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Review

# Energy Harvesting Methods for Transmission Lines: A Comprehensive Review

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**Abstract:** Humanity faces important challenges concerning the optimal use, security, and availability of energy systems, particularly electrical power systems and transmission lines. In this context, data-driven predictive maintenance plans make it possible to increase the safety, stability, reliability, and availability of electrical power systems. In contrast, strategies such as dynamic line rating (DLR) make it possible to optimize the use of power lines. However, these approaches require developing monitoring plans based on acquiring electrical data in real-time using different types of wireless sensors placed in strategic locations. Due to the specific conditions of the transmission lines, e.g., high electric and magnetic fields, this a challenging problem, aggravated by the harsh outdoor environments where power lines are built. Such sensors must also incorporate an energy harvesting (EH) unit that supplies the necessary electronics. Therefore, the EH unit plays a key role, so when designing such electronic systems, care must be taken to select the most suitable EH technology, which is currently evolving rapidly. This work reviews and analyzes the state-of-the-art technology for EH focused on transmission lines, as it is an area with enormous potential for expansion. In addition to recent advances, it also discusses the research needs and challenges that need to be addressed. Despite the importance of this topic, there is still much to investigate, as this area is still in its infancy. Although EH systems for transmission lines are reviewed, many other applications could potentially benefit from introducing wireless sensors with EH capabilities, such as power transformers, distribution switches, or low- and medium-voltage power lines, among others.

**Keywords:** batteryless; distributed sensors; electric power systems; energy harvesting; predictive maintenance; transmission lines; ultra-low power



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## 1. Introduction

Energy Harvesting (EH) refers to the process by which energy from ambient or other sources is converted into electrical energy to supply autonomous devices [1] as wireless sensors and to improve their effective lifetime and capability [2]. Although many of the existing EH systems generate limited power, on the order of $\mu W/cm^2$ to $mW/cm^2$ [3,4], EH is gaining popularity due to the development of very low-power sensors and wireless communication systems. Self and ubiquitous energy generation capability characterize EH, so it avoids battery replacement in many applications, allowing electronic sensors to be deployed in hostile or inaccessible places. EH also contributes to reducing carbon footprints, as in many cases, electrochemical batteries can be replaced by EH units in autonomous systems [5]. Although EH technologies often do not completely eliminate the use of storage batteries, they can maximize the duration of their use [6]. Ambient energy harvesting, e.g., wind, thermal, solar, vibration, or radio frequency (RF) [2] promises low-cost, small form factor, and an endless lifetime of low-power electronic wireless sensor nodes (WSNs) by minimizing or eliminating battery use, replacement, and related maintenance costs [7]. The finite lifetime of WNSs severely limits their ability to collect data because they are energy-constrained, as WSNs require energy to supply the sensors and transmit their data to external data collectors or gateways [2,8]. Energy Harvesting Strategies Address

WSN's limited lifetime challenge. However, different challenges related to the stochastic nature of the incoming energy [9] and the influence of environmental conditions have to be addressed to ensure the optimal performance of WSNs [10]. WSNs can be connected, forming a wireless sensor network comprising a network of numerous WSNs using a multi-hop communication arrangement that allows the expansion of the coverage area compared to a single WS while requiring very low power for operation [11].

After the digital revolutions due to the introduction of the computer and the Internet, the Internet of Things (IoT) is considered to be the third revolution, offering many potential advantages to smart grids, such as fault detection and prediction or disaster prevention and prediction, which are complex problems that transmission system operators have to deal with. Therefore, IoT technology can potentially improve power transmission stability, availability, and reliability [12]. Electric power lines are the arteries of today's power systems; therefore, their efficiency, reliability, and stability profoundly impact daily life and the national economy. Transmission lines may operate in remote areas, making routine inspections complex and expensive. Environmental factors such as wind, rain, ice, or extreme temperatures affect the operation of transmission lines. Although the rate of failures in transmission systems is lower than in distribution systems, the first tends to affect more customers and generate higher outage costs. Therefore, the use of self-powered IoT sensors for real-time monitoring of transmission lines, as shown in Figure 1 [13], has great potential to solve the problems mentioned above [12].

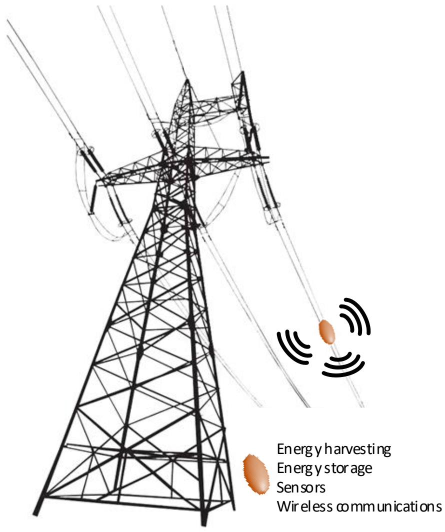



**Figure 1.** Schematic of wireless monitoring of transmission lines.

Electrical grid reliability is a major challenge for utility companies, so solutions based on grid monitoring, diagnosis, and control are receiving special attention [14]. In countries with an important growth of renewable energy sources, grid balancing and congestion is an issue [15,16]. The safe and reliable operation of transmission lines must take into account the thermal rating to ensure that conductors do not exceed the maximum allowable temperature [17]. Today, dynamic line rating (DLR) approaches are gaining popularity because they offer a solution to the congestion problem since they are based on utilizing the maximum capacity of transmission lines. To this end, DLR approaches are based on measuring weather and line variables in order to dynamically determine the maximum allowable line current to ensure that the line operates within safe operation limits [18]. These solutions also warrant an increased return on investment due to more efficient asset utilization [11]. However, due to the geographical spread of power systems, monitoring power lines and assets outside the substation is challenging due to the harsh outdoor weather conditions, the vast distances to be covered, and the power requirements of the required electronic sensing devices [11].

In general, in indoor applications, there is no urgent need for EH devices due to easy access to a power supply and accessibility of sensor nodes, which reduces maintenance costs, so the need for EH systems is more typical of harsh outdoor applications [19]. Developing EH systems for high-voltage applications remains a big challenge, so most sensor nodes are still battery-powered, being inconvenient due to periodic replacements and unfavorable maintenance-free operations. As a result, many studies are focusing on self-powered wireless sensors [20].

The basic architecture of a WSN includes the sensor or sensors that convert the measured variables (temperature, current, voltage, . . . ) into electric signals, the power management module, the energy storage unit [21], the energy harvesting, and the communications module, which are represented in Figure 2.

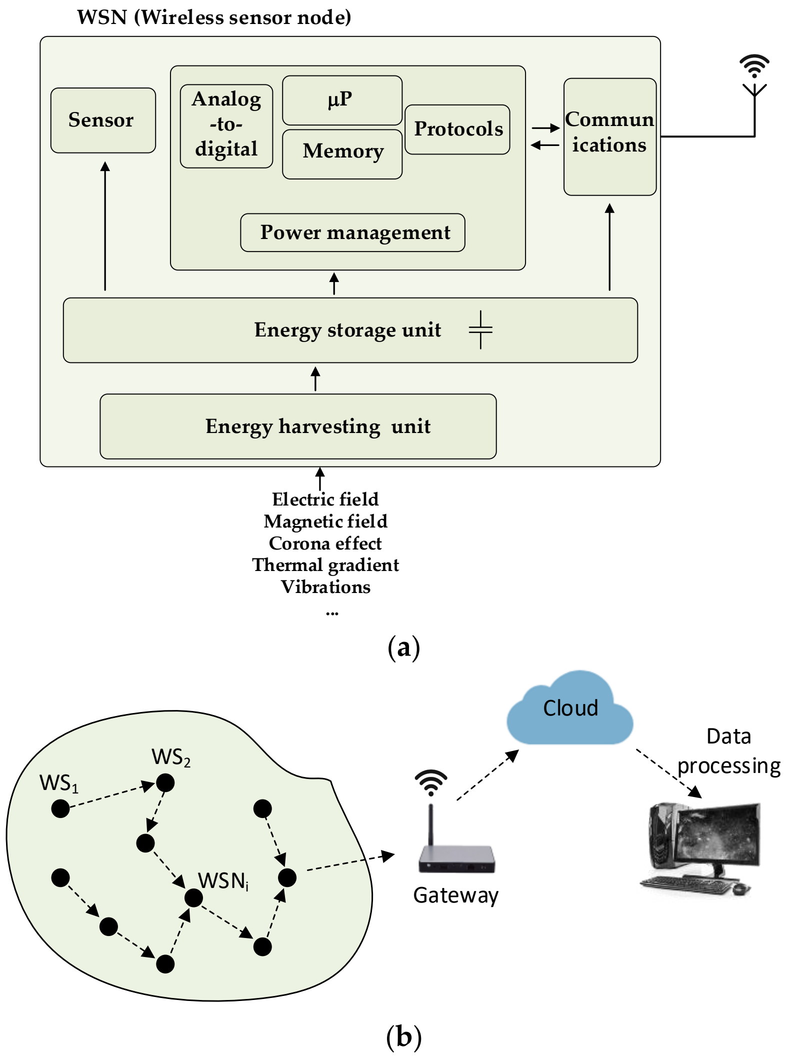



**Figure 2.** (**a**) Basic structure of a wireless sensor node (WSN). (**b**) Structure of a wireless sensor network, adapted from [22].

This work reviews and analyzes the state-of-the-art and recent progress in EH systems for WSNs intended for transmission lines while identifying challenges and research needs. This topic has a huge impact and expansion potential, but this area is still in its infancy due to the specificities and complexities of transmission lines. The information condensed in this review paper can also be applied to other applications, such as power transformers, distribution switches, or medium- and low-voltage power lines. The knowledge presented in this work has been compiled from the latest technical and scientific literature, including journal papers, review articles, conference works, doctoral theses, technical reports, and white papers.

The rest of the article is organized as follows. Section 2 reviews ultra-low-power energy harvesting technology for wireless sensor networks. Section 3 reviews the state-of-the art batteryless energy harvesting systems. Section 4 reviews the state-of-the-art of energy harvesting methods for transmission lines. Section 5 discusses the main characteristics of the analyzed energy harvesting methods. Section 6 identifies the challenges and research needs related to this topic, and finally, Section 7 concludes this review paper.

## 2. Ultra-Low-Power Technology for Energy Harvesting Wireless Sensor Networks

Although there is no exact definition of ultra-low-power (ULP) in the field of wireless sensors, it usually refers to designs that consume, on average, in the order of fractions of µW to fractions of mW. Most EH sources fall within the ULP category because they can generate as few as tens of µW [23]. Batteryless WSNs require the harvesting of energy from ambient sources in their application volume. However, due to the small volume of EH systems, very little ambient energy is available, requiring ULP circuits. In [24], it is stated that micro-power EH from indoor small-size solar cells, piezoelectric, thermoelectric (gradient temperature 1–10 °C), or RF Wi-Fi harvesters can scavenge power at ULP levels (some µW). However, power at µW level is not enough to supply IoT using commercial integrated circuits, so in addition to increasing the amount of energy harvested, reducing system power consumption to ULP levels is also required [24]. For example, according to [25], WSNs typically require 1–5 µW in standby mode, 0.5–1 mW in active mode, and 50 mW while transmitting. Similar values are provided in [21].

ULP technology aims to extend the lifetime of WSNs through significant energy savings [26]. The basic diagram of a ULP WSN is the same as shown in Figure 2a. Since WSNs are constrained in terms of processing capacity, memory and energy, and power usage, energy management is one of the challenges that must be addressed for successful WSN deployment [27]. In particular, energy-efficient wireless communication modules play a critical role in developing battery-powered and batteryless WSNs. Different approaches can be applied to address these issues at both the physical and network levels without sacrificing important metrics, such as transmission range, latency, or immunity to interference [28]. By combining energy-efficient wireless protocols with low-power communication architectures, operation below $10^{-4}$ W can be achieved [28]. Communication modules typically operate discontinuously at low duty cycles, hibernating between consecutive active states to save energy [19]. This strategy, based on periodically alternating between sleep and active modes, allows a large reduction in the average power of the power-hungry radio [29]. In [23], it is reported that by combining different techniques, such as short frame sizes, optional and synchronous receptions, asynchronous transmissions, and a light architecture, it is possible to reduce power consumption by 1 to 2 orders of magnitude compared to Bluetooth Low Energy (BLE).

## 3. Batteryless Energy Harvesting Systems

Although many EH systems use supplementary batteries, they have a finite lifetime, require regular charging or replacement, and produce electronic waste [30]. Due to IoT devices' fast deployment, millions of batteries probably need to be replaced daily [28], so battery replacement is impractical and has significant environmental impacts [3]. By reducing power consumption and voltage supply, WSNs could be self-powered, i.e., supplied directly from the EH source without using batteries [28,31]. The use of batteryless WSNs is directly related to the application of ULP devices and approaches [31].

Due to recent advances in low-power sensors, when combined with communication modules that operate in a discontinuous mode at low duty cycles hibernating between consecutive active states, they can, in some cases, be supplied directly from an independent source without using any battery [19]. Batteryless systems can use a variety of power sources, including vibration, solar power, temperature gradient, or wireless power transfer, among others, making them very attractive for applications where any intervention is challenging. In many cases, the energy collected by the EH unit is stored in small capacitors [3]. Due to the often stochastic nature of harvested energy and the restricted energy storage, associated WSNs typically operate in an intermittent on-off pattern [32]. However, in the case of power lines, this problem can be partially overcome due to the "predictability" of the energy flow, which allows better planning of the energy harvesting.

Instead of batteries, capacitors can be used to store energy, being smaller than batteries and offering lifetimes of more than a decade since they withstand a larger number of charge-discharge cycles [3,33]. However, the use of storage capacitors presents some disadvantages and challenges related to the stochastic nature of the energy transferred from the source to the energy harvester [34] and energy storage capacity, especially when using small capacitors. The WSN lacks a constant power supply so that power failure can last any duration, from seconds to hours. Further, depending on the WSN's mode of operation, the amount of power consumed can vary considerably, for example, when switching from sleep to transmission modes or during the sensing period, causing voltage changes that affect the energy stored in the capacitor. Therefore, for effective use of batteryless WSNs, applications based on such devices must have the ability to handle this intermittent behavior [32].

Another possibility is to use supercapacitors, which deliver and accept charge much faster than batteries while tolerating many more charge-discharge cycles than rechargeable batteries [35], but having much lower energy densities and exhibiting higher self-discharge currents, so once fully charged, compared to batteries they discharge at a much faster rate. Therefore, supercapacitors are used in applications that require many rapid charge-discharge cycles rather than compact, long-term energy storage. Small supercapacitors are used in WSNs because they can boot and charge batteryless WSNs in a matter of seconds when the energy is available. However, the use of small supercapacitors does not allow the WSN to perform energy-intensive operations. On the other hand, using large capacitors implies long charging times, so for start-up, the node must wait for the capacitor to reach a minimum voltage level. Moreover, the energy stored in the supercapacitor is quickly dissipated as the energy scavenged is not enough to maintain a minimum voltage across the supercapacitor, so a design trade-off is required for irregularly powered batteryless systems. However, according to [36], this topic is not well-studied in the technical literature.

Communication technologies play a critical role in deploying reliable batteryless WSNs, as they have relatively high power requirements compared to the accompanying sensors. Different low-energy communication technologies have been applied in batteryless WSNs, such as Bluetooth Low Energy (BLE) [3] or LoRaWAN, probably the most popular technology within low-power wide-area networks (LPWAN) [32].

## 4. State-of-the-Art Energy Harvesting Methods for Transmission Lines

EH circuits are designed to collect energy from ambient sources to provide a stable supply to the other modules [37]. Continuous energy supply is an important research topic for IoT and WSNs applications [7] because the power supply is a bottleneck for developing autonomous transmission line monitoring systems [38]. Monitoring and maintenance of transmission lines can be performed by line robots or by using line-mounted distributed wireless sensors, which typically use batteries as the main power source, but as explained at the expense of environmental impacts and maintenance costs [38], and presenting significant maintenance difficulties in remote areas [39].

This section reviews the EH methods that can be effectively applied to transmission lines. However, some EH technologies are not included in this section, such as wind collectors that rely on moving parts due to insulation issues and sensor costs [38], because they cannot be effectively applied in power transmission lines.

### 4.1. Solar Energy Harvesting

Solar EH is a mature technology that is being applied in many areas. Solar energy is harnessed using a photovoltaic (PV) system that converts sunlight into useful electric power. For example, in [40], a temperature monitoring system for overhead transmission lines using two solar panels fixed at the top of the tower was analyzed.

The main disadvantage of solar panels is that, due to the stochastic nature of weather conditions, a stable energy supply cannot be guaranteed [41] because, in many places, it is possible to reliably generate solar power for less than 8 h a day [42]. Further, weather conditions, dust, sand, dirt, ice, or snow can significantly impact the availability of solar energy, increasing maintenance costs [43]. Since a constant electrical supply is not feasible [44], combining solar EH with an ultracapacitor or a rechargeable battery is necessary to provide a stable supply to the sensor system [11,45]. Due to the drawbacks mentioned above, recent developments point toward using hybrid solutions that combine solar EH with other sources, such as electromagnetic or RF. For example, in [41,46], a harvester combining solar and magnetic field EH is proposed for WSNs intended for smart grid applications, where the magnetic field harvester is based on a multi-turn coil surrounding a magnetic core. In [47], a hybrid solar-RF energy harvesting system combining a solar panel and an antenna is proposed.

### *4.2. Vibration Energy Harvesting*

Vibration energy harvesting transforms mechanical vibrational energy into useful electric energy [21]. Therefore, mechanical vibrations in power lines or induced by them can be converted into electrical energy. Different energy extraction methods from vibrations are possible, such as piezoelectric [1,5,48,49], inductive [26], or electrostatic [25,50,51] approaches.

Piezoelectric EH is based on the use of piezoelectric materials, which generate electric charges, and thus voltage, when the material is subjected to mechanical stress [25]. Piezoelectric harvesters can be designed and manufactured at the scale of microelectromechanical systems (MEMS) to take advantage of ambient vibrations with a frequency usually less than 200 Hz [52]. In [53], a piezoelectric energy harvester was presented using a magnetic metal as the tip mass that vibrates due to the action of the AC magnetic field generated by a power conductor. The piezoelectric ceramic element is composed of $Ba_{0.85}Ca_{0.15}Ti_{0.90}Zr_{0.10}O_3$ + CuO 0.3 wt%, which can produce an instantaneous maximum power of 8.2 mW in a weak magnetic field of 250 μT, and exhibits an energy density of 107.9 mW/cm$^3$. In [54], a device for harvesting the energy of a galloping conductor was proposed, using a swinging piezoelectric cantilever beam collision structure and a pendulum with a swinging ball, whose motion was caused by the low-frequency vibration of the galloping conductor. Similarly, in [55], a linear Halbach array mounted on the free end of a piezoelectric cantilever beam is used to harvest the energy from the AC magnetic field generated by a power line. The presented results show that this harvester can generate 897 μW across a 212 kOhm resistor when mounted on a two-wire cable carrying opposite currents of 10 A. In [56], a cantilever (piezoelectric) beam was used together with a miniaturized permanent magnet attached to the tip, which vibrates due to the interaction with the magnetic field of the AC line, as shown in Figure 3a. In [57], a nickel–zinc ferrite ring-type core, with a piezoelectric ceramic toroidal solenoid wound around it, was presented. The nickel-zinc ferrite ring was required to convert the 50 Hz circumferential magnetic field into a 50 Hz circumferential strain, transmitted to the piezoelectric layer, generating a voltage.

Inductive EH from vibrations is based on the voltage generated due to the relative motion of a permanent magnet and a harvesting coil [26,58], as shown in Figure 3b. The amplitude of the induced voltage in the coil depends on the amplitude of the beam vibration, the number of turns, the line frequency, and the flux gradient. To increase the magnitude of the flux gradient and the flux density, [59] proposes the use of an array of tiny and powerful permanent magnets with opposite polarities attached to the vibrating beam.

The electrostatic method (see Figure 3c) is based on the capacitance change of a variable capacitor or electret due to relative motion between the two plates [11,25,50,60], although different methods can be combined to improve performance [61]. The main drawback of electrostatic EH is related to the need for an external voltage source during operation [25].

The energy produced by these harvesters increases with their volume [50]. In [51], an electrostatic energy harvester that produces 45 μW for an acceleration of 0.6 m/s$^2$ at 50 Hz with a volume of 150 mm$^3$ is presented.

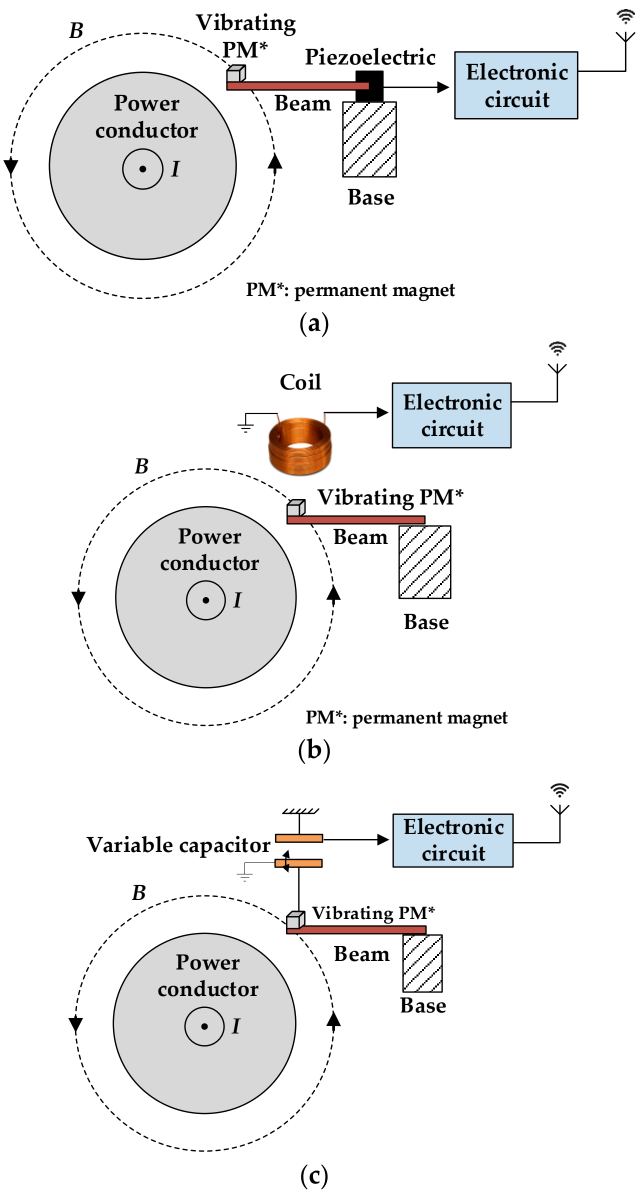



**Figure 3.** Hybrid magnetic–vibration EH using a permanent vibrating magnet due to the action of the AC magnetic field of the power line. (**a**) Piezoelectric energy harvesting adapted from [62]. (**b**) Inductive energy harvesting adapted from [63]. (**c**) Electrostatic energy harvesting.

Other methods, such as airflow energy harvesting, are not considered in this section due to the incompatibility of using rotating elements in power lines.

### *4.3. Thermoelectric Energy Harvesting*

The action of an electric current heats any conductor due to the ohmic resistance, which produces a temperature gradient between the conductor and the environment [4] so that objects at different temperatures allow energy to be harvested through heat transfer [11]. Thermoelectric energy harvesting techniques are typically based on thermoelectric generators (TEGs); that is, devices that convert the temperature difference between their two sides into electrical energy [5,64], according to the Seebeck, Peltier, and Thomson effects. Thermoelectric energy harvesting converts the temperature difference between the environment and the power line into electric energy [2]. However, the efficiency of thermal EH is governed by the Carnot cycle, so for small temperature gradients, low efficiencies are expected [11]. In addition, similar to solar and wind, thermoelectric EH often cannot generate stable electric power since it depends on environmental variables [14], and in the case of power lines, it depends on the intensity of the line current, which largely determines the temperature of the conductor. When applied to transmission lines, the wide temperature swings of both ambient and line conductors make it necessary to take special care and apply specific energy management approaches to ensure reliable and stable thermoelectric generation [38]. In the case of low temperature gradients, thermoelectric energy harvesting is increasingly applied to supply wearable devices [65]. According to [65], a 900 $mm^2$ TEG allows the extraction of between 5 and 50 μW with a few °C temperature difference, whereas in [66], it is shown that a 4-layer TEG with 5000 thermocouples can generate up to 200 μW with a temperature gradient of approximately 8 °C.

It is possible to harvest the energy of the heat flux between the conductor and the environment by wrapping a thermoelectric generator around it. A heat-transmitting paste is usually placed between the conductor and the thermoelectric generator to maximize the heat flux. A heat exchanger is often attached to the cold outer surface of the thermoelectric generator to maximize the temperature difference between the cold and hot surfaces of the thermoelectric generator [4].

In DC systems, due to the lack of a time-varying variable such as the electric or magnetic field, the development of EH systems becomes more difficult. Thermoelectric EH is especially appealing for DC systems since Joule losses are characteristic of both AC and DC systems [4]. Since AC transmission lines are much more common than DC transmission lines, few works apply thermoelectric generators for EH in DC transmission systems. In [67], thermoelectric EH was applied to supply a WSN that includes several sensors (temperature, current, and voltage drop) mounted on a cylindrical busbar for a substation connector. It was shown that the temperature gradient is a key parameter to determine the output power of the thermoelectric generator, which generated 155 μW for a temperature difference between the busbar and the ambient of 19 °C.

### *4.4. Magnetic Field Energy Harvesting*

Magnetic field EH harvesting has been extensively discussed in the literature. The magnetic field generated by a line conductor is directly proportional to the intensity of the current and decreases with distance from the conductor as,

$$B = \frac{\mu_0 I}{2\pi r} \tag{1}$$

$I$ being the intensity of the current, $\mu_0$ the magnetic permittivity of free air, and $r$ the distance from the measuring point and the center of the conductor.

From (1), it is evident that the magnetic field strength of power lines is substantial only in their close proximity, which limits the possible locations of EHs close to AC conductors. Another limitation is that energy harvesters are based on transformer action, so usually, they have wound coils, with their internal resistance limiting the extraction of energy, so a highly efficient circuit is required [68]. For efficient use, they need to be clamped around the conductor, thus limiting their application because, in some cases, it is not practical [11].

Current transformers are typically used for this purpose (see Figure 4), although power availability is highly dependent on the current level of the transmission line, so a minimum current flow is required [14].

Figure 4 shows the basic principle for energy harvesting from the magnetic field generated by power lines. Similar designs are found in numerous scientific works [59,69–74].

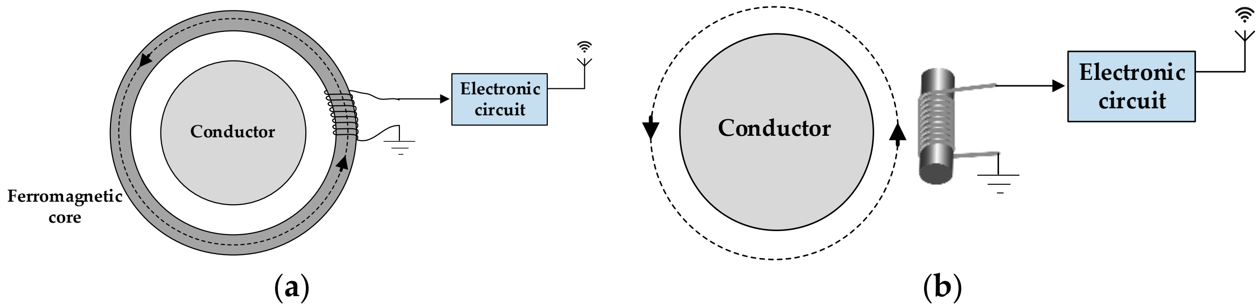



**Figure 4.** Magnetic field energy harvesting concept in power conductors, adapted from [75]. (**a**) Clamped topology. (**b**) Clampless topology.

In [39], it was shown that using a multi-winding up-conversion current transformer configuration is able to scavenge energy with a current as low as 1 A, thus providing enough power to supply wireless sensors. In [68], two inductors were placed between two parallel wires in opposite directions, carrying 8.4 A each, showing that depending on the configuration, up to 850 µW can be generated. In [76], it was shown that by using nano circular cut crystalline cores, high power densities could be achieved, around 100 mW/cm$^3$, 50 times higher than using conventional cores. In [77], the material role of magnetic toroidal cores was evaluated, showing that nanocrystalline alloy cores increase the power density about four times compared to ferrite cores. In [78], the role of core size was analyzed, showing that it is essential to optimize the power output of the harvester.

A miniature wound multicore structure made of mu-metal was proposed in [79], showing that it is able to deliver 10 mW to a 50 Ohm load. A magnetic field EH device based on a double-ring core was proposed in [80], showing that 32.8 mW can be harvested when the line current is as low as 10 A. In [11], a wound flux concentrator core made of silicon steel stuck to the conductor was proposed, which allows the concentration of the nearby flux very efficiently. The proposed design was shown to generate up to 257 mW when 1000 A flowed through the conductor. The design proposed in [11] does not have to be clamped around the conductor, which limits practical applications. In [81], an annular cored current transformer with high power density was presented, showing that it can generate 350 mW for a line current of 10 A. In [75], a toroidal core design methodology considering the saturation effect was proposed.

### *4.5. Electric-Field Energy Harvesting*

The electric field generated by a transmission line is independent of the current level since it only depends on the applied voltage. Therefore, electric field energy harvesting is the only method that can allow effective EH at any time the line is energized, even when not carrying any current. It makes electric-field EH the most feasible option to energize sensors from the point of view of predictability, availability, and controllability [14]. The idea of harvesting energy from the electric field is not new [11]. Electric-field energy harvesting does not depend on environmental variables, unlike many conventional harvesting methods [82], so it provides a more durable and reliable operation since it allows operation with any conductive material to which voltage is applied, making it ideal for applications requiring a certain quality of service. Since the frequency and voltage of transmission lines are tightly regulated, the electric field they generate is stable, allowing predictable amounts of energy to be harvested due to the constant rate of power harvested [14]. Electric-field EH is well suited for high-voltage transmission lines due to the strong associated electric fields, although different works have shown that it is also feasible in low-voltage applications [83,84] using low-power electronics and switches.

Any energized conductor generates a radial electric field. In the case of alternating current (AC) lines, the time-varying electric field produces a displacement current that can charge a nearby capacitor so that the energy stored in this capacitor $E_C$ can be expressed as,

$$E_C = \frac{1}{2} C V^2 \tag{2}$$

$C$ being the capacitance, and $V$ the voltage accumulated between the armatures of the capacitor terminals.

As shown in Figure 5, the EH unit includes diodes to rectify the generated voltage and prevent the scavenged energy from back feeding, capacitors or supercapacitors, and a controlled switch to regulate energy usage. The switch allows automatic charging of the capacitor (position 1) when the voltage is below a specific value and connects the capacitor to the load (position 2) when the stored energy is high enough for transmission. Therefore, it Is essential to use highly efficient rectifiers, microcontrollers, and regulators to optimize the overall efficiency of EH [14].

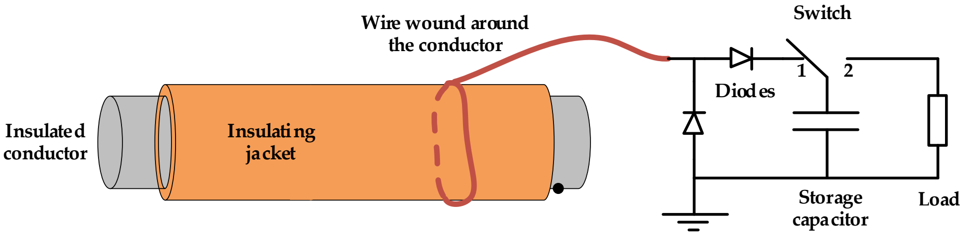



**Figure 5.** Electric-field energy harvesting using a wire wound around a conductor adapted [85].

In [85], a wire wound around an insulated single-phase 3-wire 220 V cable was used to harvest energy from the stray electric field, generating 680 nW on average. A sketch of this EH system is shown in Figure 5.

In [14,86], an EH system is proposed using a dielectric layer and a conducting sheath wrapped around the conductor that generates a stray capacitance, which is used to harvest energy from the electric field generated by the conductor. A multi-layer structure is also possible, as shown in Figure 6. A similar approach, shown in Figure 6a, was applied in [84] using a 220 V power line as a reference, showing an average power extracted of about 47 µW. In [87], using a copper sheet wrapped around a 230 V power line, the authors harvested 367.5 µW. In [88], a similar EH method was applied using a power line insulator, the authors stating that a continuous power of up to 17 mW can be extracted from a 12.7 kV medium voltage power line. Similar circuits can be applied using metallic plates instead of wrapping a conductive sheath around the conductor [85,89]. In [90], it has been shown that 2.5 µW can be extracted from a 120 V power line using a metallic plate. A similar approach is proposed in [91], showing that a displacement current of fractions of mA can be induced.

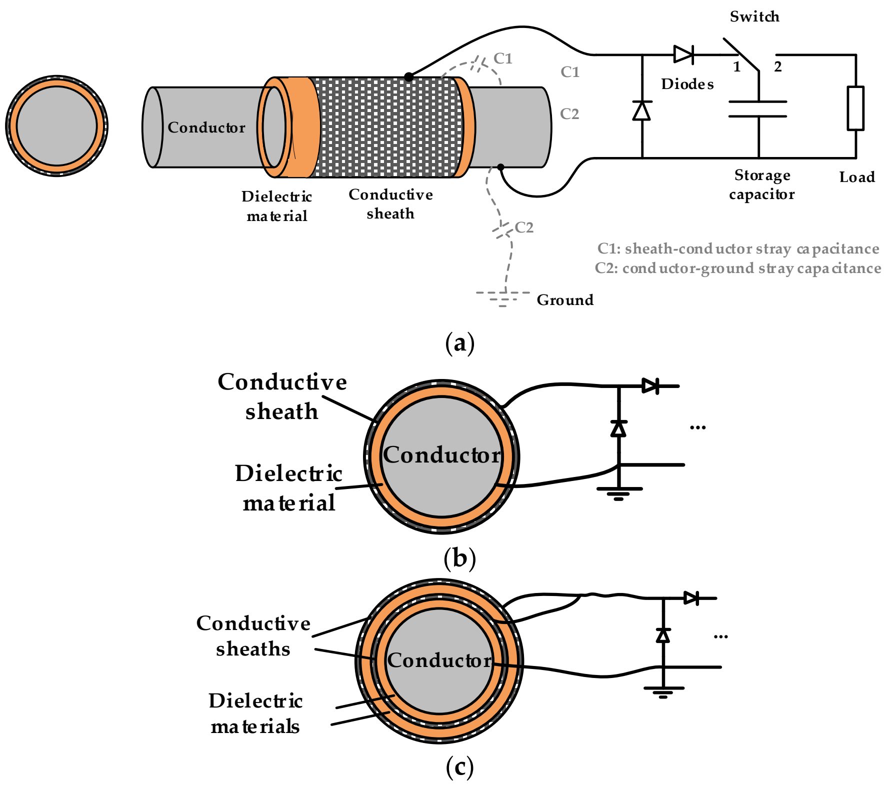



**Figure 6.** Electric-field energy harvesting concept in power conductors, adapted from [92]. (**a**) Schematics of the energy harvester. (**b**) Single-layer structure. (**c**) Two-layer structure.

*4.6. Radio-Frequency (RF) Energy Harvesting*

RF enables energy harvesting from RF sources such as base transceiver stations (BTS), TV towers, Wi-Fi, radio broadcast [93], or from dedicated RF transmitters [36] through the use of receiving antennas. These signals are then converted to DC power to supply sensor nodes [14]. RF power transmitters are broadly classified as dedicated units [94] and ambient RF power sources [95]. Ambient RF energy is found in a wide range of frequency bands, mainly in the MHz and GHz ranges [96]. Due to the widespread installation of communication systems, RF energy harvesting has become a widely analyzed technology, although it is still a challenge for low-power regions [7]. RF energy harvesting can provide a regular energy source in the presence of strong RF signals due to dedicated RF power transmitters.

Unlike wind and solar energy, local weather conditions do not affect RF sources [7]. RF EH presents notable features such as predictability, reliability, or the possibility of simultaneous power supply to different WSNs [96]. Additionally, RF signals can be found almost everywhere, 24 h a day, offering low-cost implementation, compactness, and a wireless nature [97,98].

The major drawback is related to the amount of power that can be harvested [99] due to the decay of the radiated power with the inverse square relationship with the distance to the radiation source [100]. The power density near powerful transmitters is relatively low, in the order of tens to hundreds nW/cm$^2$ [95,101] to some few µW/cm$^2$ [102–104], so power-dedicated transmitters are often required to supply WSns using inductive, capacitive, or radiative tag readers [11]. In addition, the input signal may not be permanently available due to random service usage or the duty cycle (mobile phones or Wi-Fi routers) or the size of the antenna required (AM radio waves) [105,106]. Therefore, automatic frequency tuning could be useful to maximize the output power [104].

As shown in Figure 7, a conventional RF EH circuit includes an antenna to convert the incoming RF signal into a voltage difference or vice versa, a rectifier to convert the high-frequency signal to DC, a voltage multiplier that produces a higher DC output voltage, and an energy storage device, such as a battery or a supercapacitor [96].

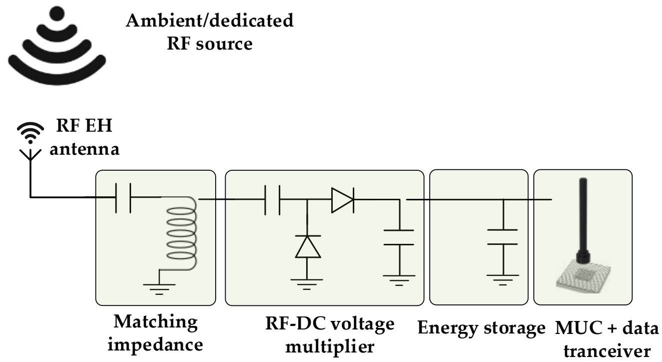



**Figure 7.** Basic structure of an RF EH node adapted from [107].

In [108], a BLE device was combined with a wireless RF energy harvester equipped with a 50 mF capacitor, charged by a GSM mobile, while in [109], a WSN prototype using an RF EH system from Wi-Fi transmissions was proposed. In [110], an ultra-high-frequency (UHF) RF energy harvesting solution was proposed to supply the electronics to monitor power lines. A planar monopole antenna was used for better resonator frequency performance. In [102], a multi-hop displacement of an array of magnetic antennas was proposed to harvest ambient energy for power cord monitoring. A far-field RF EH approach was also proposed for the same purpose.

Batteryless operation of RF-powered WSNs can be achieved by integrating the sensor into a radio-frequency identification (RFID) tag using an external RFID transmitter receiver [111]. Batteryless RF sensors can receive a steady energy flow from a nearby RFID reader during the entire measurement cycle, sufficient to supply the sensing and communication tasks [36].

Wake-up radio (WuR) is an energy-saving technique being applied in WSNs based on saving power by transiting into a low-power sleeping mode and turning off their main radios [112]. Devices implementing WuR usually maintain a low-power Wake-up Receiver waiting for any incoming Wake-up Signal (WuS). They can also sometimes include a wake-up transmitter capable of sending WuSs. The WuS wakes up the receiver device, which connects its main radio, so it is ready to communicate with other nearby devices [113]. WuR power consumption falls in the μW domain, but the IoT device often consumes several mW [114], although fractions of mW can be achieved in some cases [28]. Different works have integrated the capabilities of WuR technology into BLE devices [115–117]. In [118], a passive RF WuR device for a batteryless WSN is proposed.

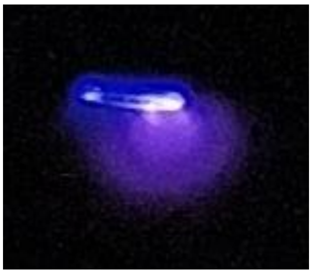
### *4.7. Corona Energy Harvesting*

Electric-field and magnetic-field EH are appropriate for AC power systems, but they are not suitable for DC systems due to the lack of an alternating field. Therefore, in DC systems, other strategies are required. Corona energy harvesting overcomes this difficulty.

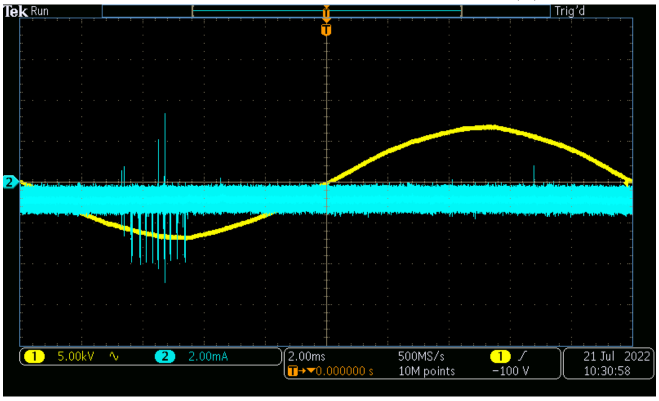
Corona is a type of electric discharge that occurs in gas insulation systems under a highly inhomogeneous AC or DC electric field [119,120]. It is generated at a lower voltage than required for complete breakdown [121]. Due to its ionization effect, the corona generates a space charge area, producing a flow of ions perceived as current pulses. In [122], it was shown that in the case of a single conductor energized at 100 kV-DC, the corona ion flow density is approximately 200 $\mu A/m^2$.

In [20], an EH approach based on the current induced by corona discharges is proposed based on using the corona current pulses generated by a corona electrode and a simple energy-harvesting circuit, resulting in a stable output of approximately 10 mW in a 22 kV-DC system, which is sufficient for the discontinuous operation of most sensors.

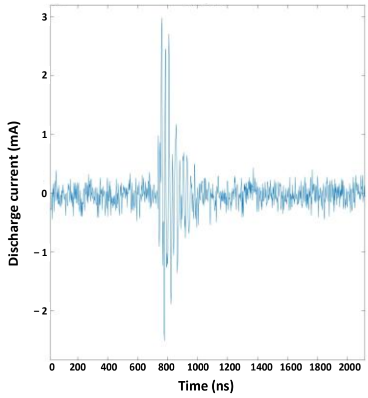
Figure 8 shows the main characteristics of a corona discharge taken by the authors of this work.



(**a**)




(**b**)




(**c**)

**Figure 8.** Corona discharges in a needle-plate geometry (needle diameter = 0.8 mm, needle tip-to-ground distance = 70 mm, 60 kPa, 3.6 kV, 50 Hz). (**a**) Photograph of the corona discharge in the tip of the needle. (**b**) Voltage (yellow) and current (blue) waveforms during the corona discharges. (**c**) Detail of a corona discharge as seen in the electrical current pattern.

## 5. Summary of EH Methods for Power Lines

This section summarizes the state-of-the-art EH systems for transmission lines found in the technical literature, shown in Figure 9.

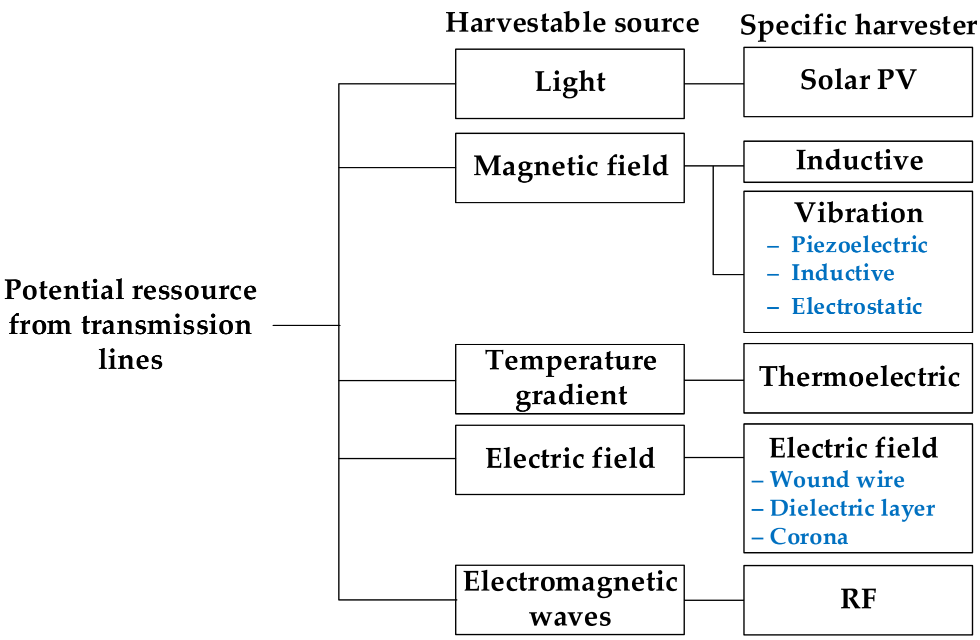



**Figure 9.** State-of-the-art EH systems for transmission lines.

Table 1 summarizes the main characteristics of the EH methods for power lines reviewed in this section.

**Table 1.** EH methods comparison for power lines.

| EH Type | Power Density | Advantages | Disadvantages | References |
|---|---|---|---|---|
| Solar | <100 mW/cm$^2$ | For AC and DC grids and high output power | No constant supply and regular maintenance | [14] |
| Vibration piezoelectric | 10–200 μW/cm$^3$ | No external supply required and high voltage output | Only for AC systems & Moving elements | [123] |
| Vibration inductive | 1–2 μW/cm$^3$ | No external supply required | Only for AC systems & Moving elements & low voltage output | [123] |
| Thermoelectric | 50 μW/cm$^2$ ($\Delta T$ = 5 °C) | For AC and DC grids | Requires current flow and a heat sink | [14] |
| Magnetic field | 280 μW/cm$^2$ | Easy to implement in AC grids | Difficult in DC grids and requires current flow | [14] |
| Electric field | 170 μW/cm$^2$ | Available under no load conditions | Difficult in DC grids | [124] |
| RF | 0.0002–1 μW/cm$^2$ | Abundant in urban areas For AC and DC grids | Low power density and scarce in remote areas | [14] |
| Corona | Not available | For AC and DC grids | Risk of overcurrent & requires more research | [20] |

The results presented in Table 1 clearly show that solar is the EH system with the highest power density, and it can be applied to both AC and DC transmission lines, although this method presents two important drawbacks related to periodic maintenance requirements and the impossibility of a constant supply. Other EH methods compatible with AC and DC lines are thermoelectric, RF and corona. RF is probably the EH system with the lowest power density. Solar, thermoelectric, electric field, and RF EH allow for generating energy even when the line is not carrying any current, i.e., under no load conditions. The results show that there is not a clear winner or universal solution, so the most suitable EH system depends on the characteristics of each particular application. These characteristics include the geographical location (it defines dust, sand, dirt, ice. or snow conditions, solar resource, or ambient RF energy), the intensity of the current flowing in the line, or the line voltage, among others.

It is worth noting that WSNs in transmission lines are often enclosed inside a metallic box that acts as a Faraday cage to block the intense electric field. In such cases, the common ground of the electronic board is connected to the metallic box, which, in turn, is in contact with the line conductor.

## 6. Identified Challenges and Research Needs

WSNs are often supplied at low power and are energy constrained, resulting in low processing capabilities, reduced power storage, and limited operational lifetime, although they offer multifunctional abilities. WSNs randomly deactivate when their storage elements are drained, thus leading to reduced duty cycles and reliability or short-range transmission [125]. All of these limitations contribute to quickly draining their stored energy when operating for extended periods [22]. Therefore, different critical issues around EH circuits have to be addressed, which are listed below in no specific order.

- WSNs must support hybrid EH configurations to extend communication frequency and range as well as onboard features. This area requires more research and development [124].
- Batteryless systems require a true self-starting operation; that is, to start their operation from any amount of ambient power without needing any special arrangement [124].

- Further developments in low-loss rectifiers, low-power micro-controllers, mV-range DC/DC converters, and highly efficient regulators are required to maximize system efficiency, thereby increasing communication reliability and system lifetime [14].
- Efficiency and integration are key points for a widespread application of WSNs, specifically batteryless, so the harvesters, interface circuits, and sensors could be integrated into the same package and even into the same semiconductor component. These advances could lead to dramatic reductions in the size and costs of WSNs [124].
- The use of improved materials with higher efficiency, such as better materials for solar cells, thermoelectric generators, piezoelectric cantilevers, magnetic components, or capacitors with loess leakage [124].
- The minimum voltage and power levels at which the system can harvest energy must be reduced to the minimum levels possible to extract all available energy [24].
- WSN devices operate a large portion of their time in sleep mode, which largely determines total power requirements, so to increase their lifespan, technologies that minimize power consumption in sleep mode need to be further optimized [24].
- The entire system can only be turned on when the voltage on the storage capacitor is beyond a threshold level, so the system's lifetime can be significantly extended by lowering the operating voltage [24].
- Due to the energy requirements, energy-efficient wireless communication modules play a critical role in increasing the lifetime of WSNs. Therefore, to optimize power transmission efficiency, ultra-low-power (ULP) transceivers are needed, along with the development of simpler modulation techniques and optimized signal waveforms and bandwidth [14].
- Multi-layer harvesting architectures allow more compact energy harvesters to be developed, which reduces storage needs, so much research is needed in this area [14].
- Data collected by WSNs must be transmitted securely and protected from cyber-attacks. Therefore, future developments need to consider this aspect [104] since power grids are strategic and critical facilities.

## 7. Conclusions

Due to the continuous increase in energy consumption worldwide, power grids in general, and transmission lines in particular, face important challenges related to their optimal use, availability, and security aspects. Predictive maintenance plans that are based on network monitoring approaches are known to be useful in increasing the stability, reliability, availability, and security of power grids. Transmission lines are found everywhere, sometimes in remote and inaccessible areas, where routine inspections are complex and expensive. For this, monitoring strategies based on wireless sensors placed in strategic places that acquire and send data in rea time to a control center becomes essential. To maximize their lifetime, such sensors must incorporate an energy harvesting (EH) unit to supply all electronic components. Due to the specificities of transmission lines, this work has reviewed and analyzed the state-of-the-art of energy harvesting strategies for transmission lines in depth, an area with enormous potential for expansion. EH methods applicable to transmission lines include solar, thermoelectric, magnetic field (inductive, and different types of vibrations induced by the magnetic field), electric field (wound wire, dielectric layer, and corona), and RF. From the state-of-the-art, it has been shown that among the different existing energy harvesting methods, there is not a universal solution since the most suitable EH system depends on the characteristics of each particular application, characteristics such as the geographical location (it defines dust, sand, dirt, ice, or snow conditions, solar resource, or available ambient RF energy), the intensity of the current flowing in the line or the line voltage among others. This work has also identified the challenges and research that needs to be addressed for a successful application of this technology because, despite the importance of this topic, there is still a long way to go as this area is still in its early stages. There is a wide range of possible applications that could potentially benefit from the introduction of such energy harvesting systems, including power transformers, distribution switches, or medium- and low- voltage power lines, among others.

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