Interfering: Capacitive Icing Detection and Capacitive Energy Harvesting on a 220-kV High-Voltage Overhead Power Line. *IEEE Trans. Ind. Electron.* 2011, 58, 2597–2604. [CrossRef]
16. Kim, H.; Choi, D.; Gong, S.; Park, K. Stray electric field energy harvesting technology using MEMS switch from insulated AC power line. *Electron. Lett.* 2014, 50, 1236–1238. [CrossRef]
17. Menéndez, O.; Kouro, S.; Pérez, M.; Cheein, F.A. Mechatronized maximum power point tracking for electric field energy harvesting sensor. *AEU Int. J. Electron. Commun.* 2019, 110, 152830. [CrossRef]
18. Kang, S.; Kim, J.; Yang, S.; Yun, T.; Kim, H. Electric field energy harvesting under actual three-phase 765 kV power transmission lines for wireless sensor node. *Electron. Lett.* 2017, 53, 1135–1136. [CrossRef]
19. Kang, S.; Yang, S.; Kim, H. Non-intrusive voltage measurement of ac power lines for smart grid system based on electric field energy harvesting. *Electron. Lett.* 2017, 53, 181–183. [CrossRef]
20. Chang, K.; Kang, S.; Park, K.; Shin, S.; Kim, H.S.; Kim, H. Electric Field Energy Harvesting Powered Wireless Sensors for Smart Grid. *J. Electr. Eng. Technol.* **2012**, *7*, 75–80. [CrossRef]

21. Jain, P.; Pahlevaninezhad, M.; Pan, S.; Drobnik, J. A Review of High-Frequency Power Distribution Systems: For Space, Telecommunication, and Computer Applications. *IEEE Trans. Power Electron.* **2014**, *29*, 3852–3863. [CrossRef]

22. Guevara, L.; Auat Cheein, F. The Role of 5G Technologies: Challenges in Smart Cities and Intelligent Transportation Systems. *Sustainability* **2020**, *12*, 6469. [CrossRef]

23. Fong, Y.C.; Raman, S.R.; Ye, Y.; Cheng, K.W.E. Generalized Topology of a Hybrid Switched-Capacitor Multilevel Inverter for High-Frequency AC Power Distribution. *IEEE J. Emerg. Sel. Top. Power Electron.* **2020**, *8*, 2886–2897. [CrossRef]

24. Raman, S.R.; Fong, Y.C.; Ye, Y.; Eric Cheng, K.W. Family of Multiport Switched-Capacitor Multilevel Inverters for High-Frequency AC Power Distribution. *IEEE Trans. Power Electron.* **2019**, *34*, 4407–4422. [CrossRef]

25. Raman, S.R.; Ye, Y.; Cheng, K.W.E. Switched-capacitor multilevel inverters for high frequency AC microgrids. In Proceedings of the 2017 IEEE Applied Power Electronics Conference and Exposition (APEC), Tampa, FL, USA, 26–30 March 2017; pp. 2559–2564.

26. International Electrotechnical Commission. *IEC Standard Voltages IEC 60038*; International Electrotechnical Commission: Geneva, Switzerland, 2009.

27. Rodríguez, J.C.; Holmes, D.G.; McGrath, B.P.; Wilkinson, R.H. Maximum energy harvesting from medium voltage electric-field energy using power line insulators. In Proceedings of the 2014 Australasian Universities Power Engineering Conference (AUPEC), Perth, Australia, 28 September–1 October 2014; pp. 1–6. [CrossRef]

28. Rodríguez, J.C.; Holmes, D.G.; McGrath, B.; Wilkinson, R.H. A Self-Triggered Pulsed-Mode Flyback Converter for Electric-Field Energy Harvesting. *IEEE J. Emerg. Sel. Top. Power Electron.* **2018**, *6*, 377–386. [CrossRef]

29. Zhang, J.; Li, P.; Wen, Y.; Zhang, F.; Yang, C. A Management Circuit with Upconversion Oscillation Technology for Electric-Field Energy Harvesting. *IEEE Trans. Power Electron.* **2016**, *31*, 5515–5523. [CrossRef]

30. Zhu, J.; Liu, X.; Shi, Q.; He, T.; Sun, Z.; Guo, X.; Liu, W.; Sulaiman, O.B.; Dong, B.; Lee, C. Development Trends and Perspectives of Future Sensors and MEMS NEMS. *Microachines* **2020**, *11*, 7. [CrossRef]

31. STMmicroelectronics. STM32L4 Series. 2020. Available online: https://www.st.com/ (accessed on 18 September 2020).

32. Cetinkaya, O.; Akan, O.B. Electric-Field Energy Harvesting From Lighting Elements for Battery-Less Internet of Things. *IEEE Access* **2017**, *5*, 7423–7434. [CrossRef]

33. Yan, D.; Li, J.; Zhang, J.; Tian, X.; Ou, D.; Gu, J. A capacitive electric-field energy harvester with double-layer copper foil for 220V power line. *J. Phys. Conf. Ser.* **2020**, *1585*, 012002. [CrossRef]

34. Honda, M.; Sakurai, T.; Takamiya, M. Wireless temperature and illuminance sensor nodes with energy harvesting from insulating cover of power cords for building energy management system. In Proceedings of the 2015 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), Brisbane, Australia, 15–18 November 2015; pp. 1–5.

35. Moghe, R.; Iyer, A.R.; Lambert, F.C.; Divan, D. A Low-Cost Electric Field Energy Harvester for an MV/HV Asset-Monitoring Smart Sensor. *IEEE Trans. Ind. Appl.* **2015**, *51*, 1828–1836. [CrossRef]

36. AsahiKASEI. Ultra Low Power Voltage Detector. 2020. Available online: https://www.microchip.com (accessed on 2 September 2020).

37. TexasInstruments. SimpleLink™ 32-bit Arm Cortex-M3 Sub 1 GHz wireless MCU with 128kB Flash. 2020. Available online: https://www.ti.com/product/CC1310 (accessed on 2 September 2020).

38. Zanella, A.; Bui, N.; Castellani, A.; Vangelista, L.; Zorzi, M. Internet of Things for Smart Cities. *IEEE Internet Things J.* **2014**, *1*, 22–32. [CrossRef]